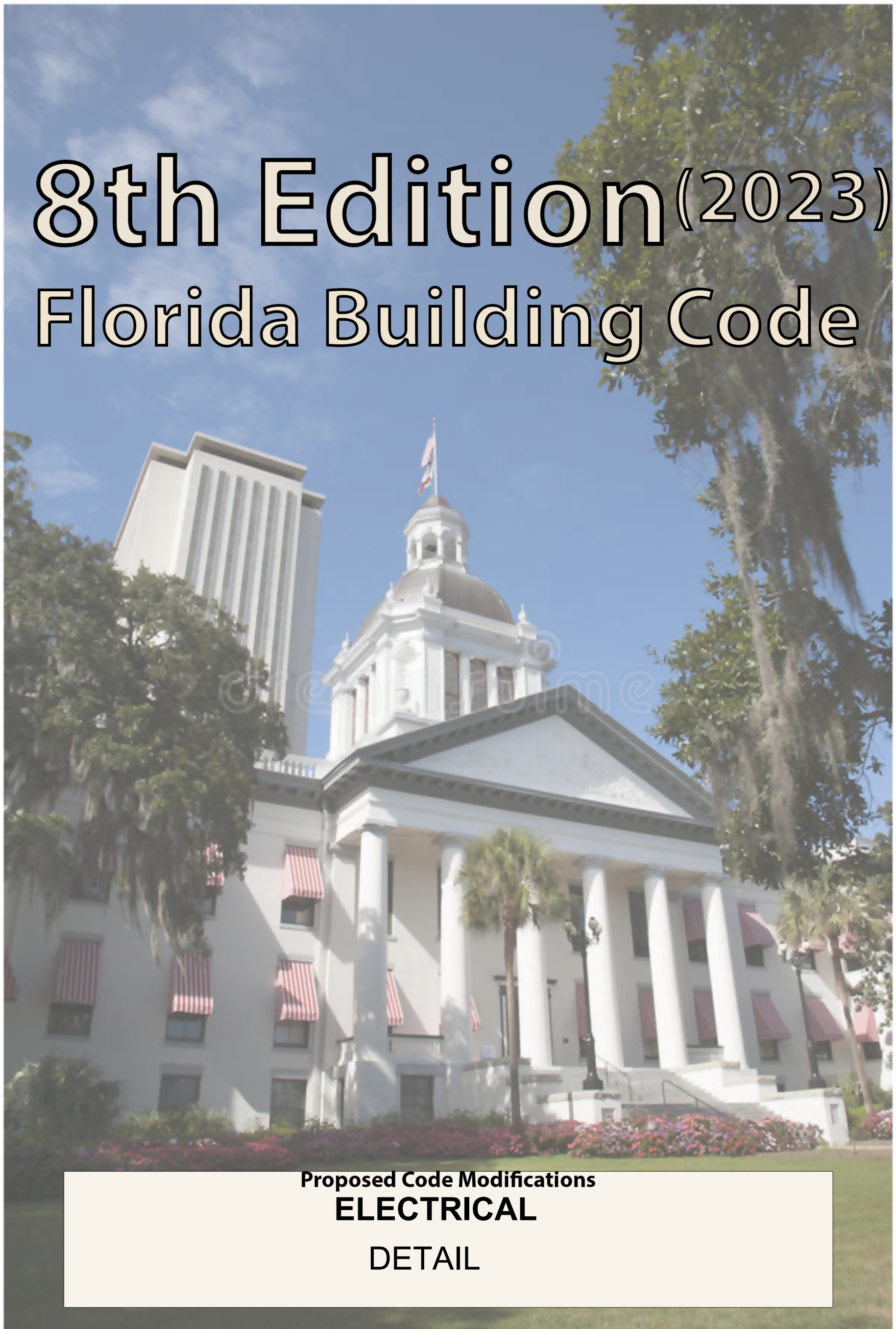

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850-487-1824

TAC: Electrical

Total Mods for **Electrical** in **Pending Review : 16**

Total Mods for report: 16

Sub Code: Building

E10316

1

Date Submitted	02/12/2022	**Section**	454.1.8.15	**Proponent**	Dallas Thiesen
Chapter	4	**Affects HVHZ**	No	**Attachments**	No
TAC Recommendation	Pending Review				
Commission Action	Pending Review				

Comments

General Comments No **Alternate Language No**

Related Modifications

Summary of Modification

Exempts spas with gravity flow drains from NEC emergency cut off switch requirements.

Rationale

Spas with gravity flow drain systems are at extremely low risk for suction entrapment incidents. The inclusion of an unnecessary cutoff switch can lead to unsanitary spa conditions when the switch is accidentally or intentionally erroneously activated. The Florida Department of Health argued for the adoption of gravity flow systems due to their inherent safety.

Fiscal Impact Statement

Impact to local entity relative to enforcement of code
None, simplifies code requirements.
Impact to building and property owners relative to cost of compliance with code
None, simplifies code requirements.
Impact to industry relative to the cost of compliance with code
None, simplifies code requirements.
Impact to small business relative to the cost of compliance with code

Requirements

Has a reasonable and substantial connection with the health, safety, and welfare of the general public
How a swimming pool system is designed and construction impact the health and safety of bathers.
Strengthens or improves the code, and provides equivalent or better products, methods, or systems of construction
Improves effectiveness of the code by simplifying and clarifying requirements.
Does not discriminate against materials, products, methods, or systems of construction of demonstrated capabilities
Does not specify particular materials, products, methods, or systems of construction.

Does not degrade the effectiveness of the code

Improves effectiveness of the code by simplifying and clarifying requirements.

454.1.8.15 Emergency cutoff switches

Spas equipped with gravity flow drain systems, regardless of when constructed, are exempted from Section 680.41 of NFPA-70.

However, ~~I~~if a spa is equipped with an emergency cutoff or kill switch, it shall include provisions for a minimum 80 decibel audible alarm near the spa to sound continuously until deactivated when such device is triggered. The following additional rule sign shall be installed to be visible by the spa which reads "ALARM INDICATES SPA PUMPS OFF. DO NOT USE SPA WHEN ALARM SOUNDS UNTIL ADVISED OTHERWISE."

TAC: Electrical

Total Mods for **Electrical** in **Pending Review : 16**

Total Mods for report: 16

Sub Code: Building

E10137

2

Date Submitted	02/15/2022	**Section**	2703	**Proponent**	Amanda Hickman
Chapter	27	**Affects HVHZ**	No	**Attachments**	Yes
TAC Recommendation	Pending Review				
Commission Action	Pending Review				

Comments

General Comments No

Alternate Language Yes

Related Modifications

10149

Summary of Modification

GFCI nuisance tripping

Rationale

This modification adds an exception to the current 2020 NEC language regarding the outdoor GFCI requirement [210.8(F)] for listed and labeled HVAC equipment.This proposed exception is urgently needed to prevent nuisance tripping that has and will continue to pose a serious health and safety risk. The sudden and unexpected loss of HVAC cooling in excessive heat due to a tripped GFCI breaker poses a danger to “at risk” populations. This ever-present risk presents a far greater threat to Floridians than does the isolated, non-code compliant incident that was used to justify the addition of 210.8 (F) to the 2020 NEC. The CDC statistics on heat-related deaths shows an annual average of 702 heat-related deaths in the U.S. from 2004 to 2018. LBA strongly encourages the Florida Building Commission to include the proposed HVAC exception or delete the requirement in its entirety to resolve the unintended safety issue caused by the current GFCI requirement.

Fiscal Impact Statement

Impact to local entity relative to enforcement of code

Will improve enforcement of code by resolving the unintended safety issue caused by the current GFCI requirement

Impact to building and property owners relative to cost of compliance with code

Will reduce cost because GFCI are not required for listed HVAC equipment.

Impact to industry relative to the cost of compliance with code

Will reduce cost because GFCI are not required for listed HVAC equipment.

Impact to small business relative to the cost of compliance with code

Requirements

Has a reasonable and substantial connection with the health, safety, and welfare of the general public

The proposed exception is urgently needed to prevent nuisance tripping that has and will continue to pose a serious health and safety risk.

Strengthens or improves the code, and provides equivalent or better products, methods, or systems of construction

Improves the code because the two technologies are not harmonized

Does not discriminate against materials, products, methods, or systems of construction of demonstrated capabilities

No, this modification will prevent nuisance tripping and not discriminate against systems of construction.

Does not degrade the effectiveness of the code

Will improve the effectiveness of the code by resolving the unintended safety issue caused by the current GFCI requirement.

Alternate Language

1st Comment Period History

E10137-A1

Proponent Bryan Holland **Submitted** 3/28/2022 8:23:31 AM **Attachments** Yes

Rationale:

It appears the original proposed modification is referencing an older version of section 210.8(F) that has been updated by TIA 20-13, issued by the NFPA Standards Council on August 26, 2021 and that has addressed the concerns expressed by the proponent. However, the current section has a sunset date of January 1, 2023 that I am proposing be deleted to allow the HVAC equipment employing power conversion equipment to remain exempt under the duration of the 8th edition FBC-B. Approval of this alternative code modification assures GFCI protection remains for outlets where shock and electrocution hazards are present while exempting certain equipment that may not be compatible with GFCI protection, at this time.

Fiscal Impact Statement

Impact to local entity relative to enforcement of code

This proposed alternative modification provides clarity to the AHJ on the enforcement of 210.8(F) with regard to HVAC equipment employing conversion equipment.

Impact to building and property owners relative to cost of compliance with code

This proposed alternative modification will reduce the cost of compliance by exempting certain equipment from the rule.

Impact to industry relative to the cost of compliance with code

This proposed alternative modification will reduce the cost of compliance by exempting certain equipment from the rule.

Impact to small business relative to the cost of compliance with code

Requirements

Has a reasonable and substantial connection with the health, safety, and welfare of the general public

This proposed alternative modification will increase health, safety, and the welfare of the general public by maintaining GFCI protection where it will be most effective while exempting non-compatible equipment.

Strengthens or improves the code, and provides equivalent or better products, methods, or systems of construction

This proposed alternative modification improves the code.

Does not discriminate against materials, products, methods, or systems of construction of demonstrated capabilities

This proposed alternative modification does not discriminate against materials, products, methods, or systems.

Does not degrade the effectiveness of the code

This proposed alternative modification improves the effectiveness of the code.

210.8(F) Outdoor Outlets. All outdoor outlets for dwellings, other than those covered in 210.8(A)(3), Exception to (3) and heating/ventilating/air-conditioning (HVAC) equipment employing power conversion equipment as a means to control compressor speed, that are supplied by single-phase branch circuits rated 150 volts to ground or less, 50 amperes or less, shall have ground-fault circuit-interrupter protection for personnel. ~~This requirement shall become effective on January 1, 2023 for mini-split-type heating/ventilating/air-conditioning (HVAC) equipment and other HVAC units employing power conversion equipment as a means to control compressor speed.~~

Informational Note: Power conversion equipment is the term used to describe the components used in HVAC equipment that is commonly referred to as a variable speed drive. The use of power conversion equipment to control compressor speed differs from multistage compressor speed control.

Exception: Ground-fault circuit-interrupter protection shall not be required on lighting outlets other than those covered in 210.8(C).

SECTION 2703
GFCI PROTECTION

2703.1 NFPA 70-20: *National Electric Code*, Article 210 (Branch Circuits), Section 210.8, Ground-Fault Circuit-Interrupter Protection for Personnel, is amended to read as follows:

210.8 Ground-Fault Circuit-Interrupter Protection for Personnel. Ground-fault circuit-interrupter protection for personnel shall be provided as required in 210.8(A) through (F). The ground-fault circuit-interrupter shall be installed in a readily accessible location.

… remaining text unchanged

(F) Outdoor Outlets. All outdoor outlets for dwellings, other than those covered in 210.8(A)(3), Exception to (3) that are supplied by single-phase branch circuits rated 150 volts to ground or less, 50 amperes or less, shall have ground-fault circuit-interrupter protection for personnel.

Exception No. 1: Ground-fault circuit-interrupter protection shall not be required on lighting outlets other than those covered in 210.8(C).

Exception No. 2: GFCI protection shall not be required for listed and labeled HVAC equipment.

Informational Note: See UL 60335-2-40, Household And Similar Electrical Appliances – Safety – Part 2-40:Particular Requirements for Electrical Heat Pumps, Air-Conditioners and Dehumidifiers or UL 1995, Heating and Cooling Equipment for product safety standards.(1)

Tentative Interim Amendment

NFPA® 70®

National Electrical Code®

2020 Edition

Reference: 210.8(F)
TIA 20-13
(SC 21-8-29 / TIA Log #1593)

Pursuant to Section 5 of the NFPA *Regulations Governing the Development of NFPA Standards*, the National Fire Protection Association has issued the following Tentative Interim Amendment to NFPA 70®, *National Electrical Code®*, 2020 edition. The TIA was processed by the National Electrical Code Panel 2, and the NEC Correlating Committee, and was issued by the Standards Council on August 26, 2021, with an effective date of September 15, 2021.

1. Revise Section 210.8(F) to read as follows:

210.8 Ground-Fault Circuit-Interrupter Protection for Personnel. …

(F) Outdoor Outlets. All outdoor outlets for dwellings, other than those covered in 210.8 (A)(3), Exception to (3), that are supplied by single-phase branch circuits rated 150 volts to ground or less, 50 amperes or less, shall have ground-fault circuit-interrupter protection for personnel. This requirement shall become effective on January 1, 2023 for mini-split-type heating/ventilating/air-conditioning (HVAC) equipment and other HVAC units employing power conversion equipment as a means to control compressor speed.

Informational Note: *Power conversion equipment* is the term used to describe the components used in HVAC equipment that is commonly referred to as a variable speed drive. The use of power conversion equipment to control compressor speed differs from multistage compressor speed control.

Exception: Ground-fault circuit-interrupter protection shall not be required on lighting outlets other than those covered in 210.8(C).

Issue Date: August 26, 2021

Effective Date: September 15, 2021

(Note: For further information on NFPA Codes and Standards, please see www.nfpa.org/docinfo**)**

TAC: Electrical

Total Mods for **Electrical** in **Pending Review : 16**

Total Mods for report: 16

Sub Code: Building

E10150

3

Date Submitted	02/15/2022	**Section**	2703	**Proponent**	Amanda Hickman
Chapter	27	**Affects HVHZ**	No	**Attachments**	Yes
TAC Recommendation	Pending Review				
Commission Action	Pending Review				

Comments

General Comments No **Alternate Language Yes**

Related Modifications

10138

Summary of Modification

GFCI nuisance tripping

Rationale

This modification deletes the problematic new requirement for outdoor GFCI outlets in Section 210.8(F) of the 2020 NEC. AHRI requests that the Florida Building Commission to set this requirement aside until a resolution to nuisance tripping has been developed. This new requirement poses a much greater risk to Floridian's life and health than does the isolated, non-code compliant incident that was used to justify the addition of 210.8 (F) to the 2020 NEC. As of January 1, 2022, the twenty states that have either adopted or in the process of adopting the 2020 NEC have deleted, modified or delayed the implementation.

Fiscal Impact Statement

Impact to local entity relative to enforcement of code
Will improve enforcement of code by setting aside requirement until a resolution is developed.
Impact to building and property owners relative to cost of compliance with code
Reduction to cost of compliance because GFCI are not required.
Impact to industry relative to the cost of compliance with code
Reduction to cost of compliance because GFCI are not required.
Impact to small business relative to the cost of compliance with code

Requirements

Has a reasonable and substantial connection with the health, safety, and welfare of the general public
This modification will protect the health and safety of the general public by deleting this section from the NEC
Strengthens or improves the code, and provides equivalent or better products, methods, or systems of construction

Improves the code by preventing nuisance tripping because the two technologies are not harmonized.

Does not discriminate against materials, products, methods, or systems of construction of demonstrated capabilities

No, simply deletes section. As of January 1, 2022, the twenty states that have either adopted or in the process of adopting the 2020 NEC have deleted, modified or delayed the implementation.

Does not degrade the effectiveness of the code

Improves effectiveness of code by addressing nuisance tripping.

Alternate Language

1st Comment Period History

E10150-A2

Proponent Bryan Holland **Submitted** 3/28/2022 8:32:45 AM **Attachments** Yes

Rationale:

It appears the original proposed modification is referencing an older version of section 210.8(F) that has been updated by TIA 20-13, issued by the NFPA Standards Council on August 26, 2021 and that has addressed the concerns expressed by the proponent. However, the current section has a sunset date of January 1, 2023 that I am proposing be deleted to allow the HVAC equipment employing power conversion equipment to remain exempt under the duration of the 8th edition FBC-B. Approval of this alternative code modification assures GFCI protection remains for outlets where shock and electrocution hazards are present while exempting certain equipment that may not be compatible with GFCI protection, at this time.

Fiscal Impact Statement

Impact to local entity relative to enforcement of code

This proposed alternative modification provides clarity to the AHJ on the enforcement of 210.8(F) with regard to HVAC equipment employing conversion equipment.

Impact to building and property owners relative to cost of compliance with code

This proposed alternative modification will reduce the cost of compliance by exempting certain equipment from the rule.

Impact to industry relative to the cost of compliance with code

This proposed alternative modification will reduce the cost of compliance by exempting certain equipment from the rule.

Impact to small business relative to the cost of compliance with code

Requirements

Has a reasonable and substantial connection with the health, safety, and welfare of the general public

This proposed alternative modification will increase health, safety, and the welfare of the general public by maintaining GFCI protection where it will be most effective while exempting non-compatible equipment.

Strengthens or improves the code, and provides equivalent or better products, methods, or systems of construction

This proposed alternative modification improves the code.

Does not discriminate against materials, products, methods, or systems of construction of demonstrated capabilities

This proposed alternative modification does not discriminate against materials, products, methods, or systems.

Does not degrade the effectiveness of the code

This proposed alternative modification improves the effectiveness of the code.

210.8(F) Outdoor Outlets. All outdoor outlets for dwellings, other than those covered in 210.8(A)(3), Exception to (3) and heating/ventilating/air-conditioning (HVAC) equipment employing power conversion equipment as a means to control compressor speed, that are supplied by single-phase branch circuits rated 150 volts to ground or less, 50 amperes or less, shall have ground-fault circuit-interrupter protection for personnel. ~~This requirement shall become effective on January 1, 2023 for mini-split-type heating/ventilating/air-conditioning (HVAC) equipment and other HVAC units employing power conversion equipment as a means to control compressor speed.~~

Informational Note: Power conversion equipment is the term used to describe the components used in HVAC equipment that is commonly referred to as a variable speed drive. The use of power conversion equipment to control compressor speed differs from multistage compressor speed control.

Exception: Ground-fault circuit-interrupter protection shall not be required on lighting outlets other than those covered in 210.8(C).

SECTION 2703
GFCI PROTECTION

2703.1 NFPA 70-20: *National Electric Code*, Article 210 (Branch Circuits), Section 210.8, Ground-Fault Circuit-Interrupter Protection for Personnel, is amended to read as follows:

210.8 Ground-Fault Circuit-Interrupter Protection for Personnel. Ground-fault circuit-interrupter protection for personnel shall be provided as required in 210.8(A) through (F). The ground-fault circuit-interrupter shall be installed in a readily accessible location.

… remaining text unchanged

~~**(F) Outdoor Outlets.** All outdoor outlets for dwellings, other than those covered in 210.8(A)(3), Exception to (3) that are supplied by single-phase branch circuits rated 150 volts to ground or less, 50 amperes or less, shall have ground-fault circuit-interrupter protection for personnel.~~

~~*Exception: Ground-fault circuit-interrupter protection shall not be required on lighting outlets other than those covered in 210.8(C).*~~

NFPA®

Tentative Interim Amendment

NFPA® 70®

National Electrical Code®

2020 Edition

Reference: 210.8(F)
TIA 20-13
(SC 21-8-29 / TIA Log #1593)

Pursuant to Section 5 of the NFPA *Regulations Governing the Development of NFPA Standards*, the National Fire Protection Association has issued the following Tentative Interim Amendment to NFPA 70®, *National Electrical Code®*, 2020 edition. The TIA was processed by the National Electrical Code Panel 2, and the NEC Correlating Committee, and was issued by the Standards Council on August 26, 2021, with an effective date of September 15, 2021.

1. Revise Section 210.8(F) to read as follows:

210.8 Ground-Fault Circuit-Interrupter Protection for Personnel. …

(F) Outdoor Outlets. All outdoor outlets for dwellings, other than those covered in 210.8 (A)(3), Exception to (3), that are supplied by single-phase branch circuits rated 150 volts to ground or less, 50 amperes or less, shall have ground-fault circuit-interrupter protection for personnel. This requirement shall become effective on January 1, 2023 for mini-split-type heating/ventilating/air-conditioning (HVAC) equipment and other HVAC units employing power conversion equipment as a means to control compressor speed.

Informational Note: *Power conversion equipment* is the term used to describe the components used in HVAC equipment that is commonly referred to as a variable speed drive. The use of power conversion equipment to control compressor speed differs from multistage compressor speed control.

Exception: Ground-fault circuit-interrupter protection shall not be required on lighting outlets other than those covered in 210.8(C).

Issue Date: August 26, 2021

Effective Date: September 15, 2021

(Note: For further information on NFPA Codes and Standards, please see www.nfpa.org/docinfo**)**

AIR-CONDITIONING, HEATING, & REFRIGERATION INSTITUTE
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February 9, 2022

Dear Florida Building Commission,

As of January 1, 2022, 18 of the 20 states that have adopted, or are in processing of adopting, the 2020 National Electrical Code (NEC) have deleted, modified, or delayed the implementation of section 210.8(F), which contains new requirements for ground-fault circuit interrupter (GFCI) protection on outdoor electrical circuits that are supplied by single-phase branch circuits rated 150 volts to ground or less. Specifically, the states that have refused to incorporate the new GFCI requirements in 210.8(F) are OR, WA, CO, TX, ND, SD, MA, IA, UT, GA, OK, SC, OH, MN, ME, NC, NJ and AL.

- Eight states (IA, NC, MA, SD, GA, SC, OK and UT) deleted 210.8(F) in its entirety.
- Four states (OH, ME, OR, and ND) modified 210.8(F).
- Six states (MN, TX, CO, WA, NJ, and AL) delayed the implementation of 210.8(F) until 1/1/2023.
- Two states (RI, DE) have adopted 2020 NEC without addressing 210.8(F).

As Florida considers how to address issues associated with this new 2020 NEC requirement, we refer you to the substantiation used by Massachusetts when they deleted 210.8(F):

> "This addition in the 2020 NEC has not been substantiated. The loss experience supporting this addition to the NEC was based on untrained and unqualified work on an air-conditioning condenser that ended up energized and a thereby caused a boy who jumped a fence and contacted the housing to become electrocuted. GFCI protection saves countless lives and certainly has its place. However, it is a fool's errand to imply to the public that improper work can be rendered essentially safe by waving the GFCI magic wand. For example, contact between two circuit conductors will never trip a GFCI. CMP-2 came within one vote of rejecting this; Massachusetts needs to set it aside and await proper support."

In addition to the above, Minnesota has encountered the same problem of nuisance tripping and issued a tentative interim amendment (TIA) request to the National Fire Protection Association (NFPA) on or about May 14, 2021 (TIA No. 1593). Minnesota's request provided the following rationale:

> "In the state of Minnesota, we began enforcing 210.8(F) on April 5, 2021, and we have already documented many cases of operational tripping occurrences which have been difficult for inspectors and electricians to resolve. The only solution at this time is for the AHJ [Authority Having Jurisdiction] to approve a temporary allowance for the installation of a circuit breaker without GFCI protection so that these HVAC units can operate."

This TIA was approved by the NFPA Code Making Panel 2 (CMP-2) and was issued by the NFPA Standards Council (TIA No. 20-13) in August 2021.

Yet another TIA request was submitted to NFPA on May 14, 2021 by the National Association of Home Builders (NAHB) (TIA No. 1589). The NAHB request notes:

> "The effects of this new requirement in the 2020 edition of the code has come to light over the past 1 to 2 weeks with the first hot/humid weather in Texas. Leading Builders of America (LBA) has collected the following data over the past couple days.
>
> > - Builder A has indicated a 73% failure rate (GFCI breaker tripping) for non-mini-split, non-variable speed systems. In other words, 100% of Builder A's failures are on single-speed conventional cooling systems.
> >
> > - Builder B has 36 homes where the HVAC system is operational. 100% of those homes have experienced a circuit trip. All of Builder B's failures are on single-stage systems. They currently have 10 open warranty tickets for closed (occupied) units where the circuit is tripping consistently, leaving the homeowners with effectively no HVAC."

NAHB goes on to note "In jurisdictions that have adopted 2020 NEC with 210.8(F) intact, there have been numerous instances of field tripping of the GFCI breaker on ductless mini splits, units containing power conversion equipment, and on many single-stage units." This TIA was rejected by NFPA CMP-2 and an appeal to the NFPA Standards Council in August 2021 was rejected.

The Air-Conditioning, Heating, and Refrigeration Institute (AHRI) previously submitted a similar TIA to NFPA (TIA No. 1564) requesting a delay in the effective date of this requirement (as it relates to inverter-driven HVAC equipment) to allow the industry to (1) update certification requirements in UL 943 and UL/CSA 60335-2-40 to address leakage current testing requirements at higher frequencies and (2) to allow manufacturers to make revisions to their equipment (both GFCI breakers and HVAC equipment manufacturers) to comply with new requirements. This TIA request was rejected by NFPA CMP-2, and an appeal was rejected by the NFPA Standards Council in August 2021.

Yet another TIA (No. 1529) was submitted to NFPA in August 2020 by an electrical inspector in Shelby County, Alabama because of the same problem existing in the Birmingham area. This TIA request was approved by CMP-2, for both "Technical Merit" and "Emergency Nature" by a vote of 12-2. However, the Code Correlating Committee unanimously approved the TIA on "correlation" but failed the TIA by a vote of 8-3 (75% required) as to the "emergency nature."

The HVAC industry has experienced many nuisance trips of GFCI breakers operating with inverter-driven HVAC equipment, as well as non-inverter-driven HVAC equipment. 100 percent of all inverter-driven HVAC products that we are aware of, when paired with a GFCI breaker, experience nuisance tripping. As noted in TIA No. 1589, single-stage and two-stage HVAC products also have nuisance tripping when paired with GFCI breakers. The long history of TIA efforts, including three active TIAs, shows that section 210.8(F) is truly problematic.

The NFPA Standards Council (during the AHRI/NAHB Appeals) requested that CMP-2 create a Task Group (including HVAC industry experts, GFCI experts, and other interested parties) to look further into the HVAC/GFCI issue at the urgence of the HVAC industry. The Standards Council expects that the outcome of this Task Group's work will be a new TIA concerning both the 2020 NEC and the 2023 NEC (currently under development).

Technical Justification

HVAC equipment complies with safety standards that have been in use for over 40 years.
Over 90% of HVAC equipment in use today is labeled and listed per UL 1995.[1] Safety standards have ensured that products certified to them are safe. This safety is evidenced by the installation of more than 120 million HVAC units throughout the U.S. in the last twenty years without a documented fatality from equipment that was properly installed by qualified individuals per manufacturer's instructions. [2]

These existing HVAC safety standards focus on the touch current hazard instead of the leakage current in various operating modes and single fault conditions while also ensuring grounding resistance measurements under load.
Specifically:

- UL 1995 clauses 21, 22, 24, 54, 78 and 79 ensure grounding/earthing.
- UL 60335-2-40 (4th ed) sections 13 and 16 cover leakage/electrical strength, while section 27 covers earthing.

Furthermore, GFCI breakers are approved to product safety standard UL 943. This standard specifies leakage current trip requirements only at 60Hz, where a leakage current of 6 mA at 60 Hz must trip the breaker and a leakage current of 4 mA at 60 Hz must not trip the breaker. Leakage current at other frequencies is not addressed by UL 943. As such, there are no test requirements covering additional frequencies used by inverter-driven HVAC equipment.

Air conditioner/heat pumps (AC/HP) are approved to product safety standard UL 1995 which does not specify a maximum for this type of leakage current. UL 1995 is the standard to which all AC/HP have been certified since the early 1990s. There is a new version of standard UL 60335-2-40 (4th edition), earmarked to replace UL 1995, but mandatory compliance with this new standard is not required until January 1, 2024. This new version of the standard UL 60335-2-40 has leakage current requirements but allows up to 10 mA. UL 60335-2-40 4th edition will also contain alternative grounding provisions that continue to ensure safe use and installation without using GFCIs.

The UL Standards Technical Panels (STPs) for both UL 943 and UL 60335-2-40 are addressing the conflict between these two standards, but there is no fixed resolution on the immediate horizon. And

[1] UL 1995 Heating and Cooling Equipment.

[2] AHRI, Central Air Conditioners and Air-Source Heat Pumps, https://ahrinet.org/resources/statistics/historical-data/central-air-conditioners-and-air-source-heat-pumps (showing the number of central air conditioners installed from 2001 to 2020).

once the standards are modified to resolve the conflict, it will still take time for manufacturers to develop products and get them in the market.

As the committee from Massachusetts noted, the 210.8(F) requirement was added as a result of one incident as a result of "untrained and unqualified work." We note that a CDC report published in 2020 states, "During 2004–2018, an average of 702 heat-related deaths occurred in the United States annually."[3] This CDC report documents 10,527 heat-related deaths in a 15-year period (702/year), and an additional 6,220 deaths where heat was the primary factor (414/year). The CDC report, on pg. 732, further explains that "Past studies have demonstrated a relationship between ambient temperatures and mortality (8). In particular, extreme heat exposure can exacerbate certain chronic medical conditions, including hypertension and heart disease (4,5). In addition, medications that are typically used to treat these chronic medical conditions such as beta-blockers, diuretics, and calcium-channel blockers, can interfere with thermoregulation and result in a reduced ability to respond to heat stress (5)." (*NOTE: The numbers in parenthesis are reference numbers in the CDC document*). It is clear, therefore, that health related concerns associated with heat exposure (lack of cooling) can be significant based on items reported by the CDC.

Recommendation

As such, the HVAC industry recommends that Florida delete 210.8(F) concerning new requirements for ground-fault circuit interrupter (GFCI) protection on outdoor electrical circuits that are supplied by single-phase branch circuits rated 150 volts to ground or less, 50 amperes or less, and to delay incorporating 210.8(F) until a future code cycle when the industry is better prepared to meet these requirements.

Sincerely,

Mary E. Koban

Air-Conditioning, Heating, and Refrigeration Institute
Senior Director Regulatory Affairs
Cell: 484-220-3011
E-mail: mkoban@ahrinet.org

AHRI
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[3] *Heat-Related Deaths – United States, 2004-2018,* Centers For Disease Control and Prevention, Morbidity and Mortality Weekly Report, Vol. 69, No. 24, June 19, 2020, Page 732, available at https://www.cdc.gov/mmwr/volumes/69/wr/pdfs/mm6924a1-H.pdf.

Reference documents:
The following links/summaries document the actions taken by the noted 18 states to delete, modify or delay 210.8(F) in the 2020 NEC.

IA: Section 210.8(F) was deleted in an amendment after adoption
https://dps.iowa.gov/divisions/electrical-examining-board/electrical-code-updates

MA: GFCI protection was removed for outdoor, non-receptacle outlets during the adoption process.
https://www.mass.gov/doc/527-cmr-12-massachusetts-electrical-code-amendments/download

NC (Proposed): Section 210.8(F) is proposed to be deleted when the 2020 edition is adopted later this year.
https://www.ncosfm.gov/media/2068/open - Due to procedural issue – NC remaining on 2017 NEC

ND: An exception is provided for mini-split & A/C units with DC invertors. The installer is required to fill out a form including information describing what the contractor has done to the resolve the issue.
https://www.ndseb.com/

OR: Section 210.8(F) was modified to only apply to outdoor receptacles for other than dwelling units.
https://www.oregon.gov/bcd/codes-stand/Documents/21oesc-table1-E-2021April.pdf

SD: Section 210.8(F) was not adopted with the 2020 NEC.
https://dlr.sd.gov/electrical/documents/adopted_code_2020.pdf

TX: An emergency rule delayed the requirements of Section 210.8(F) effective May 20, 2021.
https://www.sos.state.tx.us/texreg/archive/November122021/Adopted%20Rules/16.ECONOMIC%20REGULATION.html#70
https://www.sos.state.tx.us/texreg/archive/November122021/Adopted%20Rules/16.ECONOMIC%20REGULATION.html#68

UT: Section 210.8(F) is deleted – effective 7/1/2021. Bill SB 0033 signed by Governor 3/16/2021 (see page 29 of link).
https://legiscan.com/UT/text/SB0033/id/2335968/Utah-2021-SB0033-Enrolled.pdf

WA: The state is delaying enforcement of Section 210.8(F) until January 1, 2023.
https://lni.wa.gov/licensing-permits/_docs/Elc2011.pdf

GA: State adopted 2020 NEC effective 1/1/2021. State deleted 210.8(F) due to nuisance tripping issues associated with the expanded GFCI requirements effective 9/1/2021.
https://www.dca.ga.gov/sites/default/files/2021_nec_amendments.pdf

CO: State issued a 1-year temporary Variance to the requirements in 210.8(F) on 6/29/2021.
https://content.govdelivery.com/accounts/CODORA/bulletins/2e613c2

MN: MN adopted TIA 20-13, adding the following statement to 210.8(F) – "This requirement shall become effective on January 1, 2023 for mini-split-type heating/ventilating/air-conditioning (HVAC) equipment and other HVAC units employing power conversion equipment as a means to control compressor speed."

https://www.dli.mn.gov/sites/default/files/pdf/review60fall21.pdf

ME: An exception from these requirements added for heat pumps.
https://up.codes/viewer/maine/nfpa-70-2020/chapter/2/wiring-and-protection#2

DE: Adopted the 2020 NEC at June 2021 meeting and it is effective 9/1/2021.

OK: Deleted 210.8(F) during OUBCC meeting 10/19/2021.
https://www.ok.gov/oubcc/documents/2021%2010%2019%20Meeting%20Minutes.pdf

SC: SC Building Code Council voted to delete 210.8(F) at 10/6/2021 meeting. Amendments to 2020 NEC will be effective 1/1/2023.

NJ: NJ UCC voted to delay the implementation of 210.8(F) until 1/1/2023 unless there is still uncertainty in the practicability of the requirement, in which case the Division can revisit the issue.
https://www.nj.gov/dca/divisions/codes/advisory/pdf_ucc/CAB_minutes_08_13_2021.pdf

OH: Proposal amending 210.8(F) to exempt HVAC units employing power conversion equipment (variable speed drive) as a means to control compressor speed. There is no delay in the proposed amendments so this exclusion would be permanent - not simply delayed until 1/1/2023 per e-mail from OH on 9/2/2021.

AL: Will adopt TIA 20-13 to address concerns over 210.8(F) when completing review/adoption process in 2022.

RI: Effective 2/1/2022, RI adopts the 2020 NEC as the Rhode Island Electrical Code with 210.8(F) intact.
https://rules.sos.ri.gov/Regulations/part/510-00-00-5?reg_id=11323&utm_source=Campaign%3a+Code+Alerts&utm_medium=newsletter&utm_campaign=11+January+2022

NAHB TIA No. 1589 and MN Dept. of Labor and Industry TIA No. 1593
https://www.nfpa.org/codes-and-standards/all-codes-and-standards/list-of-codes-and-standards/detail?code=70

NFPA TIA No. 20-13:
https://www.nfpa.org/codes-and-standards/all-codes-and-standards/list-of-codes-and-standards/detail?code=70

TAC: Electrical

Total Mods for **Electrical** in **Pending Review : 16**

Total Mods for report: 16

Sub Code: Building

E10220

4

Date Submitted	02/11/2022	**Section**	2703	**Proponent**	John Lovett
Chapter	27	**Affects HVHZ**	No	**Attachments**	Yes
TAC Recommendation	Pending Review				
Commission Action	Pending Review				

Comments

General Comments Yes **Alternate Language No**

Related Modifications

Summary of Modification

This is a proposal to drop the arc fault requirement for the state of Florida.

Rationale

Majority of the trips are nuisance trips. Not constant. Only constant trips I've experienced with arc fault protection are either from an overcurrent or from a direct short. Same protection he would get with a standard trip breaker. No documented proof (that I know of) of arc fault protection actually preventing any fires, but there is very much proof of arc fault protection having nuisance trips. Actually causes a problem and doesn't prevent anything. Causes more problems than was meant to rectify. Documented proof of causing problems and no documented proof of solving problems. "Upgrading" (to AFCI protection), the NEC has downgraded the integrity of any circuit with arc fault protection. Arc fault protection is supposed to detect a spark. Once the spark is already happened it's too late. Like saying, "hello" to somebody after they've walked by you. Michigan and Indiana have completely dropped the requirement. Cost money. Every time nuisance trip being called by homeowner. Creates heat. Causes bus bars to burn over time. A first responder told me that when they cannot find a specific cause of a fire they fill in the blank with “electrical fire”. Have to fill in the blank. Reason there are so many documented electrical fires. Cost money. Every time nuisance trip being called by homeowner. Like taking a medication that causes more side effects than there are symptoms.

Fiscal Impact Statement

Impact to local entity relative to enforcement of code

would not impact entity either way.

Impact to building and property owners relative to cost of compliance with code

Material would cost less. This would eliminate "nuisance trips" which would save homeowners time, frustration, and money.

Impact to industry relative to the cost of compliance with code

Would eliminate "nuisance trips". Every time the ARC fault breaker trips, the homeowner will be calling the electrician. this could be totally eliminated by this proposal

Impact to small business relative to the cost of compliance with code

Requirements

Has a reasonable and substantial connection with the health, safety, and welfare of the general public

no

Strengthens or improves the code, and provides equivalent or better products, methods, or systems of construction

Yes. No more nuisance trips caused by arc fault breakers. This would save homeowners and contractors time, money and frustration.

Does not discriminate against materials, products, methods, or systems of construction of demonstrated capabilities

no

Does not degrade the effectiveness of the code

no

1st Comment Period History

E10220-G1

Proponent Bryan Holland Submitted 3/28/2022 8:50:09 AM Attachments No

Comment:

NEMA strongly opposes this proposed modification. AFCI protection is a fundamental fire-safety component of a premises wiring system. Deletion of these sections will result in an increased risk of fire as a result of unmitigated arcing-faults in branch circuits, outlets, appliances, and other utilization equipment. The reports of unwanted tripping have not been substantiated by the proponent. Guidance and other AFCI protection related resources have been shared with the proponent to assist him with the proper installation and troubleshooting of AFCI protected branch circuits in new and existing dwellings. NEMA urges the Electrical TAC and Commission oppose this proposed modification.

210.12 Arc-Fault circuit-interrupter protection. Arc-fault circuit-interrupter protection shall be provided as required in 210.12(A), (B), (C), and (D). Arc-fault circuit-interrupter shall be installed in a readily accessible location.

210.12(**A**) **Dwelling units**. All 120 volt, single Phase, 15 and 20 ampere branch circuit supplying outlets or devices installed and dwelling unit kitchens, family rooms, dining rooms, living rooms, parlors, libraries, dens, bedrooms, sunrooms, recreation rooms, Closets, hallways, laundry areas, or similar rooms or areas shall be protected by any of the means described in 210.12 (A)(1) through (6)

406.4(4) Arc-Fault circuit interrupter protection. If a receptacle outlet located in any area specified in 210.12 (A), (B) or (C) is replaced, a replacement receptacle at this outlet she'll be one of the following:

(1) a listed outlet branch-circuit type arc-fault circuit-interrupter receptacle

(2) A receptacle protected by a listed outlet branch-circuit type arc-fault circuit-interrupter type receptacle

(3) A receptacle protected by a listed combination type arc-fault circuit- interrupter type circuit breaker

SILVER STRAND ELECTRIC, INC.
117 POINSETTIA ST.
ATLANTIC BEACH, FL.
32233
LIC.# EC13003769

RE: Arc Fault Protection

2020 NEC

210.12 Arc-Fault circuit-interrupter protection. ~~Arc-fault circuit-interrupter protection shall be provided as required in 210.12(A), (B), (C), and (D). Arc-fault circuit-interrupter shall be installed in a readily accessible location.~~

210.12(A) **Dwelling units**. ~~All 120 volt, single Phase, 15 and 20 ampere branch circuit supplying outlets or devices installed and dwelling unit kitchens, family rooms, dining rooms, living rooms, parlors, libraries, dens, bedrooms, sunrooms, recreation rooms,~~
~~Closets, hallways, laundry areas, or similar rooms or areas shall be protected by any of the means described in 210.12 (A)(1) through (6)~~

406.4(4) Arc-Fault circuit interrupter protection. ~~If a receptacle outlet located in any area specified in 210.12 (A), (B) or (C) is replaced, a replacement receptacle at this outlet she'll be one of the following:~~

~~(1) a listed outlet branch-circuit type arc-fault circuit-interrupter receptacle~~

~~(2) A receptacle protected by a listed outlet branch-circuit type arc-fault circuit-interrupter type receptacle~~

~~(3) A receptacle protected by a listed combination type arc-fault circuit- interrupter type circuit breaker~~

E10220Text Modification

Mod_ 10220_ Text_ striked arc fault.pdf Page: 2

SILVER STRAND ELECTRIC, INC.

117 POINSETTIA ST.

ATLANTIC BEACH, FL.

32233

LIC.# EC13003769

Majority of the trips are nuisance trips. Not constant. Only constant trips I've experienced with arc fault protection are either from an overcurrent or from a direct short. Same protection he would get with a standard trip breaker.

No documented proof (that I know of) of arc fault protection actually preventing any fires, but there is very much proof of arc fault protection having nuisance trips. Actually **causes** a problem and doesn't prevent anything.

Causes more problems than was meant to rectify. **Documented proof of causing problems and no documented proof of solving problems.**

"Upgrading" (to AFCI protection), the NEC has **downgraded** the integrity of any circuit with arc fault protection.

Arc fault protection is supposed to detect a spark. Once the spark is already happened it's too late. Like saying, "hello" to somebody after they've walked by you.

Michigan and Indiana have completely dropped the requirement.

Cost money. Every time nuisance trip being called by homeowner.

Creates heat. Causes bus bars to burn over time.

A first responder told me that when they cannot find a specific cause of a fire they fill in the blank with "electrical fire". Have to fill in the blank. Reason there are so many documented electrical fires.

Cost money. Every time nuisance trip being called by homeowner.

Like taking a medication that causes more side effects than there are symptoms.

E10220Rationale

Mod_10220_Rationale_Why change.pdf Page: 2

TAC: Electrical

Total Mods for **Electrical** in **Pending Review : 16**

Total Mods for report: 16

Sub Code: Energy Conservation

5

E9974

Date Submitted	02/02/2022	**Section**	405.9	**Proponent**	John Hall
Chapter	4	**Affects HVHZ**	No	**Attachments**	Yes
TAC Recommendation	Pending Review				
Commission Action	Pending Review				

Comments

General Comments Yes **Alternate Language Yes**

Related Modifications

None

Summary of Modification

This modification creates new section C405.9 to require electric vehicle charging equipment (EVSE) in all new commercial construction. The number of EV Ready and EV Capable parking spaces required would be determined by the attached chart that is part of the modification.

Rationale

Florida is ranked number two in the United States for the number of registered electric vehicle as of the latest ranking in June 2021. EVs provide significant economic benefits for consumers through fuel and maintenance cost savings, and have been identified as a key climate strategy to reduce GHG emissions from the U.S. transportation sector. The interest in EVs has grown alongside greater EV model availability and increased vehicle range. Every major auto manufacturer in the world has announced a plan to electrify a significant portion of their vehicle fleets over the next 3-5 years. Ford recently announced an $11 billion investment to reach their goal of 40 EV models by 2022. The goal for GM: 20 EV models by 2023; for VW: 27 EV models by 2022; for Toyota: 10 BEVs by the early 2020's; and similar goals for Volvo, Daimler, Nissan, BMW, and Fiat-Chrysler. However, the lack of access to EV charging stations continues to be a critical barrier to EV adoption. In particular, there are significant logistical barriers for commercial building tenants to upgrade existing electrical infrastructure and install new EV charging stations. A lack of pre-existing EV charging infrastructure, such as electrical panel capacity, raceways, and pre-wiring, can make the installation of a new charging station cost-prohibitive for a potential EV-owner. The installation of an EV charging station is made three to four times less expensive when the infrastructure is installed during the initial construction phase as opposed to retrofitting existing buildings to accommodate the new electrical equipment.

Fiscal Impact Statement

Impact to local entity relative to enforcement of code

This modification will increase the number of inspections to be performed. The cost of enforcement will be offset by permit fees.

Impact to building and property owners relative to cost of compliance with code

The proposed modification increases the cost of construction. Costs for new EV Capable parking spaces i range from $300 to $850 per space. Costs for new EV Ready spaces range from $800 to $1300. The cost for EVSE retrofit in can be three or more times the cost of installations in new construction.

Impact to industry relative to the cost of compliance with code

Industry will likely benefit from this modification. Industry is adjusting by adopting a business model that involves installation, maintenance, and operation by an off site entity that then shares a portion of the revenue with the property or business owner.

Impact to small business relative to the cost of compliance with code

Requirements

Has a reasonable and substantial connection with the health, safety, and welfare of the general public

This modification provides an additional resource to reduce greenhouse gas emissions from petroleum fueled vehicles, thus contributing to the reduction in the effects of climate change, which has been identified as a hazard too the health and welfare of the general public.

Strengthens or improves the code, and provides equivalent or better products, methods, or systems of construction

This modification strengthens the code by providing guidance on the installation electric vehicle service equipment.

Does not discriminate against materials, products, methods, or systems of construction of demonstrated capabilities

This modification does not discriminate against any materials, products, methods, or systems of construction of demonstrated capabilities.

Does not degrade the effectiveness of the code

This modification does not degrade the effectiveness of the code. To the contrary, this modification provides guidance on the installation of electric vehicle service equipment.

Alternate Language

1st Comment Period History

E9974-A1

Proponent Bryan Holland **Submitted** 3/28/2022 5:20:22 PM **Attachments** Yes

Rationale:

This alternative proposed modification makes a few minor revisions to the original proposed modification. This includes editorial revisions to the definitions and the rules to provide technical clarity. Otherwise, NEMA fully supports the concept of EV-ready provisions in the FBC-EC as proposed and substantiated in the original proposed modification. NEMA urges the TAC(s) and Commission approve this proposed modification.

Fiscal Impact Statement

Impact to local entity relative to enforcement of code

This alternative proposed modification provides clear and enforceable language for the AHJ.

Impact to building and property owners relative to cost of compliance with code

This alternative proposed modification will increase the cost of compliance for buildings/property owners at time of initial construction while reducing the cost of compliance for an existing building that does not have the capacity or infrastructure in-place for the installation of EVSE.

Impact to industry relative to the cost of compliance with code

This alternative proposed modification will increase the cost of compliance for industry.

Impact to small business relative to the cost of compliance with code

Requirements

Has a reasonable and substantial connection with the health, safety, and welfare of the general public

This alternative proposed modification improves the general welfare of the public as the electrification of transportation becomes a fundamental of modern society.

Strengthens or improves the code, and provides equivalent or better products, methods, or systems of construction

This alternative proposed modification improves the code.

Does not discriminate against materials, products, methods, or systems of construction of demonstrated capabilities

This alternative proposed modification does not discriminate against materials, products, methods, or systems of construction.

Does not degrade the effectiveness of the code

This alternative proposed modification improves the code.

1st Comment Period History

E9974-G1

Proponent John Hall Submitted 3/31/2022 10:35:28 AM Attachments No

Comment:

I support the alternate language comment submitted by Bryan Holland and endorse it's submission to the TAC(s) for consideration of inclusion in the 2023 FBC.

1st Comment Period History

E9974-G2

Proponent Susannah Troner Submitted 4/12/2022 11:24:34 PM Attachments No

Comment:

Writing to express strong SUPPORT for proposed code modification EN 9974. The transportation sector, dominated by traditional internal combustion engine vehicles, currently generates 55% of our community’s carbon pollution. EVs greatly reduce this pollution. Therefore this code modification will help minimize future impacts such as sea level rise and intensification of storms that are associated with carbon pollution (GHGs). These pollution reductions resulting from the code change will lead to community health and safety benefits which are core objectives of the Florida Building Code. Our office is fielding more inquiries every day from stakeholders regarding the lack of EVSE and standardization and perceived costs. It is time to standardize the process and require EV Ready Spaces and EV Capable Spaces for new commercial construction. This will help prevent future EVSE scarcity and extreme costs associated with facility retrofits.

1st Comment Period History

E9974-G3

Proponent	kamrath christian	Submitted	4/13/2022 12:35:56 PM	Attachments	No

Comment:

I am writing to express strong SUPPORT for proposed code modification EN 9974. The transportation sector, dominated by traditional internal combustion engine vehicles, generates 55% of our community’s carbon pollution. EVs greatly reduce this pollution and help create healthier environments. And we need to be doing everything we can to reduce carbon pollution faster to stem the accelleration of rising water levels and climate disruption. Therefore this code modification will help minimize future impacts such as sea level rise and intensification of storms that are associated with carbon pollution (GHGs). Pollution reductions resulting from the code change will lead to community health and safety benefits which are core objectives of the Florida Building Code. Our County's office is fielding more inquiries every day from stakeholders regarding the lack of EVSE and standardization, and perceived costs. It is time to standardize the process and require EV Ready Spaces and EV Capable Spaces for new commercial construction. This will help prevent future EVSE scarcity and extreme costs associated with facility retrofits.

1st Comment Period History

E9974-G4

Proponent	Matthew Chen	Submitted	4/13/2022 4:44:23 PM	Attachments	No

Comment:

SemaConnect, a leading provider of EV charging solutions with many EVSE projects in Florida, supports proposed code modification EN 9974, which establishes modest but necessary EVSE commercial requirements for new construction. We also support the proposed alternative modification submitted by Bryan Holland. We respectfully recommend inclusion of the proposed alternative modification in the 2023 Florida Building Code.

1st Comment Period History

E9974-G5

Proponent	Nicholas Gunia	Submitted	4/14/2022 10:09:32 AM	Attachments	No

Comment:

As past Chair of the Miami Branch of the South Florida Chapter of the US Green Building Council, I am writing to voice my support for EN10370 for requiring new commercial to have EVSE. I believe the proposed changes will help future-proof our commercial buildings given the rise of EVs. As such, the proposed changes should be adopted.

1st Comment Period History

E9974-G6

Proponent	Amanda Hickman	Submitted	4/14/2022 11:16:08 AM	Attachments	No

Comment:

LBA does not support the modification, as it is not appropriate for Florida and/or is not cost justified.

1st Comment Period History

E9974-G7

Proponent Jared Walker Submitted 4/14/2022 2:25:00 PM Attachments No

Comment:

EN 9974 - Electric vehicle charging infrastructure (EVSE) commercial requirements The Electrification Coalition (EC) is a national, nonpartisan, not-for-profit organization committed to promoting policies and actions that facilitate the deployment of electric vehicles on a mass scale to combat the national security, economic, and public health impacts associated with our nation's dependence on oil. The EC SUPPORTS proposed code modification EN 9974, establishing modest but necessary EVSE commercial requirements for new construction. Mass adoption of EVs is key to addressing the U.S.'s reliance on oil, which currently powers 91% of our nation's transportation system. Not only will ongoing transportation electrification policies such as Miami Dade's code modification (EN 9974) accelerate EV adoption, but fostering investments in the future of electric transportation will be a boon to Miami-Dade's economy and job growth.

1st Comment Period History

E9974-G8

Proponent Estela Tost Submitted 4/14/2022 6:56:52 PM Attachments Yes

Comment:

I am in support of EN9974 Electrical Vehicle Charging Station infrastructure for new commercial construction

1st Comment Period History

E9974-G9

Proponent Richard Logan Submitted 4/15/2022 9:57:28 AM Attachments No

Comment:

AIA Florida supports this code modification with the alternate language

1st Comment Period History

E9974-G10

Proponent James Ellis Submitted 4/15/2022 2:34:08 PM Attachments No

Comment:

EV Connect, a leading electric vehicle infrastructure network and services provider with many EVSE projects in Florida, SUPPORTS proposed code modification EN 9974, which establishes modest but necessary commercial EVSE requirements for new construction. EV Connect encourages this body to consider diversity of electric supply for more than 10 parking spaces in accordance with 2017 NFPA 70. Please Note: An omission of the number "20" in Table C405.9.2.1 under Total Number of Parking Spaces requires revision for clarity.

1st Comment Period History

E9974-G11

Proponent Sandra St. Hilaire Submitted 4/15/2022 2:44:53 PM Attachments No

Comment:

Writing to express strong SUPPORT for proposed code modification EN 9974. The transportation sector, dominated by traditional internal combustion engine vehicles, generates 55% of our community's carbon pollution. EVs greatly reduce this pollution. Therefore this code modification will help minimize future impacts such as sea level rise and intensification of storms that are associated with carbon pollution (GHGs). Pollution reductions resulting from the code change will lead to community health and safety benefits which are core objectives of the Florida Building Code. Our office is fielding more inquiries every day from stakeholders regarding the lack of EVSE and standardization, and perceived costs. It is time to standardize the process and require EV Ready Spaces and EV Capable Spaces for new commercial construction. This will help prevent future EVSE scarcity and extreme costs associated with facility retrofits.

1st Comment Period History

E9974-G12

Proponent	Mike Gibaldi	Submitted	4/15/2022 4:50:58 PM	Attachments	No

Comment:

No brainer here. Our firm with hundreds of EVSE charging ports installed throughout the State, fully SUPPORTS this proposed code modification which establishes modest but necessary EVSE commercial requirements for new construction. This will encourage more emission-free driving in Florida which will in turn greatly reduce CO2 pollution.

1st Comment Period History

E9974-G13

Proponent	Chris Sanchez	Submitted	4/15/2022 5:12:18 PM	Attachments	No

Comment:

I am strongly in favor of the proposed modifications to EN 9974. The transportation sector currently generates 55% of our community’s carbon pollution. EVs greatly reduce this pollution by shifting from tail-pipe to electricity grid. Therefore this code modification will help minimize future impacts such as sea level rise and intensification of storms that are associated with carbon pollution (GHGs). Pollution reductions resulting from the code change will lead to community health and safety benefits which are core objectives of the Florida Building Code. Our office is fielding more inquiries every day from stakeholders regarding the lack of EVSE and standardization, and perceived costs. It is time to standardize the process and require EV Ready Spaces and EV Capable Spaces for new commercial construction. This will help prevent future EVSE scarcity and extreme costs associated with facility retrofits.

1st Comment Period History

E9974-G14

Proponent	Marta Marello	Submitted	4/17/2022 4:02:30 PM	Attachments	No

Comment:

I express strong SUPPORT for proposed code modification EN 9974. It is time to standardize the process and require EV Ready Spaces and EV Capable Spaces for new commercial construction. As more EV models are coming onto the market and the share of EVs increases, it is important to integrate EVSE in buildings in a cost-effective way and avoid very costly retrofits. The transportation sector is the number one cause of our region’s carbon pollution. EVs greatly reduce this pollution. Pollution reductions resulting from the code change will lead to community health and safety benefits which are core objectives of the Florida Building Code. Miami-Dade County's Office of Resilience has responded to an increasing number of inquiries from stakeholders regarding the lack of EVSE, EVSE standardization, and perceived costs.

C405.9. Electric Vehicle Service Equipment

ELECTRIC VEHICLE SUPPLY EQUIPMENT (EVSE). Equipment for plug-in power transfer including the ungrounded, grounded, and equipment grounding conductors, and the Electric Vehicle connectors, attachment plugs, and all other fittings, devices, power outlets, or apparatus installed specifically for the purpose of transferring energy between the premises wiring and the Electric Vehicle.

EV CAPABLE SPACE. Electrical distribution equipment capacity and space to support a minimum 40-ampere, 208-volt or 240-volt branch circuit for each EV parking space, and the installation of necessary wiring methods and materials to supply *EVSE.*

EV READY SPACE. A designated parking space which is provided with one 40-ampere, 208-volt or 240-volt individual branch circuit for *EVSE* supplying *Electric Vehicles*. The circuit shall terminate in a suitable termination point such as a receptacle, outlet box, enclosure, or an *EVSE*, and be located in close proximity to the proposed location of the EV parking spaces.

C405.9.2. Electric Vehicle (EV) power transfer for new construction. New construction shall facilitate future installation and use of *EVSE* in accordance with the NFPA 70.

C405.9.2.1. New commercial buildings. *EV Ready Spaces* and *EV Capable Spaces* shall be provided in accordance with Table C405.9.1. Where the calculation of percent served results in a fractional parking space, it shall be shall rounded up to the next whole number. The electrical distribution equipment circuit directory shall identify the spaces reserved to support EV power transfer as "EV Capable" or "EV Ready". The box or enclosure provided for future EVSE shall be marked "FOR EVS USE." The marking shall comply with NFPA 70, Section 110.25

TABLE C405.9.2.1.

***EV READY SPACE* AND *EV CAPABLE SPACE* REQUIREMENTS**

Total Number of Parking Spaces	**Minimum number of *EV Ready Spaces***	**Minimum number of *EV Capable Spaces***
1	1	-
2 – 10	2	-
11 – 15	2	3
16 – 19	2	4
21 - 25	2	5
26+	2	20% of total parking spaces

C405.9.2.2. Identification. Construction documents shall indicate the raceway or cable assembly termination point and proposed location of future EV spaces and EVSE. Construction documents shall also provide information on the wiring methods, wiring schematics, and electrical load calculations to verify that the service capacity and premises wiring system have sufficient capacity to simultaneously charge all EVs at all required EV spaces at the full rating of the *EVSE.*

SECTION C405

ELECTRICAL POWER AND LIGHTING SYSTEMS

C405.1General (Mandatory).

This section covers lighting system controls, the maximum lighting power for interior and exterior applications and electrical energy consumption.

Dwelling units within multifamily buildings shall comply with Section R404.1. All other dwelling units shall comply with Section R404.1, or with Sections C405.2.4 and C405.3. Sleeping units shall comply with Section C405.2.4, and with Section R404.1 or C405.3. Lighting installed in walk-in coolers, walk-in freezers, refrigerated warehouse coolers and refrigerated warehouse freezers shall comply with the lighting requirements of Section C403.2.14.

C405.9. Electric Vehicle Service Equipment

-

-

ELECTRIC VEHICLE SUPPLY EQUIPMENT (EVSE). The conductors, including the ungrounded, grounded, and equipment grounding conductors, and the Electric Vehicle connectors, attachment plugs, and all other fittings, devices, power outlets, or apparatus installed specifically for the purpose of transferring energy between the premises wiring and the Electric Vehicle.

EV CAPABLE SPACE. Electrical panel capacity and space to support a minimum 40-ampere, 208/240-volt branch circuit for each EV parking space, and the installation of raceways, both underground and surface mounted, to support the *EVSE*.

EV READY SPACE. A designated parking space which is provided with one 40-ampere, 208/240-volt dedicated branch circuit for EVSE servicing *Electric Vehicles*. The circuit shall terminate in a suitable termination point such as a receptacle, junction box, or an *EVSE*, and be located in close proximity to the proposed location of the EV parking spaces.

C405.9.2. Electric Vehicle (EV) charging for new construction. New construction

shall facilitate future installation and use of *Electric Vehicle Supply Equipment (EVSE)* in accordance with the NFPA 70.

C405.9.2.1. New commercial buildings. *EV Ready Spaces* and *EV Capable Spaces* shall be provided in accordance with Table C405.9.1. Where the calculation of percent served results in a fractional parking space, it shall be shall rounded up to the next whole number. The service panel or sub panel circuit directory shall identify the spaces reserved to support EV charging as “EV Capable” or “EV Ready”. The raceway location shall be permanently and visibly marked as “EV Capable”.

TABLE C405.9.2.1.

***EV READY SPACE* AND *EV CAPABLE SPACE* REQUIREMENTS**

Total Number of Parking Spaces	**Minimum number of *EV Ready Spaces***	**Minimum number of *EV Capable Spaces***
1	1	-
2 – 10	2	-
11 – 15	2	3
16 – 19	2	4
21 - 25	2	5
26+	2	20% of total parking spaces

-

C405.9.2.2. Identification. Construction documents shall indicate the raceway termination point and proposed location of future EV spaces and EV chargers. Construction documents shall also provide information on amperage of future *EVSE*, raceway methods, wiring schematics and electrical load calculations to verify that the electrical panel service capacity and electrical system, including any on-site distribution transformers, have sufficient capacity to simultaneously charge all EVs at all required EV spaces at the full rated amperage of the *EVSE*.

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Proposed Code Modifications
USER: Estela Tost

Proposed Code Modifications Menu > Modification Search > Modification List > Modification Detail > Submit a Comment > **General Comment Detail**

OFFICE OF THE SECRETARY

* Required fields

Modification #	EN9974-G8
Name	Estela Tost
Address	8500 SW 117 Avenue Suite 120
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Code Change Cycle	2023 Triennial First Comment Period 03/03/2022 - 04/17/2022
Code Version	2023
Sub Code	Energy Conservation
Chapter & Topic	Chapter 4 - [CE] - Commercial Energy Efficiency
Section	405.9
	-
Status	Pending DBPR Review

General Comment*

I am in support of EN9974 Electrical Vehicle Charging Station infrastructure for new commercial construction

Upload Comment File

Date Submitted	04/14/2022

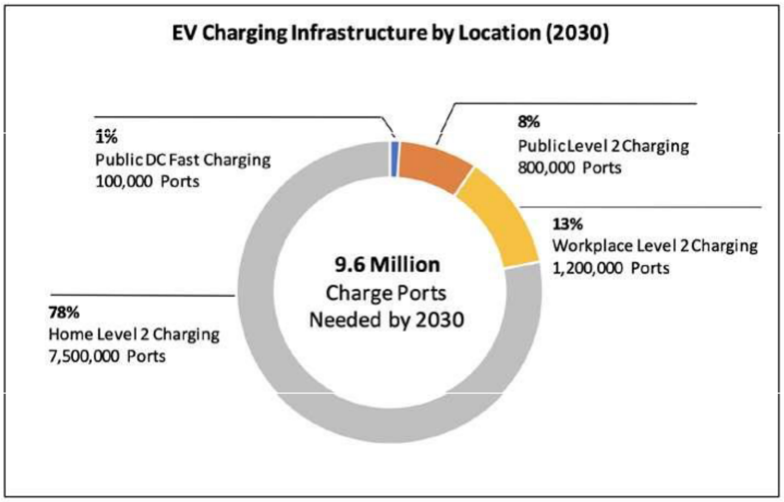
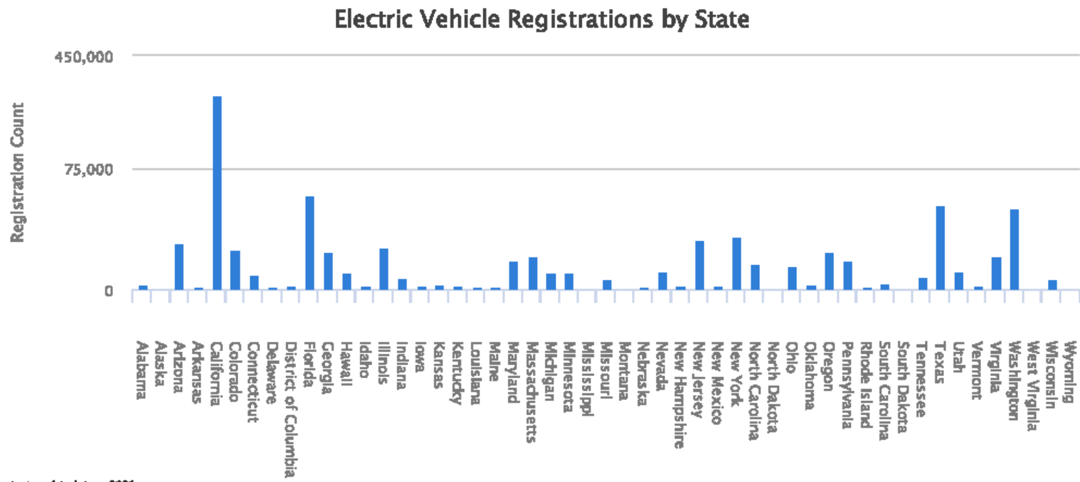


Figure 1. EV Charging Infrastructure in 2030 Based on EEI/IEI Forecast.



Last updated: June 2021
Printed on: January 10

TAC: Electrical

Total Mods for **Electrical** in **Pending Review : 16**

Total Mods for report: 16

Sub Code: Energy Conservation

E9993

6

Date Submitted	02/01/2022	**Section**	403	**Proponent**	Bryan Holland
Chapter	4	**Affects HVHZ**	No	**Attachments**	Yes
TAC Recommendation	Pending Review				
Commission Action	Pending Review				

Comments

General Comments Yes **Alternate Language No**

Related Modifications

Summary of Modification

This proposed modification adds requirements for fault detection and diagnostics (FDD) for new buildings with an HVAC system serving a gross conditioned floor area of 100,000 square feet or larger.

Rationale

Fault Detection and Diagnostics (FDD) technology significantly reduces costs and improves operational efficiency. It incorporates a standard library of fault rules that can be customized to predict equipment failures and advise personnel of preventive actions. Before the emergence of FDD software solutions, many organizations relied on institutional knowledge in order to fix or maintain their wide variety of equipment. After the development of FDD tech, this type of info (the numerous symptoms, causes and recommended actions) that may have only existed in the heads of senior personnel or, if lucky, in print or electronic archives, could now be used in algorithms to help organizations move from reactionary “break/fix” maintenance to more modern, more cost-effective predictive maintenance. Return on investment studies indicate typical ROI within 12 to 18 months following installation. Please see the attached reports from the Lawrence Berkeley National Laboratory and American Society of Heating, Refrigerating and Air-Conditioning Engineers/Pacific Northwest National Laboratory. This proposed modification improves the code and meets the mandate outlined in F.S. 553.886 that states; "the Florida Building Code must facilitate and promote the use of cost-effective energy conservation, energy-demand management, and renewable energy technologies in buildings.

Fiscal Impact Statement

Impact to local entity relative to enforcement of code

This proposed modification will require the local entity to confirm FDD is included on the construction documents at time of plan review and has been installed and operational at time of inspection.

Impact to building and property owners relative to cost of compliance with code

This proposed modification will increase the cost of compliance with the code but will result in improved HVAC system efficiency and have a return on investment not greater than 18 months from time of installation.

Impact to industry relative to the cost of compliance with code

This proposed modification will increase the cost of compliance with the code for industry. FDD software and hardware is readily available in the marketplace by a multitude of manufacturers. FDD design, installation, and operation requires specialized training.

Impact to small business relative to the cost of compliance with code

Requirements

Has a reasonable and substantial connection with the health, safety, and welfare of the general public

This proposed modification will improve the health and welfare of the general public by improving HVAC system efficacy and reducing operating costs for large HVAC systems.

Strengthens or improves the code, and provides equivalent or better products, methods, or systems of construction

This proposed modification improves the code and meets the mandate outlined in F.S. 553.886 that states; "the Florida Building Code must facilitate and promote the use of cost-effective energy conservation, energy-demand management, and renewable energy technologies in buildings."

Does not discriminate against materials, products, methods, or systems of construction of demonstrated capabilities

This proposed modification does not discriminate against any materials, methods, or systems of constructions.

Does not degrade the effectiveness of the code

This proposed modification improves the effectiveness of the code.

1st Comment Period History

E9993-G1

Proponent	Muthusamy Swami	Submitted	4/17/2022 12:49:49 PM	Attachments	No

Comment:

The change requires permanently installed sensors, sample data every 15 minutes, and communicate faults and recommended repair remotely. R-1 and R-2 group buildings are exempted from this requirement. The proposed code change increases construction cost but it is economical per FSEC’s cost-benefit analysis with an average payback period of under 2.5 years and with a SIR value range of 1.57 - 15.21. Note that this proposed code impacts building floor area greater than 100,000 square foot. FSEC encourages this change.

C403.2.15 Fault Detection and Diagnostics. New buildings with a gross conditioned floor area of 100,000 square feet (9290 square meters) or larger shall include a fault detection and diagnostics (FDD) system to monitor the HVAC system's performance and automatically identify faults. The FDD system shall:

1. Include permanently installed sensors and devices to monitor the HVAC system's performance;

2. Sample the HVAC system's performance at least once per 15 minutes;

3. Automatically identify and report HVAC system faults;

4. Automatically notify authorized personnel of identified HVAC system faults;

5. Automatically provide prioritized recommendations for repair of identified faults based on analysis of data collected from the sampling of HVAC system performance; and

6. Be capable of transmitting the prioritized fault repair recommendations to remotely located authorized personnel.

LBNL-2001075

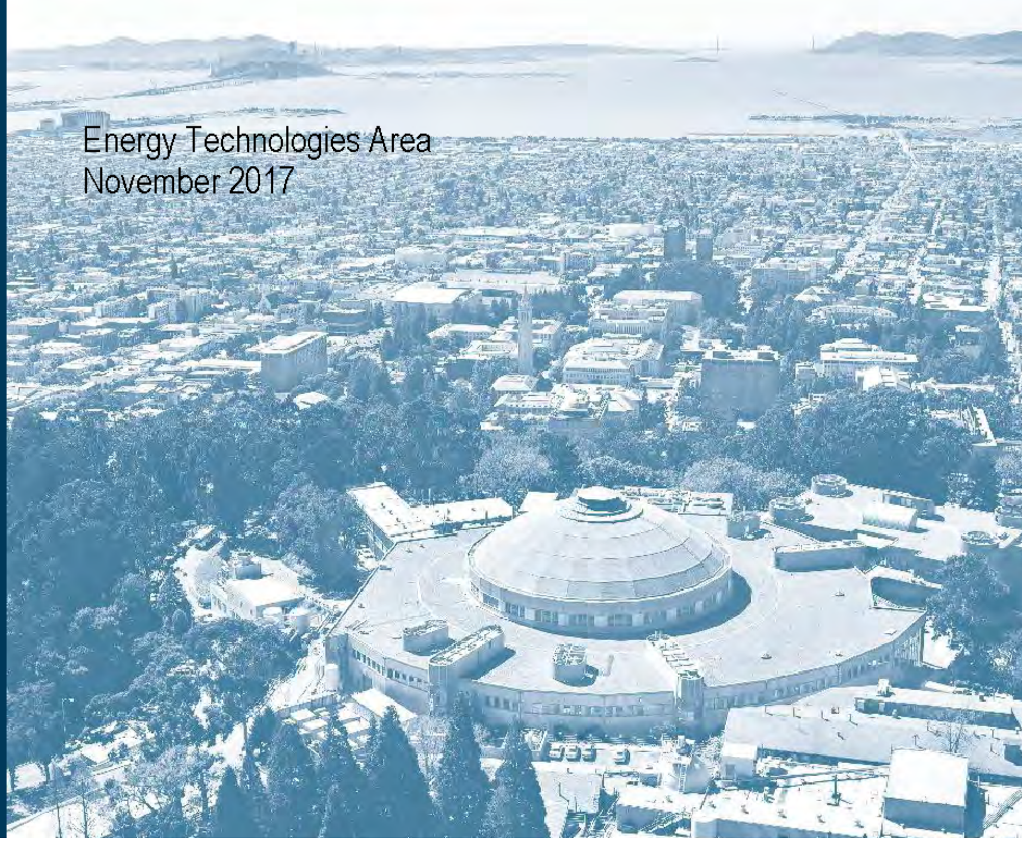
Lawrence Berkeley National Laboratory

Characterization and Survey of Automated Fault Detection and Diagnostic Tools

Jessica Granderson and Rupam Singla
Building Technology and Urban Systems Division
Lawrence Berkeley National Laboratory

Ebony Mayhorn, Paul Ehrlich and Draguna Vrabie
Pacific Northwest National Laboratory

Stephen Frank
National Renewable Energy Laboratory



Energy Technologies Area
November 2017

Disclaimer

Acknowledgement

This work was supported by the Assistant Secretary for Energy Efficiency and Renewable Energy, Building Technologies Office, of the U.S. Department of Energy under Contract No. DE-AC02-05CH11231. The authors thank Amanda Farthing, Xin Jin, and Grant Wheeler (National Renewable Energy Laboratory), as well as Guanjing Lin (Lawrence Berkeley National Laboratory), for their support with the developer interviews that were conducted in this work. We also recognize each of the fault detection and diagnostic tool developers who participated in this survey.

Executive Summary

Background

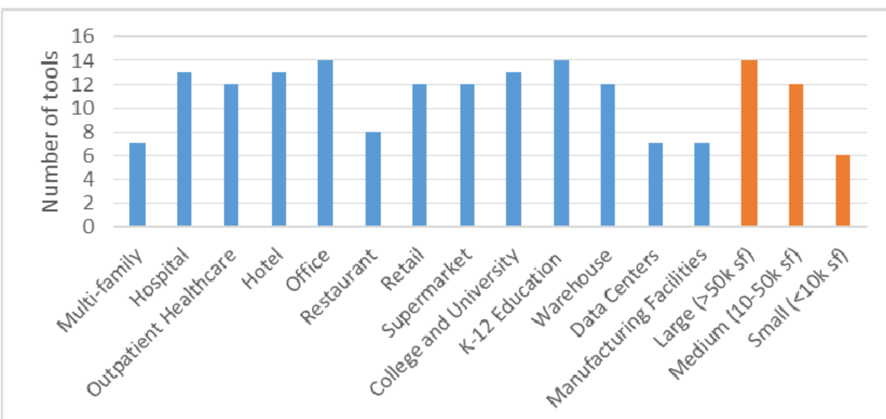
It is estimated that 5%–30% of the energy used in commercial buildings is wasted due to faults and errors in the operation of the control system. Tools that are able to automatically identify and isolate these faults offer the potential to greatly improve performance, and to do so cost effectively. This document characterizes the diverse landscape of these automated fault detection and diagnostic (AFDD) technologies, according to a common framework that captures key distinguishing features and core elements.

Approach

To understand the diversity of technologies that provide AFDD, a framework was developed to capture key elements to distinguish the functionality and potential application of one offering from another. The AFDD characterization framework was applied to 14 currently available technologies, comprising a sample of market offerings. These 14 technologies largely represent solutions that integrate with building automation systems, that use temporary in field measurements, or that are implemented as retrofit add-ons to existing equipment. To characterize them, publicly available information was gathered from product brochures and websites, and from technical papers. Additional information was acquired through interviews and surveys with the developers of each AFDD tool. The study concludes with a discussion of technology gaps, needs for the commercial sector, and promising areas for future development.

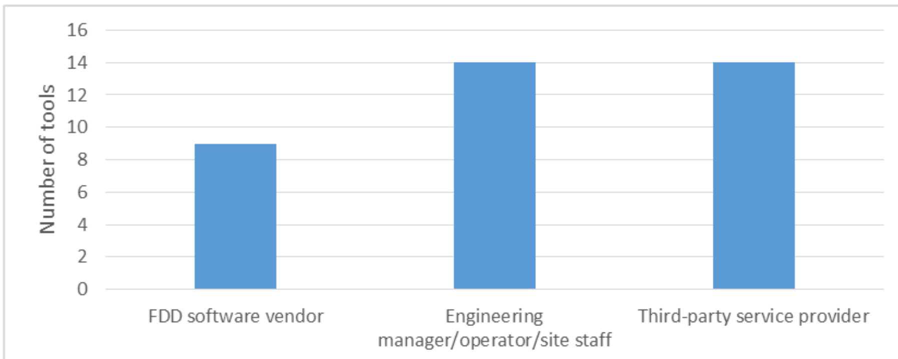
Key Findings

Today's AFDD technologies are being used in nearly all commercial building sectors. Smaller facilities, however, are less commonly served, and when they are it is often through portfolios of small buildings as opposed to single sites.

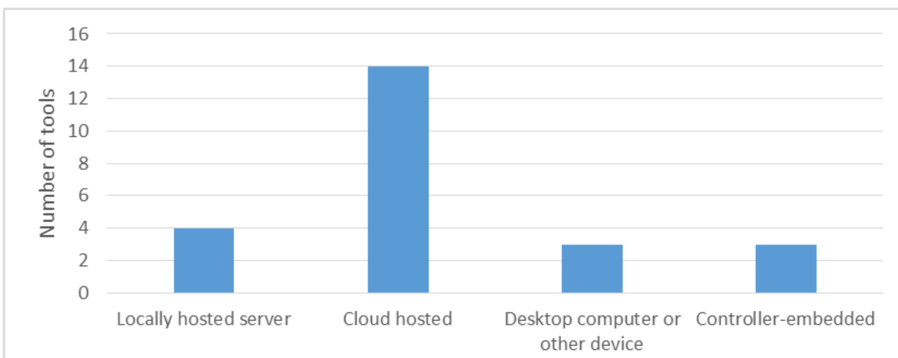


Market presence of surveyed FDD tools

Software-as-a-service models have quickly become the norm for AFDD technologies; even vendors providing on premise and desktop applications also tend to offer SaaS options. A compelling evolution in the industry is seen in the expansion of market delivery of FDD through third-party service providers using the tools as a way to provide value-add to their customers. This expansion offers the potential to increase access to the technology and its associated benefits for a new class of owners who otherwise may not be using it, however third parties' costs may vary significantly and each cost component should be defined in full to be able to compare across delivery options.



Intended users of surveyed AFDD tools



Location of surveyed AFDD tools

While rule-based methodologies to detect and diagnose faults are still heavily used, vendors are beginning to use process history-based techniques. Independent of the FDD methodology used, vendors report a high degree of commonality in the systems and types of faults that their products can cover. That is, coverage of systems and faults is driven more by site data availability than by product offering. Most AFDD tools surveyed accept real-time BAS data and external meters and sensors; many accept historical data from the BAS, and several accept equipment's onboard/ internal measures without going through the BAS. The majority of the AFDD tool vendors surveyed cover major the HVAC systems found in commercial buildings, as well as lighting systems and whole building energy use. Many tools have large libraries that are able to determine at least some types of faults across all systems for whatever data can be provided. Nearly all of the tool vendors surveyed are able to detect faults in the major categories, including: sensors, energy consumption, economizers and ventilation, commercial refrigeration, cooling/heating systems, equipment cycling, scheduling, and lighting or other end uses. Configuration of the technologies does require site-specific tuning. While this is not a fully automated process, some elements of the process may be automated for streamlining.

Distinguishing factors are often associated with the additional features offered to complement the AFDD, and with the available delivery models. The market offers great diversity in additional analytics and reporting capabilities, integration architectures, and purchase models, making it possible to custom fit the technology to the needs of the organization. While custom solutions are desirable for some portions of the buildings market— such as campuses, enterprises, and large or complex facilities—others may benefit from higher degrees of commoditization.

An important theme in interpreting the findings from this survey is that many products are sold with an emphasis on broad-scale applicability, and in analyzing the features and capabilities across all offerings as whole, there is indeed a high degree of similarity. However, it is critical for prospective technology users to probe providers to understand the precisely what is entailed in a given offering's implementation of a feature of interest. For example, there are many ways to prioritize faults and estimate their impacts, and effective prioritization may be dependent on customer input. Similarly, root cause analysis (diagnosis) may be supported for just a subset of faults, or require manual input from operational staff. Analogously, ease of integration with different makes and vintages of BAS is another critical element of implementation for which "the devil is in the details."

Outstanding Needs

FDD technology is seeing increased uptake in the market, and is constantly developing and evolving. Best practice implementations can deliver significant improvements in energy efficiency, utility expenses, operations and maintenance processes, and operational performance—all with rapid return on investment. However, for the full potential to be realized at scale, a core set of interrelated informational, organizational, and technical needs and barriers must be addressed.

The primary informational barriers for prospective users are rooted in interpreting the value proposition of FDD for their facilities, and in accessing best practices in implementation — for example all-in costs and benefits, effective use of contractors and service providers, and integration with higher level energy management practices. Organizationally, successful implementation of AFDD can be slowed by a need to diverge from existing business practices and norms. While the costs are modest compared to capital projects and can be quickly recovered, decision makers must buy in to an increase in operation and maintenance expenses and be willing to manage a certain degree of risk. Finally, from a technical standpoint, IT and data integration represent one of the largest challenges. Even once data is accessible through cross-system integration, it must be interpreted for use in analytic applications. The current lack of common standards in data, metadata, and semantic representation also poses difficulties in scaling. Lastly, today's AFDD offerings can prove difficult and expensive to apply in smaller commercial buildings.

Future Work

AFDD has matured significantly since its first introduction into commercial buildings. Based on information gathered through this survey and discussion with both vendors and users, several opportunities emerge to further advance the technology. Continued development of algorithms that include machine learning and other promising techniques could reduce tuning needs, simplify configuration, and enhance diagnostic power. Following the trends in other industries, there is also potential to move beyond diagnostics into prognostics and predictive maintenance. Machine-to-machine integration presents further opportunity for advancement to realize pervasive "plug-and-play" functionality, thereby enabling tighter coupling of AFDD with computerized maintenance management systems, meter analytics, and operations and asset management tools. Finally, there are gains to be achieved through the development of corrective and adaptive controls, in combination with tool chains that can ensure that operational design intent is correctly implemented and maintained over the duration of the operational stage in the building lifecycle.

1. Overview

Energy Management and Information Systems (EMIS) comprise a broad family of tools and services to analyze, monitor, and control commercial building equipment and energy use. These technologies include, for example, meter analytics or energy information systems (EIS), some types of automated fault detection and diagnostic tools (AFDD), benchmarking and utility bill tracking tools, and building automation systems. These technologies may encompass uses that include monitoring-based and ongoing commissioning, remote audits and virtual assessments, enterprise monitoring and asset tracking, continuous savings estimation, and energy anomaly detection. There are a wide a wide variety of EMIS products available on the commercial market, and they are increasingly heavily marketed to the energy management community.

It is estimated that 5%–30% of the energy used in commercial buildings is wasted due to faults and errors in the operation of the control system[1, 2, 3]. Tools that are able to automatically identify and isolate these faults offer the potential to greatly improve performance, and to do so cost effectively.

This document characterizes the diverse landscape of technologies that offer AFDD functionality, according to a common framework that captures key distinguishing features and core elements. These technologies can reside on local servers or in the cloud, as well as at the network edge within equipment or controller-embedded solutions.

The primary audience for this document is building owners and operators, who are seeking an understanding of the functionality available in AFDD products and services to inform piloting and procurement decisions. It also may be useful to utility energy efficiency program stakeholders who are interested in emerging technologies to test and pilot for incentive programs. A secondary audience includes developers of AFDD solutions who are looking for information to inform and target their efforts.

In the following sections of this review we present a general overview of FDD and other analytics technology types, followed by a common framework to distinguish among various types of AFDD tools. We then apply this framework to evaluate a sampling of AFDD tools and discuss the findings. The evaluation focused primarily on solutions that integrate with building automation systems, that use temporary in-field measurements, or that are implemented as retrofit add-ons to existing equipment; it did not include OEM-embedded AFDD offerings (although in a few instances these variants are available through the AFDD vendor). We conclude with a discussion of technology gaps, needs for the commercial sector, and promising areas for future development.

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[1] Roth, K. W., D. Westphalen, M. Y. Feng, P. Llana, and L. Quartararo. *Energy Impact of Commercial Building Controls and Performance Diagnostics: Market Characterization, Energy Impact of Building Faults and Energy Savings Potential*. 2005. Report prepared by TIAC LLC for the U.S. Department of Energy.

[2] Katipamula, S., and M. Brambley. 2005. "Methods for fault detection, diagnostics, and prognostics for building systems – a review, part 1." *HVAC&R Research* 11(1): 3–25.

[3] Fernandez, N., et al. 2017. *Impacts on commercial building controls on energy savings and peak load reduction*. Pacific Northwest National Laboratory. PNNL Report Number PNNL-25985.

2. Introduction to Fault Detection and Diagnostics

FDD is the process of identifying (detecting) deviations from normal or expected operation (faults) and resolving (diagnosing) the type of problem or its location. FDD has been used for decades to great success in industries that include aerospace, nuclear, and industrial applications, and its use in building operation and control applications is growing. In practice, FDD in buildings is most commonly conducted for heating, ventilation, and air conditioning (HVAC) systems, however as a process, FDD is applicable to all systems in the building. Although currently underutilized, FDD is a powerful approach to ensuring efficient building operations.

As further detailed in the characterization framework that follows, AFDD technology may be delivered through a variety of implementation models. The FDD code may be integrated into either server-based software, desktop software, or software that is embedded in an equipment controller. The AFDD algorithms may rely on historical or near-real time data from building automation systems (BAS), from data local to the equipment or controller, from external sensors and meters, or from some combination of these data sources. AFDD software may be used by the building operator or energy manager, or may be delivered through analysis-as-a-service contracts that do not require direct “in-house” use of the technology.

The software tools that offer AFDD may include additional functionality such as energy consumption monitoring and analytics, visualization, benchmarking, reporting of key performance indicators, or fault prioritization and impact assessment. The server-based offerings rely on continuous data acquisition and analysis; these types of AFDD tools are commonly considered part of the broader family of tools called Energy Management and Information Systems (EMIS). Although not within the scope of this document, other EMIS technologies such as meter analytics or energy information systems, automated (HVAC) system optimization, and building automation systems are powerful tools for ensuring persistent low-energy commercial building operations—both at the facility and enterprise levels.

3. FDD Technology Characterization Framework

To understand the diversity of technologies that provide AFDD, a characterization framework was developed to capture key elements that can be used to distinguish the functionality and potential application of one offering from another. Content contained in this framework was developed through review with a subset of providers, and is based on the authors’ collective subject matter expertise, knowledge of AFDD technology and its use in commercial building energy management applications. The categories in the framework are defined in the following sections, with characteristics spanning delivery to market, technical capabilities, and additional software functionality.

3.1 Delivery to Market

Company or institution name: The developer of the AFDD technology.

Tool name: The name of the AFDD software or service offering.

Software type: Whether the AFDD is offered as a commercial product or service, or as open source code.

Availability to market: Whether the AFDD is commercially available or still being researched (pre-commercial).

Current markets served: What markets are currently served in terms of:

- Building type (multi-family, hospital, outpatient healthcare, hotel, office, restaurant, retail, supermarket, college and university, K–12 education, warehouse).
- Building size (large [> 50k square feet (sf)], medium [10–50k sf], small [< 10k sf]).

Software location: Whether the AFDD software is cloud hosted, locally hosted on an "on-site" server, located on a desktop computer or other device, or controller-embedded.

Purchase model: Whether the AFDD software is a one-time purchase, software as a service (with monthly or annual fee), or other. Additionally, whether the AFDD software comes with updates and/or periodic maintenance in the initial offering costs, or whether additional purchase is required.

Intended users: Whether the AFDD software is intended for use by the vendor (for analysis-as-a-service), an engineering manager/operator/site staff, and/or a third-party service provider.

Software configuration: Whether the party typically responsible for the AFDD software installation and configuration is the software vendor; an integrator, distributor, or third-party service provider; or an engineering manager/operator/site staff.

Data sources: Whether the AFDD software relies upon data from BAS real-time data (i.e., live, continuous), from BAS historical data (e.g., trend logs, csv, xls), from on-board or internal equipment measures, or from external meters and sensors.

Data ownership: Whether the owner(s) of the AFDD software tool inputs and outputs is the end-customer, the FDD software vendor, and/or a third-party service provider.

FDD method tailoring: Whether the AFDD software requires tailoring of the tuning algorithm parameters and associated thresholds manually or automatically, or whether it is not applicable or unnecessary.

Notification of findings: Whether the AFDD software tool delivers results through a software user interface with fault findings, through a service to the user that includes periodic reports of fault findings, and/or through automated notifications, e.g., via email or text.

3.2 Technical Capabilities

Systems covered: Whether the FDD software has existing libraries and rules for the following systems: air conditioners/heat pumps (including packaged rooftop units), chillers and towers, air handler units (AHUs) and variable air volumes (VAVs), fan coil units (FCUs), commercial refrigeration, lighting, boilers/furnaces, water heaters, and/or whole-building.

Categories of faults detectable: These are broad categories of faults that the AFDD tool is able to detect and potentially diagnose. The fault categories included in this framework include:

- Sensor errors/faults
- Energy consumption (explicit energy use fault)
- Economizers and ventilation
- Control-related pressurization issues
- Commercial refrigeration (related to vapor/compression)
- Space cooling/heating (related to vapor/compression)
- Heating system (boiler, heat exchanger, furnace, etc.)
- Cooling system (chillers, towers, etc.)
- Equipment cycling
- Pump and fan systems
- Scheduling (too little, too long, wrong time, etc.)
- Simultaneous heating and cooling
- Lighting or other end uses

Note that problems such as mechanical failures and departures from setpoint or intended sequences may be included under multiple fault categories in the list above.

Methods/algorithms: These are the categories of analytical methods used in the AFDD software. The schematic diagram below depicts the definition of algorithm types that are used in this framework.

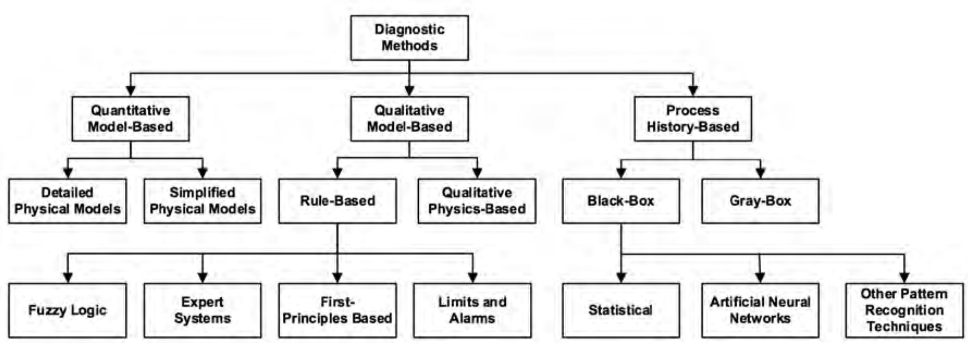

Figure 1. Depiction of algorithm types used in this framework, from Katipamula and Brambley, 2005[2]

As illustrated in Figure 1, FDD methods may be model-based or based purely on process history data. The model-based methods rely upon knowledge of the underlying physical processes and first principles governing the system(s) being analyzed. Quantitative model-based approaches are not yet frequently employed in commercial AFDD tool offerings, however qualitative model-based approaches which include rule-based FDD, have been extensively used in the industry and provide intuitive representations of engineering principles. The process history-based (data-driven) approaches do not rely upon knowledge of first principles, but may leverage some degree of engineering knowledge; they rely upon data from the system in operation. These include statistical regression models, neural networks, and other methods. Process history-based AFDD algorithms are increasingly being explored for use in commercial tool offerings. Although the distinctions between these method types may become blurry (even to developers), AFDD users may have interest in understanding whether a technology uses rules-based techniques versus newer data driven approaches, or less commonly employed first principles – or a combination of several approaches.

Detection and diagnosis capabilities: Whether the AFDD tool is capable of identifying fault presence (reporting a fault without specification of the physical location, severity, or root cause), fault location, fault severity (degree of faultiness as opposed to impact on energy or dollars, which is covered in "additional functionality"), root cause, and/or estimated costs of resolution and payback.

3.3 Additional Functionality

Other features: Additional features of the AFDD tool that are not represented above, and may include:

- Detection of equipment degradation
- Fault prioritization
- Automated work order request system integration
- Assessment of energy impacts
- Conversion of energy impacts to cost impacts
- Assessment of cost impacts other than energy cost, e.g., reduced equipment life
- Meter data analytics
- Time series visualization and plotting
- Key performance indicator (KPI) tracking and reporting
- Longitudinal and cross-sectional benchmarking (within a given portfolio or via ENERGY STAR Portfolio Manager)

4. Technology Characterization Findings

The AFDD characterization framework was applied to 14 currently available technologies, comprising a sample of market offerings (see the Appendix for a list of those surveyed). These technologies were identified based on factors including:

- Diversity across defining characteristics to illustrate market breadth
- Known use in commercial buildings based on the authors' knowledge of the market and engagement with the community of AFDD users
- Vendor or developer willingness and ability to share information necessary for a full characterization

It is important to emphasize that inclusion in this survey does not indicate endorsement, and conversely, absence from the survey does not indicate non-endorsement.

To characterize the technologies, publicly available information was gathered from product brochures and websites, and from technical papers. Additional information was acquired through interviews and surveys with the vendors and developers of each AFDD tool. The information that was acquired was therefore based on self-reporting from the technology provider. It was not within the scope of this effort to independently verify reported functionality and characteristics of each technology that is included. Moreover, as the market is constantly evolving and technologies are continuously modified, these market findings represent a snapshot in time. Although specific offerings may evolve, it is expected that the characterization framework itself will remain a viable tool to distinguish key AFDD technology elements well into the future.

The tables in the Appendix provide a summary of the capability of each tool surveyed, with respect to each category in the characterization framework.

4.1 Delivery to Market

All tool vendors surveyed offered proprietary, commercially available software and/or hardware. However, several of the software vendors noted that they provide an open application programming interface (API) to support integration with third-party applications.

The markets currently served by the AFDD tool vendors are represented in Figure 2. Multi-family, restaurant, data centers, and manufacturing facilities are less commonly served, with a mostly even coverage of other sectors. In addition to the market segments shown in the figure, several tool vendors noted additional facility types such as industrial subsectors, arenas, multi-event facilities, and correctional facilities. The technologies are commonly used in large and medium facilities, with less penetration in smaller buildings. Several tool vendors also noted that they do not serve a particular building size and that their product would be applicable to any size building.

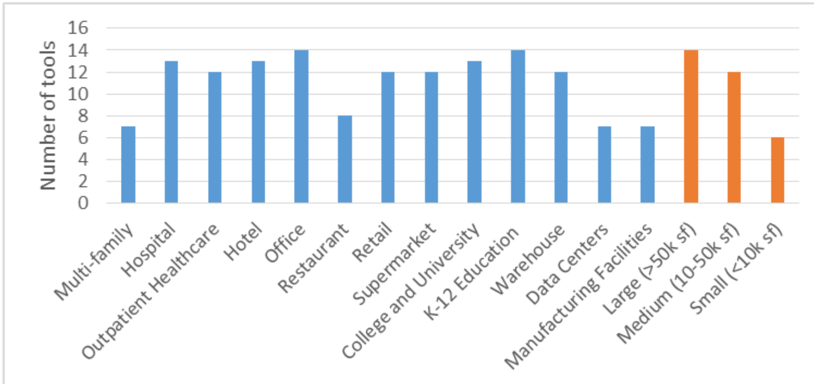

Figure 2.Market presence of surveyed FDD tools

As shown in Figure 3, the software for all 14 tool vendors can be cloud hosted; eight of them offer that as the only option. Additionally, four AFDD tools can be installed on a locally hosted on-site server, and three can be located on a desktop computer or other device (such as a handheld device). Three can be controller-embedded, reflecting emerging variants in software delivery that can entail relationships with OEMs.

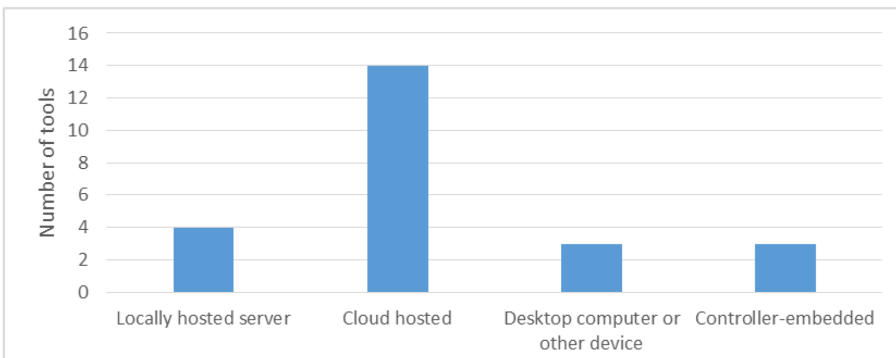

Figure 3. Software location

AFDD tool vendors offer a wide range of variability in purchase models. Many vendors noted that there is no standard, and that often the purchase model is tailored to what the customer wants. Typically tools that are hosted on the cloud offer a software-as-a-service (SaaS) model with ongoing updates and maintenance included for either an annual or a monthly fee. Maintenance and updates may come bundled or optionally in an upfront fee, or can be deferred for later purchase.

As reflected in the tallies in Figure 4, all of the AFDD tool vendors surveyed have multiple intended users. The traditional model of in-house technology used by the end customer is still prevalent—all vendors surveyed listed engineering manager/operator/site staff as an intended user. However, tools are increasingly being used by and resold by third-party service providers as a value-add to customers, with all of the AFDD tool vendors surveyed also listing a third-party service provider as an intended user. Nine vendors provide analysis-as-a-service directly to their clients and are therefore an intended user of the tool. This is expected to grow as the market matures and alternative business models are explored by the industry.

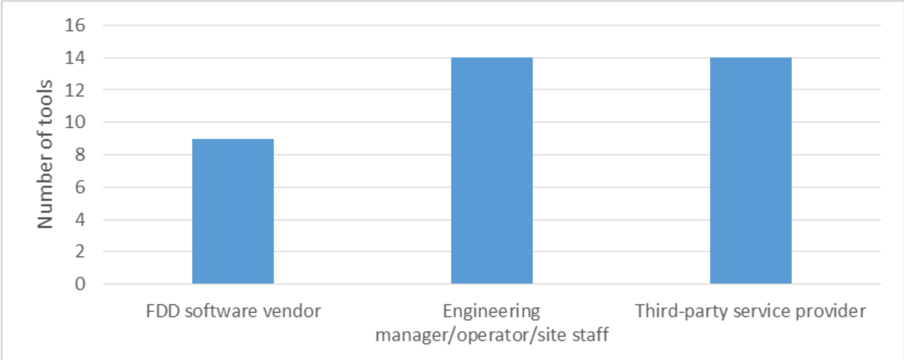

Figure 4. Intended Users

The majority of the AFDD tools are installed and configured by some combination of the software vendor, an integrator/distributor/third-party service provider, and the engineering manager/operator/site staff, as shown in Figure 5. In most cases, the vendor plus a third party do the configuration, working from owner requirements. In some cases multiple parties are required for the installation, and in some cases the vendor offers several options for who does the installation.

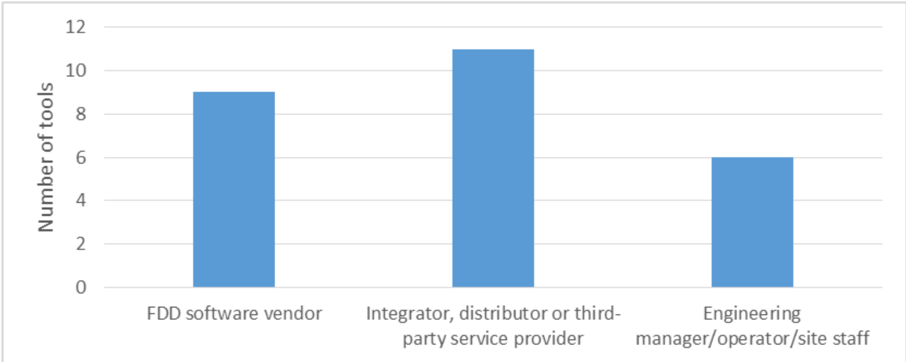

Figure 5. Parties involved in software configuration

There is a range of input data that are required by AFDD tools and a range of data that they can accept, as shown in Figure 6. Most of the tools take in real-time BAS data, which would be expected, given the large number of cloud-based solutions that serve as a BAS overlay. Eleven tools are also able to utilize historical data from the BAS. Most of the tools are also able to utilize external meters and sensors. Three tools are able to utilize equipment's onboard/ internal measures without going through the BAS. Typically not all of the data points that *can* be processed by the tool are required, and the technologies operate based on the data that are available. Though the tool vendor may have a short list of critical points, additional data are used to enhance the spectrum of diagnostics that can be performed.

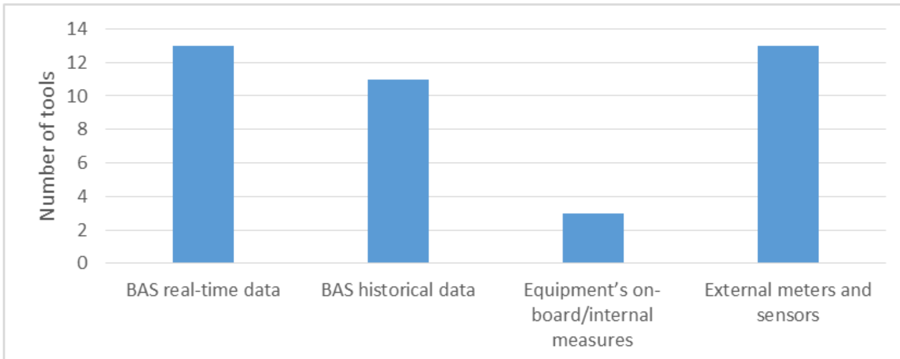

Figure 6. Data sources for surveyed FDD tools

All AFDD tool vendors note that primarily, the customer owns the data. Additionally, two vendors noted that they themselves also have ownership over the data and one other tool vendor noted that a third-party service provider has ownership over the data. Several tool vendors noted that they retain the right to use aggregate and anonymous data for benefit of all their users; for example, to provide peer benchmarking analyses.

All 14 tools require some degree of tuning or tailoring algorithm configuration and implementation. While none offer fully automated tuning, six vendors noted that they provide automated routines and/or GUIs to streamline the process. At least one tool comes with a fault library with default thresholds, with which the customer may subsequently tune parameters or hire consultants to help.

All of the AFDD tool vendors provide access and viewing of fault findings through a software interface, as shown in Figure 7. In addition to user-facing GUIs, the majority of offerings surveyed also provide services to periodically output reports of fault findings. All but two of the tools provide automated notifications via text, e-mail, or even other novel communications options such as tweets. Several tool vendors have the capability to have reports sent via e-mail at user-defined intervals (daily, weekly, monthly) and on customer demand.

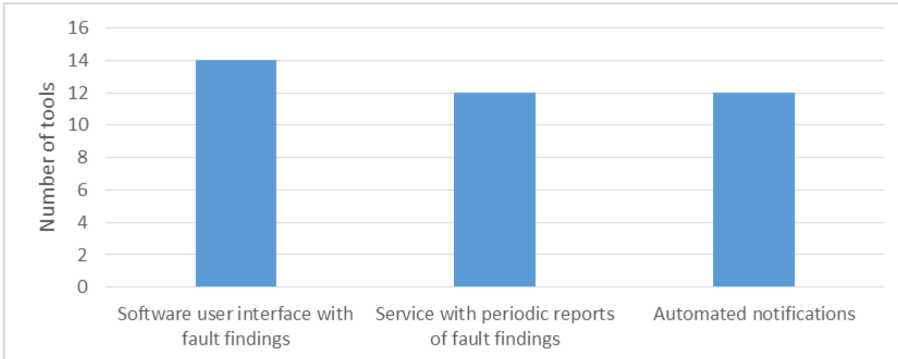

Figure 7. Notification of findings

4.2 Technical Capabilities

As seen in Figure 8, the majority of the AFDD tool vendors surveyed cover most of the systems that were included in the survey (AC/heat pump which includes packaged rooftop units, chillers and towers, AHU and VAV, FCUs, commercial refrigeration, lighting, boilers/furnaces, water heaters, and whole-building). Many tools have large libraries that are able to determine at least some types of faults across all systems for whatever data can be provided. Several vendors reported that they additionally include energy recovery ventilators (ERVs), other terminal units besides VAV boxes, solar panels, industrial processes, variable refrigerant flow (VRF) systems, BAS controls, cogeneration, and manufacturing equipment.

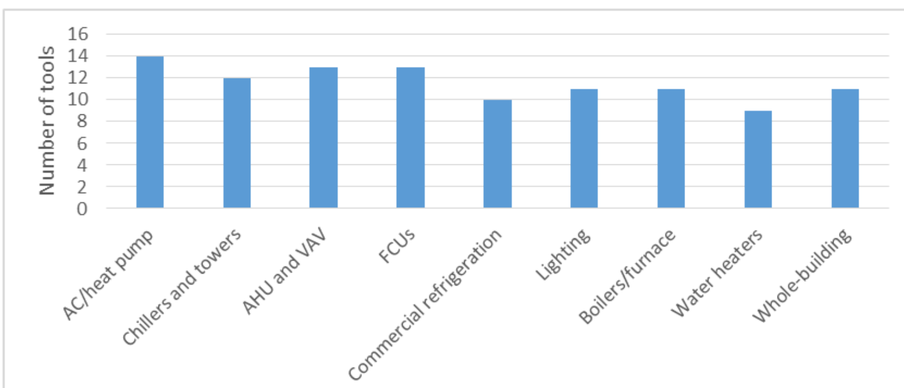

Figure 8. Systems covered

Nearly all of the tool vendors surveyed are able to detect faults in the majority of the fault categories in the survey: sensor errors/faults, energy consumption, economizers and ventilation, control-related pressurization issues, commercial refrigeration, space cooling/heating, heating system, cooling system, equipment cycling, pump and fan systems, scheduling, simultaneous heating and cooling, and lighting or other end uses. Many tools have large libraries that are able to determine at least some types of faults for whatever data can be provided. See Figure 9 for details.

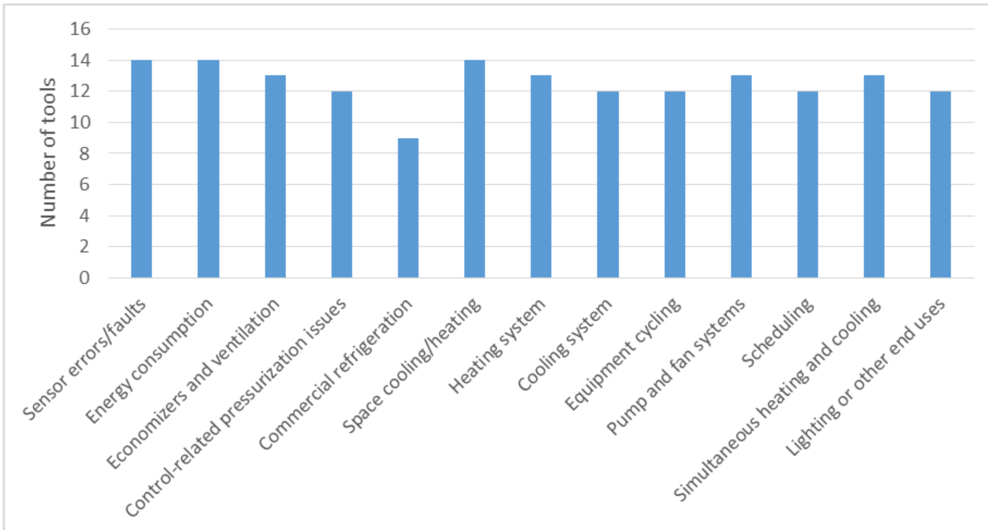

Figure 9. Categories of detectable faults

Most of the tools (12 out of 14) use rule-based algorithms, the majority of which apply some combination of expert systems, first principles-based, and limits and alarms. Many of the rule-based tools are supplemented with other approaches, and in one case the offering is a platform that is most commonly programmed and configured to deliver rule-based algorithms, but also includes machine learning functions. Three tools use black-box process history-based approaches; one of these also uses a gray-box approach. Two tools use quantitative model-based approaches. Figure 10 illustrates these findings graphically—dark shading indicates approaches used by ten or more tools, medium shading indicates approaches used by two or three tools, and light shading indicates approaches used by one or no tools.

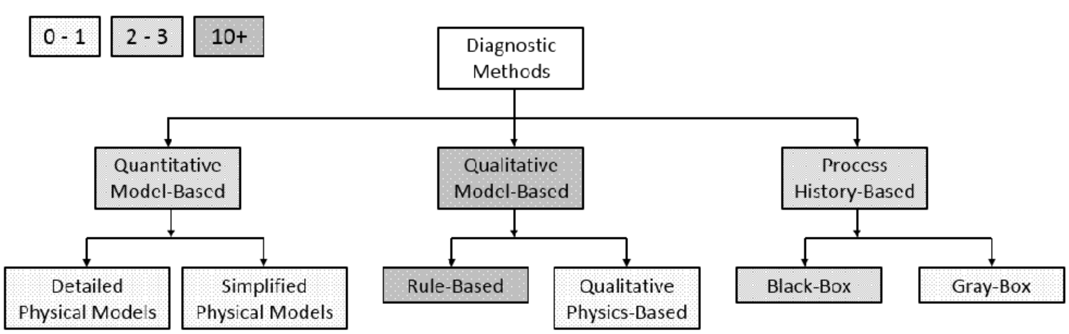

Figure 10. Methods and algorithms

As shown in Figure 11, all vendors surveyed reported the ability to identify fault presence as well as physical fault location. All but one tool is able to identify potential root causes. Depending on the specific fault identified, root case identification may be more or less precise, or in some cases, not possible. In addition, all but one reported some quantification of fault severity, e.g., degree of leakage. The degree of faultiness may be determined based on the frequency of a fault, fault magnitude (e.g., how far a point is away from setpoint), and fault duration. Several tools associate fault severity with assessment of the degree to which energy, energy cost, comfort, and maintenance costs are affected. At least one of these tools prioritizes the faults, then displays only one fault at a time to the user.

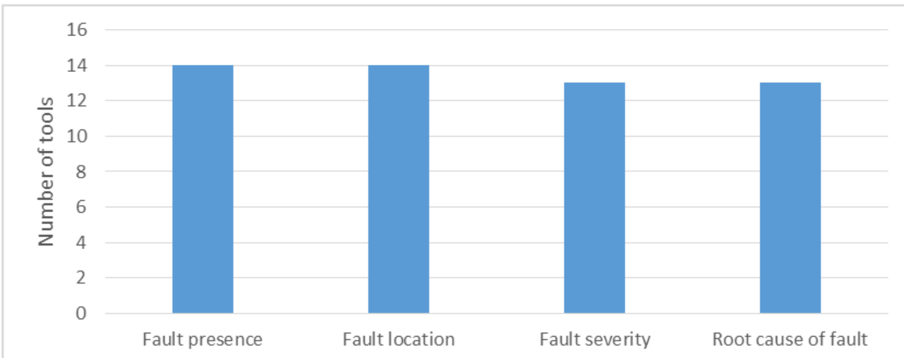

Figure 11. Detection and diagnosis capabilities

4.3 Additional Functionality

AFDD tools are commonly delivered with many supplementary features. Out of the tools surveyed, the most common features were time series visualization and plotting, quantification of energy impacts, and fault prioritization, as shown in Figure 12. Other very common features were equipment degradation, conversion of energy impacts to cost impacts, KPI tracking and reporting, automated work order request system integration, and meter data analytics. Less common but still prevalent features were cost impacts other than energy cost (such as the cost of pending equipment failure), longitudinal and cross-sectional benchmarking, and estimated cost of fault resolution and payback.

In addition, tool vendors noted a number of other features, including feedback for load management and demand response applications, verification of corrective actions, savings measurement and verification (M&V), equipment level M&V, asset data and service history, and issue-tracking systems. These other features were not exhaustively reviewed in the survey (or Tabulated findings in the Appendix) but are important complements to the AFDD capabilities.

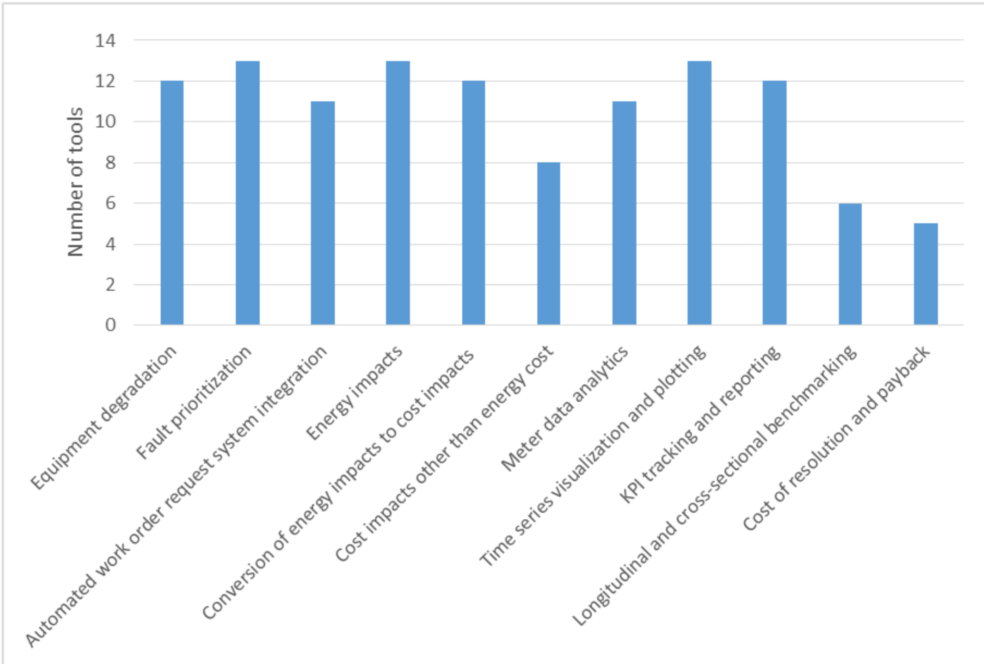

Figure 12. Relative frequency of a selected set of additional features of AFDD tools

5. Industry Needs and Future Development

This survey focused on AFDD solutions that integrate with building automation systems, that use temporary in-field measurements, or that are implemented as retrofit add-ons to existing equipment. As indicated in the findings, today's AFDD technologies are being used in nearly all commercial building sectors. Smaller facilities, however, are less commonly served, and when they are it is often through portfolios of small buildings as opposed to single sites. Cost effectiveness and complexity of implementation may vary as the technology is applied to different sectors and building sizes. For example, with a historic emphasis on HVAC systems and larger buildings, solutions for built-up systems may be simultaneously more developed, yet also more complex than those for packaged systems.

Software-as-a-service models have quickly become the norm for AFDD technologies; even vendors providing on-premise and desktop applications also tend to offer SaaS options. A compelling evolution in the industry is seen in the expansion of market delivery of FDD through third-party service providers using the tools as a way to provide value-add to their customers. Illustrated in Figure 13, these third-party services may cover a spectrum of activities. This is in contrast to earlier models that relied on in-house direct organizational use, and also from analysis-as-a-service provided by the AFDD vendor. This expansion offers the potential to increase access to the technology and its associated benefits for a new class of owners who otherwise may not be using it, however third parties' costs may vary significantly and each cost component should be defined in full to be able to compare across delivery options.

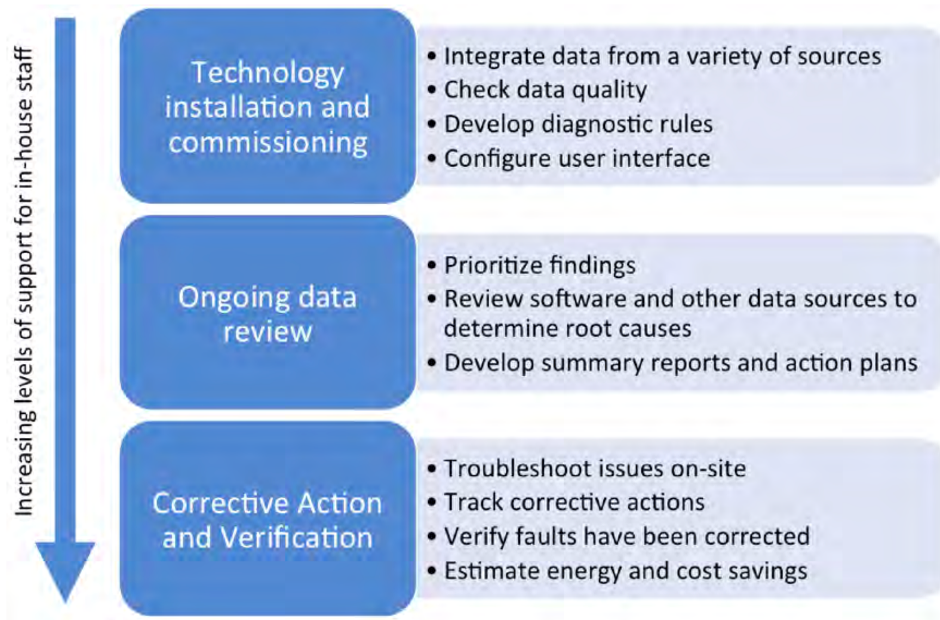

Figure 13. A spectrum of analytics-focused activities that service providers may offer their customers

While rule-based methodologies to detect and diagnose faults are still the norm, vendors are beginning to use process history-based techniques. Independent of the FDD methodology used, vendors report a high degree of commonality in the systems and types of faults that their products can cover. That is, coverage of systems and faults is driven more by site data availability than by product offering. Configuration of the technologies does require site-specific tuning, which may be conducted by vendors and service providers with varying degrees of involvement from site staff. While this is not a fully automated process, some elements of the process may be automated for streamlining.

Distinguishing factors are often associated with the additional features offered to complement the AFDD, and with the available delivery models. The market offers great diversity in additional analytics and reporting capabilities, integration architectures, and purchase models, making it possible to custom fit the technology to the needs of the organization. While custom solutions are desirable for some portions of the buildings market— such as campuses, enterprises, and large or complex facilities—other portions of the market may benefit from higher degrees of commoditization.

An important theme in interpreting the findings from this survey is that many products are sold with an emphasis on broad-scale applicability, and in analyzing the features and capabilities across all offerings as whole, there is a high degree of similarity. However, actual implementation needs can differ widely from one application case to another. Moreover, it is critical for prospective technology users to probe providers to understand the precisely what is entailed in a given offering's implementation of a feature of interest. For example, there are many ways to prioritize faults and estimate their impacts, ranging from those that rely upon static assumptions of fault persistence versus intermittence, to those that rely upon more dynamic calculations of concurrent operational conditions – and effective prioritization may be dependent on customer input. Similarly, root cause analysis (diagnosis) may be supported for just a subset of faults, or require manual input from operational staff. Analogously, ease of integration with different makes and vintages of BAS is another critical element of implementation for which "the devil is in the details."

FDD technology is seeing increased uptake in the market, and is constantly developing and evolving. Best practice implementations can deliver significant improvements in energy efficiency, utility expenses, operations and maintenance processes, and operational performance—all with rapid return on investment (see the Smart Energy Analytics Campaign Year 1 Report[4] for a snapshot of EIS, FDD and ASO performance and cost). However, for the full potential to be realized at scale, a core set of interrelated informational, organizational, and technical needs and barriers must be addressed.

Informational:

1. Prospective users remain challenged in interpreting the value proposition of FDD for their facilities. Common questions include: what will it really take to make this work for my buildings? What will the all-in costs and benefits be, up-front, and in the long-term? How do I navigate this developing market with numerous evolving players and product options?
2. Prospective users also face more specific implementation questions such as: What is the distinction between automated fault detection and diagnostics (AFDD) and BAS alarms, and which products support one versus the other? What are best practices for tuning and avoidance of false positives? What is the benefit of integrating AFDD within higher-level energy management practices such as strategic energy management and ongoing monitoring-based commissioning? How do I best integrate the support of contractors and service providers with in-house activities?

[4] Smart Energy Analytics Campaign. Synthesis of year 1 outcomes in the Smart Energy Analytics Campaign [Internet]. 2017 [accessed on September 25, 2017]. Available from: https://smart-energy-analytics.org/

Organizational:

3. Successful implementation of AFDD can be slowed by a need to diverge from existing business practices and norms. While the costs are modest compared to capital projects and can be quickly recovered, decision makers must buy in to an increase in operation and maintenance expenses and be willing to manage a certain degree of risk. Translation of information into action requires allocation of resources for staff time and training to act upon on identified fixes; it also requires effective operational response processes.

Technical:

4. While improving, IT and data integration represent one of the largest barriers to scale. It is complex, expensive and crosses organizational business units, and communications infrastructures are not easily leveraged for installation of analytics technologies.
5. Once data is accessible through cross-system integration, it must be interpreted for use in analytic applications. The current lack of common standards in data, metadata, and semantic representation also poses difficulties in scaling.
6. Similar to many efficiency solutions, today's AFDD offerings can be difficult and expensive to apply in smaller commercial buildings. Smaller facilities do not commonly have building automation systems or energy management staff and present much tighter payback constraints due to smaller energy expenditures.

A number of academic, industry, utility, and federal efforts are seeking to address these barriers. These collective efforts are far too varied and numerous to comprehensively describe, however, a few examples from current work sponsored by the U.S. Department of Energy (DOE) are provided as an illustration.

- The University of New Haven is conducting a public-facing field evaluation[5] of approximately 10 AFDD solutions to quantify technology costs and benefits, and is partnering with the utility community to inform the development of incentive programs for scaled regional deployment.
- The National Renewable Energy Laboratory (NREL) is conducting early-stage development of AFDD solutions for small commercial facilities that are based on simulation modeling and smart meter data.[6]
- Lawrence Berkeley National Laboratory (LBNL) is administering the Smart Energy Analytics Campaign[7] to provide technical assistance to AFDD and other analytics users, track gaps and benefits, and synthesize barriers.

[5] U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy. Department of Energy announces scaling up the next generation of building efficiency packages funding awards [Internet]. 2017 [accessed on August 29, 2017]. Available from: https://energy.gov/eere/buildings/articles/department-energy-announces-scaling-next-generation-building-efficiency

[6] Frank, S., et al. 2016. Hybrid model-based and data-driven fault detection and diagnostics for commercial buildings. *Proceedings of the 2016 ACEEE Summer Study on Energy Efficiency in Buildings.*

[7] Smart Energy Analytics Campaign. Smart Energy Analytics Campaign [Internet]. 2017 [accessed on August 29, 2017]. Available from: https://smart-energy-analytics.org/

- LBNL and NREL are conducting public-facing multi-site field evaluations of technologies for rooftop unit AFDD and combined FDD/HVAC optimization.[8] Performance results are intended to inform the market at large, with a particular focus on public and private sector portfolio owners.

AFDD has matured significantly since its first introduction into commercial buildings. Based on information gathered through this survey and discussion with both vendors and users, several opportunities emerge to further advance the technology. Some of these are technical development challenges, and some strongly tied to the interplay between market demand and business choices concerning standardization and interoperability.

Continued development of algorithms that include machine learning and other promising techniques could reduce tuning needs, simplify configuration, and enhance diagnostic power. Following the trends in other industries, there is also potential to move beyond fault diagnostics into controls optimization, prognostics, and predictive maintenance. Integration of physics-based models to complement data-driven approaches holds promise to increase diagnostic power and support predictive analytics.

Machine-to-machine integration presents further opportunity for advancement. For example, truly pervasive “plug-and-play” functionality is still being developed, as are solutions to automatically extract and semantically interpret data across diverse systems and data types. The ability to interface AFDD tools with computerized maintenance management systems (CMMS) is just beginning to be explored, and will streamline the process of operationalizing action-taking based on the findings from analytics tools. Similarly, the practice of energy management will be enhanced through an ability to more tightly couple today’s disparate systems and platforms with more pervasive data and connectivity for controls optimization, FDD, site and portfolio meter analytics, and operations and asset management. While an “all in one” tool is not likely, nor necessarily optimal, some convergence for users would be beneficial.

Finally, there are gains to be achieved through the development of corrective and adaptive controls, in combination with tool chains that can ensure that operational design intent is correctly implemented and maintained over the duration of the operational stage in the building lifecycle.

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[8] U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy. BuildingIQ Inc: Predictive Energy Optimization [Internet]. 2017 [accessed on August 29, 2017]. Available from: https://energy.gov/eere/buildings/downloads/buildingiq-inc-predictive-energy-optimization

Appendix

Table 1 summarizes aspects of market delivery for each tool surveyed, and Table 2 summarizes their AFDD technical capabilities and additional software features.

Table 1. Market delivery aspects of each tool surveyed

Tool name	Company	Building type of markets served	Building size of markets served	Software location	Purchase model	Intended users	Software configuration	Data sources	Data ownership	FDD method tailoring	Notification of findings
SkySpark (platform)	SkyFoundry	Hospital, Outpat. Health., Hotel, Office, Restaurant, Retail, Supermarket, College and Univ, K-12 Ed, Warehouse	Large, Medium, Small	Cloud hosted, Desktop computer or other device, Controller-embedded	One time purchase with maintenance included; SaaS through partners	FDD vendor, Site staff, Third-party provider	Third-party provider; Site staff	BAS real-time and historical data, Equipment on-board/internal measures, External meters and sensors	End-customer	Manual	Software user interface, Service with periodic reports, Automated notifications
SkySpark (implementn.)	CBRE|ESI	Hospital, Office, Retail, Supermarket, College and Univ, K-12 Ed	Large, Medium	Locally hosted server, Cloud hosted	SaaS. Optional updates and maintenance after first year	Site staff, Third-party provider	Third-party provider	BAS real-time and historical data, External meters and sensors	End-customer, FDD vendor, Third-party provider	Manual	Software user interface, Service with periodic reports, Automated notifications
True Analytics	Ecorithm	Multi-fam., Hospital, Hotel, Office, College and Univ, K-12 Ed, Warehouse	Large	Cloud hosted	SaaS. Updates and maintenance included	Site staff, Third-party provider	FDD vendor, Third-party provider	BAS real-time and historical data	End-customer	Manual and Automated	Software user interface, Service with periodic reports
Clockworks	KGS	Multi-fam., Hospital, Outpat. Health., Hotel, Office, Retail, Supermarket, College and Univ, K-12 Ed, Warehouse	Large, Medium	Cloud-hosted (via platform-as-a-service)	SaaS. Updates and maintenance included	FDD vendor, Site staff, Third-party provider	FDD vendor, Third-party provider	BAS real-time and historical data, External meters and sensors	End-customer	Manual	Software user interface, Service with periodic reports, Automated notifications

Tool name	Company	Building type of markets served	Building size of markets served	Software location	Purchase model	Intended users	Software configuration	Data sources	Data ownership	FDD method tailoring	Notification of findings
Kaizen	CopperTree Analytics	Multi-fam., Hospital, Outpat. Health., Hotel, Office, Restaurant, Retail, Supermarket, College and Univ, K-12 Ed, Warehouse	Large, Medium, Small	Cloud hosted	SaaS. Use partners as value-added resell distributers Updates and maintenance included	FDD vendor, Site staff, Third-party provider	FDD vendor, Third-party provider	BAS real-time and historical data, External meters and sensors	End-customer	Manual and Automated	Software user interface, Service with periodic reports, Automated notifications
BuildPulse	BuildPulse Inc.	Hospital, Outpat. Health., Hotel, Office, Retail, College and Univ, K-12 Ed	Large, Medium	Cloud hosted	SaaS. Updates and maintenance included	FDD vendor, Site staff, Third-party provider	Third-party provider, Site staff	BAS real-time data, External meters and sensors	End-customer	Manual and Automated	Software user interface, Service with periodic reports, Automated notifications
Analytika	Cimetrics	Hospital, Outpat. Health., Hotel, Office, Supermarket, College and Univ, K-12 Ed, Warehouse, Mfg Facilities	Large, Medium	Cloud hosted	SaaS. Updates and maintenance included	FDD vendor, Site staff, Third-party provider	FDD vendor	BAS real-time and historical data, External meters and sensors	End-customer	Manual and Automated	Software user interface, Service with periodic reports, Automated notifications
Niagara Analytics 2.0	Tridium	Multi-fam., Hospital, Outpat. Health., Hotel, Office, Restaurant, Retail, Supermarket, College and Univ, K-12 Ed, Warehouse, Data Centers, Mfg Facilities	Large, Medium, Small	Locally hosted server, Cloud hosted, Controller-embedded	One time purchase with optional updates and maintenance	FDD vendor, Site staff, Third-party provider	FDD vendor, Third-party provider	BAS real-time and historical data, Equipment on-board/internal measures, External meters and sensors	End-customer	Manual and Automated	Software user interface, Automated notifications
IntelliCommand	JLL	Hospital, Outpat. Health., Hotel, Office, Retail, Supermarket, College and Univ, K-12 Ed, Warehouse, Data Centers, Mfg Facilities	Large, Medium	Cloud hosted	SaaS. Updates and maintenance included	Site staff, Third-party provider	FDD vendor	BAS real-time and historical data, External meters and sensors	End-customer	Manual	Software user interface, Service with periodic reports, Automated notifications

Tool name	**Company**	**Building type of markets served**	**Building size of markets served**	**Software location**	**Purchase model**	**Intended users**	**Software configuration**	**Data sources**	**Data ownership**	**FDD method tailoring**	**Notification of findings**
Balance	EEI	Multi-fam, Hospital, Outpat. Health., Hotel, Office, Restaurant, Retail, Supermarket, College and Univ, K-12 Ed, Warehouse, Data Centers, Mfg Facilities	Large, Medium	Cloud hosted	SaaS. Updates and maintenance included.	FDD vendor, Site staff, Third-party provider	FDD vendor, Third-party provider, Site staff	BAS real-time and historical data, External meters and sensors	End-customer, FDD vendor	Manual	Software user interface, Service with periodic reports
Facility Analytix	ICONICS	Hospital, Outpat. Health., Hotel, Office, Restaurant, Retail, Supermarket, College and Univ, K-12 Ed, Warehouse, Data Centers, Mfg Facilities	Large	Locally hosted server, Cloud hosted	One-time purchase or SaaS. Maintenance included, updates optional	Site staff, Third-party provider	FDD vendor, Third-party provider, Site staff	BAS real-time and historical data, External meters and sensors	End-customer	Manual	Software user interface, Service with periodic reports, Automated notifications
eIQ	Transformative Wave	Hospital, Outpat. Health., Hotel, Office, Restaurant, Retail, Supermarket, College and Univ, K-12 Ed, Warehouse, Data Centers, Mfg Facilities	Large, Medium, Small	Cloud hosted	SaaS. Updates and maintenance included	FDD vendor, Site staff, Third-party provider	FDD vendor, Third-party provider, Site staff	BAS real-time and historical data, External meters and sensors	End-customer	Manual	Software user interface, Automated notifications
ClimaCheck Onsite/ ClimaCheck Online	ClimaCheck	Multi-fam, Hospital, Outpat. Health., Hotel, Office, Restaurant, Retail, Supermarket, College and Univ, K-12 Ed, Warehouse, Data Centers, Mfg Facilities	Large, Medium, Small	Locally hosted server, Cloud hosted, Desktop computer or other device	Onsite: One-time purchase. Optional updates Online: Updates and maintenance included.	FDD vendor, Site staff, Third-party provider	Third-party provider, Site staff	BAS real-time data, External meters and sensors	End-customer	Manual and Automated	Software user interface, Service with periodic reports, Automated notifications
HVAC Service Assistant, SA Mobile, Onboard controller	Field Diagnostic Services	Multi-fam, Outpat. Health., Hotel, Office, Restaurant, Retail, Supermarket, K-12 Ed, Warehouse, Data Centers	Large, Medium, Small	Cloud hosted, Desktop computer or other device, Controller-embedded	One-time purchase or SaaS. Updates included	Site staff, Third-party provider		Equipment on-board/internal measures, External meters and sensors	End-customer	Manual	Software user interface, Service with periodic reports, Automated notifications

Table 2. Technical capabilities and additional features of each tool surveyed

Tool name	Company	Systems covered	Categories of faults detectable	Methods/algorithms	Detection and diagnosis capabilities	Additional functionality
SkySpark	SkyFoundry	AC/HP, Chillers & towers, AHU & VAV, FCU, Com. refrig., Lighting, Boilers/furnace, Water heaters, Whole-building	Sensor errors, Energy consumption, Econ. & vent., Pressurization issues, Com. refrig., Space Clg./Htg., Htg. system, Clg. system, Equip cycling, Pump & fan systems, Scheduling, Sim. htg. & clg., Lighting or other end uses	Rule-based. Platform supports full programmability of rules and includes machine learning functions for use in FDD algorithms.	Fault presence, location, severity, root cause	Equip degradation, Fault prioritization, Auto work order, Energy impacts, Energy cost impacts, Other cost impacts, Meter data analytics, Time series visualization, KPI tracking and reporting, Benchmarking, Cost of resolution and payback
SkySpark (implementn.)	CBRE|ESI	AC/HP, Chillers & towers, AHU & VAV, FCU, Lighting, Boilers/furnace, Whole-building	Sensor errors, Energy consumption, Econ. & vent., Pressurization issues, Space Clg./Htg., Htg. system, Clg. system, Equip cycling, Pump & fan systems, Scheduling, Sim. htg. & clg., Lighting or other end uses	Rule-based	Fault presence, location, severity, root cause	Equip degradation, Fault prioritization, Auto work order, Energy impacts, Energy cost impacts, Meter data analytics, Time series visualization, KPI tracking and reporting, Benchmarking, Cost of resolution and payback
True Analytics	Ecorithm	AC/HP, Chillers & towers, AHU & VAV, FCU, Com. refrig., Lighting, Boilers/furnace, Water heaters, Whole-building	Sensor errors, Energy consumption, Econ. & vent., Pressurization issues, Com. refrig., Space Clg./Htg., Htg. system, Clg. system, Equip cycling, Pump & fan systems, Scheduling, Sim. htg. & clg., Lighting or other end uses	Qual. Model-based, Rule-based, Expert Systems, First Principles-based, Machine learning techniques, fast-sampling algorithms, and the spectral method.	Fault presence, location, severity, root cause	Equip degradation, Fault prioritization, Energy impacts, Meter data analytics, Time series visualization, KPI tracking and reporting, Benchmarking
Clockworks	KGS	AC/HP, Chillers & towers, AHU & VAV, FCU, Com. refrig., Lighting, Boilers/furnace, Water heaters, Whole-building	Sensor errors, Energy consumption, Econ. & vent., Pressurization issues, Com. refrig., Space Clg./Htg., Htg. system, Clg. system, Equip cycling, Pump & fan systems, Scheduling, Sim. htg. & clg., Lighting or other end uses	Simplified Physical Models, Expert Systems, First Principles-based, Limits and Alarms, Statistical	Fault presence, location, severity, root cause	Equip degradation, Fault prioritization, Auto work order, Energy impacts, Energy cost impacts, Meter data analytics, Time series visualization, KPI tracking and reporting, Benchmarking

Tool name	Company	Systems covered	Categories of faults detectable	Methods/algorithms	Detection and diagnosis capabilities	Additional functionality
Kaizen	CopperTree Analytics	AC/HP, Chillers & towers, AHU & VAV, FCU, Com. refrig., Lighting, Boilers/furnace, Water heaters, Whole-building	Sensor errors, Energy consumption, Econ. & vent., Pressurization issues, Com. refrig., Space Clg./Htg., Htg. system, Clg. system, Equip cycling, Pump & fan systems, Scheduling, Sim. htg. & clg., Lighting or other end uses	Rule-based. Includes an open library of rules for users to download, publish and share	Fault presence, location, severity, root cause	Equip degradation, Fault prioritization, Auto work order, Energy impacts, Energy cost impacts, Other cost impacts, Meter data analytics, Time series visualization, KPI tracking and reporting
BuildPulse	BuildPulse Inc.	AC/HP, Chillers & towers, AHU & VAV, FCU, Lighting, Boilers/furnace, Water heaters, Whole-building	Sensor errors, Energy consumption, Econ. & vent., Pressurization issues, Space Clg./Htg., Htg. system, Clg. system, Equip cycling, Pump & fan systems, Scheduling, Sim. htg. & clg., Lighting or other end uses	Rule-based, Qualitative model	Fault presence, location, severity, root cause	Equip degradation, Fault prioritization, Auto work order, Energy impacts, Energy cost impacts, Other cost impacts, Meter data analytics, Time series visualization, KPI tracking and reporting, Benchmarking, Cost of resolution and payback
Analytika	Cimetrics	AC/HP, Chillers & towers, AHU & VAV, FCU, Com. refrig., Lighting, Boilers/furnace, Water heaters, Whole-building	Sensor errors, Energy consumption, Econ. & vent., Pressurization issues, Com. refrig., Space Clg./Htg., Htg. system, Clg. system, Equip cycling, Pump & fan systems, Scheduling, Sim. htg. & clg., Lighting or other end uses	Quant. Model-based, Qual. Model-based, Rule-based, Expert Systems, First Principles-based, Limits and Alarms, Process History-based, Black Box, Statistical, Gray Box	Fault presence, location, severity, root cause	Equip degradation, Fault prioritization, Auto work order, Energy impacts, Energy cost impacts, Other cost impacts, Meter data analytics, Time series visualization, KPI tracking and reporting, Benchmarking
Niagara Analytics 2.0	Tridium	AC/HP, Chillers & towers, AHU & VAV, FCU, Com. refrig., Lighting, Boilers/furnace, Water heaters, Whole-building	Sensor errors, Energy consumption, Econ. & vent., Pressurization issues, Com. refrig., Space Clg./Htg., Htg. system, Clg. system, Equip cycling, Pump & fan systems, Scheduling, Sim. htg. & clg., Lighting or other end uses	Rule-based, Limits and Alarms	Fault presence, location, severity, root cause	Equip degradation, Fault prioritization, Auto work order, Energy impacts, Energy cost impacts, Other cost impacts, Meter data analytics, Time series visualization, KPI tracking and reporting, Cost of resolution and payback
IntelliCommand	JLL	AC/HP, Chillers & towers, AHU & VAV, FCU, Com. refrig., Lighting, Boilers/furnace, Whole-building	Sensor errors, Energy consumption, Econ. & vent., Pressurization issues, Space Clg./Htg., Htg. system, Clg. system, Equip cycling, Pump & fan systems, Scheduling, Sim. htg. & clg., Lighting or other end uses	Rule-based, Limits and Alarms, Statistical, Other Pattern Recognition Techniques	Fault presence, location, severity, root cause	Equip degradation, Fault prioritization, Auto work order, Energy impacts, Energy cost impacts, Other cost impacts, Meter data analytics, Time series visualization, KPI tracking and reporting

Tool name	Company	Systems covered	Categories of faults detectable	Methods/algorithms	Detection and diagnosis capabilities	Additional functionality
Balance	EEI	AC/HP, Chillers & towers, AHU & VAV, FCU, Com. refrig., Lighting, Boilers/furnace, Water heaters, Whole-building	Sensor errors, Energy consumption, Econ. & vent., Pressurization issues, Com. refrig., Space Clg./Htg., Htg. system, Clg. system, Equip cycling, Pump & fan systems, Scheduling, Sim. htg. & clg., Lighting or other end uses	Rule-based, Expert Systems, First-Principles Based	Fault presence, location, severity	Equip degradation, Fault prioritization, Auto work order, Energy impacts, Energy cost impacts, Other cost impacts, Meter data analytics, Time series visualization, KPI tracking and reporting, Cost of resolution and payback
Facility Analytix	ICONICS	AC/HP, Chillers & towers, AHU & VAV, FCU, Com. refrig., Lighting, Boilers/furnace, Water heaters, Whole-building	Sensor errors, Energy consumption, Econ. & vent., Pressurization issues, Com. refrig., Space Clg./Htg., Htg. system, Clg. system, Equip cycling, Pump & fan systems, Scheduling, Sim. htg. & clg., Lighting or other end uses	Rule-based, First Principles-based, Limits and Alarms	Fault presence, location, severity, root cause	Fault prioritization, Auto work order, Energy impacts, Energy cost impacts, Other cost impacts, Meter data analytics, Time series visualization, KPI tracking and reporting
eIQ	Transformative Wave	AC/HP	Sensor errors, Energy consumption, Econ. & vent., Pressurization issues, Space Clg./Htg., Htg. system, Pump & fan systems, Sim. htg. & clg.	Rule-based, Expert Systems, Limits and Alarms	Fault presence, location, root cause	Fault prioritization, Energy impacts, Energy cost impacts, Time series visualization
ClimaCheck Onsite/ ClimaCheck Online	ClimaCheck	AC/HP, Chillers & towers, AHU & VAV, FCU, Com. refrig.	Sensor errors, Energy consumption, Econ. & vent., Com. refrig., Space Clg./Htg., Htg. system, Clg. system, Equip cycling, Pump & fan systems, Scheduling, Sim. htg. & clg., Lighting or other end uses	Thermodynamic Evaluation, Energy Signatures	Fault presence, location, severity, root cause	Equip degradation, Energy impacts, Energy cost impacts, Time series visualization, KPI tracking and reporting
HVAC Service Assistant, SA Mobile, Onboard controller	Field Diagnostic Services	AC/HP, AHU & VAV, FCU	Sensor errors, Energy consumption, Space Clg./Htg.		Fault presence, location, severity, root cause	Equip degradation, Fault prioritization, Auto work order

REVIEW ARTICLE

Methods for Fault Detection, Diagnostics, and Prognostics for Building Systems— A Review, Part II

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This paper is the second of a two-part review of methods for automated fault detection and diagnostics (FDD) and prognostics whose intent is to increase awareness of the HVAC&R research and development community to the body of FDD and prognostics developments in other fields as well as advancements in the field of HVAC&R. The first part of the review focused on generic FDD and prognostics, provided a framework for categorizing methods, described them, and identified their primary strengths and weaknesses (Katipamula and Brambley 2005). In this paper we address research and applications specific to the fields of HVAC&R, provide a brief discussion on the current state of diagnostics in buildings, and discuss the future of automated diagnostics in buildings.

INTRODUCTION

Poorly maintained, degraded, and improperly controlled equipment wastes an estimated 15% to 30% of energy used in commercial buildings. Much of this waste could be prevented with widespread adoption of automated condition-based maintenance. Automated fault detection and diagnostics (FDD) along with prognostics provide a cornerstone for condition-based maintenance of engineered systems. Although FDD has been an active area of research in other fields for more than a decade, applications for heating, ventilating, air conditioning, and refrigeration (HVAC&R) and other building systems have lagged those in other industries. Nonetheless, over the last decade there has been considerable research and development targeted toward developing FDD methods for HVAC&R equipment. Despite this research, there are still only a handful of FDD tools that are deployed in the field.

This paper, which is the second of two parts, provides a review of fault detection, diagnostics, and prognostics (FDD&P) research in the HVAC&R field and concludes with discussions of the current state of applications for buildings and likely contributions to operating and maintaining buildings in the future. In the first paper (Katipamula and Brambley 2005), we provided an overview of FDD&P, starting with descriptions of the fundamental processes and some important definitions, and then identified the strengths and weaknesses of methods across the broad spectrum of approaches.

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FDD RESEARCH IN HVAC&R

In this section we review FDD research relating to refrigerators, air conditioners, chillers, and air-handling units (AHUs), which represent most of the HVAC&R FDD research completed to date. This review is an update to the review previously published by Katipamula et al. (2001) and includes recent FDD publications. For information on FDD for other building systems refer to Pape et al. (1990), Dexter and Benouarets (1996), Georgescu et al. (1993), Jiang et al. (1995), and Han et al. (1999) for HVAC&R plants; Fasolo and Seborg (1995) for HVAC&R control systems; Li et al. (1996, 1997) for heating systems; Isermann and Nold (1988) and Dalton et al. (1995) for pumps; Noura et al. (1993) for large thermal plants; Isermann and Ballé (1997) for applications for motors; and Dodier and Kreider (1999) for whole-building systems.

Refrigerators

One of the early applications of FDD was to vapor-compression-cycle-based refrigerators (McKellar 1987; Stallard 1989). Although McKellar (1987) did not develop an FDD system, he identified common faults for a refrigerator based on the vapor-compression cycle and investigated the effects of the faults on the thermodynamic states at various points in the cycle. He concluded that the suction pressure (or temperature), discharge pressure (or temperature), and the discharge-to-suction pressure ratio were sufficient for developing an FDD system. The faults considered were compressor valve leakage, fan faults (condenser and evaporator), evaporator frosting, partially blocked capillary tubes, and improper refrigerant charge (under and over charge).

Building upon McKellar's work, Stallard (1989) developed an automated FDD system for refrigerators. A rule-based expert system was used with simple limit checks for both detection and diagnosis. Condensing temperature, evaporating temperature, condenser inlet temperature, and the ratio of discharge-to-suction pressure were used directly as classification features. Faults were detected and diagnosed by comparing the change in the direction of the measured quantities with expected values and matching the changes to expected directional changes associated with each fault.

Air Conditioners and Heat Pumps

There are many applications of FDD to air conditioners and heat pumps based on the vapor-compression cycle. Some of these studies are discussed below (Yoshimura and Ito 1989; Kumamaru et al. 1991; Inatsu et al. 1992; Wagner and Shoureshi 1992; Rossi 1995; Rossi and Braun 1996, 1997; Breuker 1997; Breuker and Braun 1998b; Ghiaus 1999; Chen and Braun 2000). Breuker and Braun (1998a) summarized common faults in air conditioners and their impact on performance. In addition, the frequency of fault occurrence and the relative cost of service for various faults were estimated from service records.

Yoshimura and Ito (1989) used pressure and temperature measurements to detect problems with condenser, evaporator, compressor, expansion valve, and refrigerant charge on a packaged air conditioner. The differences between measured values and expected values were used to detect faults. Expected values were estimated from manufacturers' data, and the thresholds for fault detection were experimentally determined in the laboratory. Both detection and diagnosis were conducted in a single step. No details were provided as to how the thresholds for detection were selected.

Wagner and Shoureshi (1992) developed two different fault detection methods and compared their abilities to detect five different faults in a small heat pump system in the laboratory. The five faults included abrupt condenser and evaporator fan failures, capillary tube blockage, compressor piston leakage, and seal system leakage. The first method was based on limit and trend

Table 1. Symptom Patterns for Selected Faults (Grimmelius et al. 1995)

Fault Modes	Compressor Suction Pressure	Compressor Suction Temperature	Compressor Discharge Pressure	Compressor Discharge Temperature	Compressor Pressure Ratio	Oil Pressure	Oil Temperature	Oil Level	Crankcase Pressure	Compressor Electric Power	Subcooling of Refrigerant	ΔT Refrigerant and Cooling Water	ΔT Cooling Water	Inlet Temperature at Expansion Valve	Filter Pressure Drop	Evaporator Outlet Pressure	Superheat	ΔT Chilled Water	Evaporator Outlet Temperature	Number of Acting Cylinders
Compressor, Suction Side, Increase in Flow Resistance	↓	→	→	→	→	↓	→	→	↓	↓	→	→	→	→	→	↑	↑	↓	→	→
Compressor, Discharge Side, Increase in Flow Resistance	↑	→	↑	→	→	↑	→	→	↑	→	→	→	→	→	→	↑	↑	↓	→	→
Condenser, Cooling Water Side, Increase in Flow Resistance	→	→	↑	→	→	→	→	→	→	↑	↓	→	↑	→	→	→	→	→	→	→
Fluid Line Increase in Flow Resistance	→	→	→	→	→	→	→	→	→	↓	→	→	→	↓	→	→	↑	↑	→	→
Expansion Valve, Control Unit, Power Element Loose from Pipe	↑	→	→	→	→	↑	→	→	↑	↑	→	→	→	→	→	↑	↓	↑	→	→
Evaporator, Chilled Water Side, Increase in Flow Resistance	↓	→	→	→	→	↓	→	→	↓	↓	→	→	→	→	→	↓	↑	↑	→	→

checking (qualitative model-based), and the second method was a simplified physical model-based approach. In the second approach, differences between predictions from a simplified physical model and the monitored observations are transformed into useful statistical quantities for hypothesis testing. The transformed statistical quantities are then compared to predetermined thresholds to detect faults.

The two fault detection strategies were operated in parallel on a heat pump in a psychrometric room. The qualitative method was able to detect four of five faults that were introduced abruptly, while the simplified physical model-based method was successful in only detecting two faults. Because the selection of thresholds for both methods is critical in avoiding false alarms and reduced sensitivity, Wagner and Shoureshi (1992) provide a brief discussion of how to trade off diagnostic sensitivity against false alarms. Their implementation is only capable of detecting faults and does not include diagnosis, evaluation, and decision making.

Rossi (1995) described the development of a statistical rule-based fault detection and diagnostic method for air-conditioning equipment with nine temperature measurements and one humidity measurement. The FDD method is capable of detecting and diagnosing condenser fouling, evaporator fouling, liquid-line restriction, compressor valve leakage, and refrigerant leakage. In addition to the detection and diagnosis, Rossi and Braun (1996) also describe an implementation of fault evaluation. A detailed explanation of the fault evaluation method can be found in Rossi and Braun (1997). The methods were demonstrated in limited testing with a rooftop air conditioner in the laboratory.

Breuker (1997) performed a more detailed evaluation of the methods developed by Rossi (1995). The detailed evaluation relied on steady-state and transient tests of a packaged air conditioner in a laboratory over a range of conditions and fault levels (Breuker and Braun 1998b). Seven polynomial models (ranging from first to third order) were developed to characterize the performance of the air conditioner (evaporating, condensing, and compressor outlet temperatures, suction line superheat, liquid line subcooling, temperature rise across the condenser, and temperature drop across the evaporator) using steady-state data representing normal (unfaulted) operations. The steady-state normal data are also used to determine the statistical thresholds for fault detection, while transient data with faults were used to evaluate FDD performance. Breuker and Braun (1998b) concluded that refrigerant leakage, condenser fouling, and liquid line restriction were detected and diagnosed before 8% reduction in capacity or COP occurred. The technique, however, was less successful in detecting evaporator fouling and compressor valve leakage. The authors also concluded that increasing the measurements from 6 (2 inputs and 4 outputs) to 10 (3 inputs and 7 outputs) and using higher order polynomial models improved the performance by a factor of two.

Ghiaus (1999) presented a bond-graph model for a direct-expansion vapor-compression system and applied it to diagnosing two faults in an air conditioner. The author states that this qualitative approach of modeling faults does not need *a priori* knowledge of possible faults as long as the bond model is complete and accurate.

Chillers

Several researchers have applied FDD methods to detect and diagnose faults in vapor-compression-based chillers; some of the studies are summarized below (Grimmelius et al. 1995; Gordon and Ng 1994, 1995; Stylianou and Nikanpour 1996; Tsutsui and Kamimura 1996; Peitsman and Bakker 1996; Stylianou 1997; Bailey 1998; Sreedharan and Haves 2001; Castro 2002). Comstock et al. (1999) and Reddy et al. (2001) provide a detailed review of FDD literature relating to chiller systems up to their respective times. Comstock et al. (2002) presented a list of common chiller faults and their impacts on performance.

Grimmelius et al. (1995) developed a fault diagnostic system for a chiller, in which fault detection and diagnostics are carried out in a single step. The FDD method uses a reference model based on multivariate linear regression that was developed with data from a properly operating chiller to estimate values for process variables for a healthy (unfaulted) chiller. These estimates are subsequently used to generate residuals (i.e., differences between actual measured values and the values from the reference model). Patterns of these residuals are compared to characteristic patterns corresponding to faulted conditions, and scores are assigned indicating the degree to which the patterns match the pattern corresponding to each fault mode. Fault modes with good fits (high scores) are judged as probably existing in the chiller. Fault modes with poor fits (low scores) are judged as unlikely to exist in the chiller, and faults with intermediate scores are labeled as possibly existing. Twenty different measurements are used including

Table 2. Scoring of Fault Modes for a Highly Idealized Example

Fault Mode/ Score		Symptom 1	Symptom 2	Symptom 3	Symptom 4	Total Score	Normalized Score
F1		↓	→	↓	↑		
	Scores	10	10	10	10	40	1.0
F2		↑	→	↑	→		
	Scores	0	9	0	3	12	0.3
Measurement-Based Pattern		↓	→	↓	↑		

temperatures, pressures, power consumption, and compressor oil level. In addition to the measured variables, some derived variables, such as liquid subcooling, superheat, and pressure drop, are used. The inputs to the model also include the outdoor ambient temperature and load conditions.

To identify potential fault modes, the chiller is classified into seven components: compressor, condenser, evaporator, expansion valve, liquid line immediately downstream of the condenser and including a filter drier, liquid line with solenoid and sight glass between the other liquid line and the evaporator, and the crankcase heater. Fault modes are associated with any component that is serviceable, which leads to 58 different fault modes. A cause and effect study of the 58 fault modes helped establish the expected influence of the faults on the components, measured variables, and subsequent chiller behavior. Symptoms are defined as a difference in any measured or derived variable from its expected value for normal unfaulted operation (i.e., the value given by the reference model). Symptoms associated with all 58 fault modes were generated and arranged into symptom patterns. Fault modes having identical symptom patterns were aggregated into a single fault mode, reducing the total number of fault modes from 58 to 37. These symptom patterns are arranged in a symptom matrix as shown in Table 2, with each row giving the symptom pattern associated with a particular fault. A symptom (cell in the matrix) shown by an arrow pointing up, ↑, indicates a value for the variable greater than that given by the reference model. Likewise, an arrow pointing down, ↓, indicates a symptom corresponding to a value for the variable less than the value from the reference model, and a horizontal arrow, →, indicates the fault has no effect on the corresponding variable.

To diagnose a fault, a symptom pattern corresponding to a set of measurements is compared to the symptom patterns for all of the fault modes. Scores are assigned to each fault mode indicating the probability that its symptom pattern matches the measured symptom pattern as follows. For each fault mode, each symptom is compared to its corresponding measured symptom and assigned a score between 0 and 10. If the symptom for the fault mode matches the measured symptom very well, it is assigned a high score (close to 10). If it weakly matches, it is assigned a score around 5, and if it does not match well at all, it is assigned a score close to zero. A total score for each fault mode is generated by adding the individual scores of all symptoms and dividing the total by the maximum possible score per pattern (i.e., the number of symptoms in the pattern multiplied by 10) to obtain a normalized score. These normalized scores are then classified into three categories. A normalized score of 0.9 or higher indicates a probable fault, a score between 0.5 and 0.9 indicates a possible fault, and scores lower than 0.5 indicate that the fault is likely not present.

A highly simplified example is shown in Table 2. Symptom patterns for two faults, F1 and F2, are shown along with a symptom pattern derived from measurements. Each pattern consists of symptoms based on four variables. Scores have been assigned to the symptoms in each pattern based on how well the symptom shown in the symptom matrix corresponds to the symptom based on measurements. For example, Symptom 1 for fault mode F1 corresponds identically to Symptom 1 in the pattern derived from measurements, so it is assigned a score of 10. The normalized scores in this example lead to the conclusion that fault F1 with a score of 1.0 probably exists in this system and fault F2 with a score of 0.3 is likely not present. In actual implementation, this methodology accounts for uncertainty in measurements by establishing threshold bands around numerical values of measured and derived variables and using the proximity to them in assigning scores to symptoms. The exact algorithm for assigning numerical scores, however, is not available in the paper.

Although the method proved effective in identifying faults in systems before the chiller system failed completely, faults with only a few symptoms tended to get high scores more often. Because the reference model is a simple regression model developed with data from a specific test chiller, the same model cannot be used on other chillers but instead new models would need to be developed for each chiller. Nonetheless, this generic approach provided a foundation for diagnostic work that followed.

Stylianou and Nikanpour (1996) used the universal chiller model developed by Gordon and Ng (1995) and the pattern matching approach outlined by Grimmelius et al. (1995) as part of their FDD system. Like Grimmelius et al. (1995), Stylianou and Nikanpour also perform detection and diagnosis in a single step. The methods used in the FDD system included a thermodynamic model for fault detection and pattern recognition from expert knowledge for diagnosis of selected faults. The diagnoses of the faults are performed by an approach similar to that outlined by Grimmelius et al. (1995). Seventeen different measurements (pressures, temperatures, and flow rates) were used to detect four different faults: refrigerant leak, refrigerant line flow restriction, condenser water-side flow resistance, and evaporator water-side flow resistance.

The FDD system is subdivided into three parts: one used to detect problems when the chiller is off, one used during chiller start-up, and one used at steady-state conditions. The off-cycle module is deployed when the chiller is turned off and is primarily used to detect faults in the temperature sensors. The temperature sensor readings at different locations on the system are compared to one another after the chiller is shut down and reaches steady state (under the assumption that the temperature of refrigerant will reach equilibrium conditions and reach the ambient state when the chiller is shut down overnight). The differences are then compared to the difference observed during commissioning (if the sensors are calibrated during commissioning, the differences should be zero). The monitored rate of change of a sensor value is used to check whether a particular sensor has reached steady state or not before comparing measurements across sensors.

The start-up module is deployed during the first 15 minutes after the chiller is started. The module uses four measured inputs (discharge temperature, crankcase oil temperature, and refrigerant temperatures entering and leaving the evaporator) scanned at five-second intervals to detect refrigerant flow faults, which are easier to detect before the system reaches steady state. To detect faults, the transient trends in measured variables during start-up are compared to the baseline trend from normal start-up. For example, a shift (in time or magnitude) in the peak of the discharge temperature may indicate liquid refrigerant flood back, refrigerant loss, or a refrigerant line restriction. Because ambient conditions affect the baseline response, the baseline response has to be normalized before a comparison is made.

The steady-state module is deployed after the chiller reaches steady state (steady-state condition is established by monitoring the rate of change of the sensor values just as in off-cycle analysis) and stays deployed until the chiller is turned off. In this mode, the module performs two functions: (1) verifies performance of the system and (2) detects and diagnoses selected faults.

Table 3. Fault Patterns Used in the Diagnostic Module (Stylianou and Nikanpour 1996)

Fault	Discharge Temperature	High Pressure Liquid Line Temperature	Discharge Pressure	Low Pressure Liquid Line Temperature	Suction Line Temperature	Suction Pressure	ΔT_{cond}	ΔT_{Evap}
Restriction in Refrigerant Line	↑	↓	↓	↓	↑	↓	↓	↑
Refrigerant Leak	↑	↓	↓	↓	↑	↓	↓	↑
Restriction in Cooling Water	↑	↑	↑	↓	↓	↓	↑	↓
Restriction in Chilled Water	↑	↓	↓	↓	↓	↓	↓	↓

Performance is verified using the thermodynamic models developed by Gordon and Ng (1995). For fault diagnostics, linear regression models are used to generate estimates of pressure and temperature variables that are then compared to actual measurements in an approach similar to that described by Grimmelius et al. (1995). The estimated variables are compared to the measured values, and the residuals are matched to predefined patterns corresponding to the various faults using a rule-base (as shown in Table 3).

Although Stylianou and Nikanpour (1996) extended the previous work of Gordon and Ng (1995) and Grimmelius et al. (1995), their evaluation of the FDD systems was not comprehensive and lacked several key elements including sensitivity and rate of false alarms. In addition, it is not clear whether the start-up module can be generalized easily.

Stylianou (1997) replaced the rule-based model used to match the patterns shown in Table 3 with a statistical pattern recognition algorithm. This algorithm uses the residuals generated from comparison of predicted (using linear regression models) and measured pressures and temperatures to generate patterns that identify faults. Because this approach relies on the availability of training data for both normal and faulty operation, it may be difficult to implement in the field. Only limited testing of the method was presented in the paper.

Tsutsui and Kamimura (1996) developed a model based on a topological-case-based reasoning (TCBR) technique and applied it to an absorption chiller. Case-based reasoning is a knowledge-based problem-solving technique that solves new problems by adapting old solutions. It is based on defining neighborhoods that provide the needed measure of similarity between cases. In contrast, TCBR defines "the neighborhood theoretically, based on the assumption that the input/output relationship is locally continuous" (Tsutsui and Kamimura 1996). Tsutsui and Kamimura (1996) also compared the diagnostic capabilities of TCBR with a linear regression model. The authors state that although the linear regression model had a better overall modeling error (mean error) than the TCBR model, the TCBR model was better at identifying abnormal conditions.

Peitsman and Bakker (1996) used two types of black-box models (artificial neural networks [ANNs] and auto regressive with exogenous inputs [ARX[1]]) to detect faults in the system and at the component level of a reciprocating chiller system. The inputs to the system models included condenser supply water temperature, evaporator supply glycol temperature, instantaneous power of the compressor, and flow rate of cooling water entering the condenser (for the ANN only). The choice of the inputs was limited to those that are commonly available in the field. Using these inputs with both the ANN and ARX models, 14 outputs were estimated. For the ANN models, inputs from the current and the previous time step and outputs from two previous time steps were used.

Peitsman and Bakker (1996) compared diagnostic capabilities of two types of models—a multiple input/output ARX model and ANN models. They used a two-level approach in which system-level models were used to detect "faulty" operation and component-level models were used to diagnose the cause of the fault. They developed 14 system-level models and 16 component-level models to detect and diagnose faults in a chiller; however, only one example (air in the system) is described in their paper. ANN models appeared to have a slightly better performance than the ARX models in detecting faults at both the system and the component levels. The authors also note that it is critical to find a global minimum when using ANN models. If an incorrect initial state is chosen, it may lead to a local minimum rather than the global minimum.

Bailey (1998) also used an ANN model to detect and diagnose faults in an air-cooled chiller with a screw compressor. The detection and diagnosis were carried out in a single step. The faults evaluated included refrigerant under- and overcharge, oil under- and overcharge, condenser fan loss (total failure), and condenser fouling. The measured data included superheat for heat exchanger circuits 1 and 2, subcooling from circuits 1 and 2, power consumption, suction pressure for circuits 1 and 2, discharge pressures for circuits 1 and 2, chilled water inlet and outlet temperatures from the evaporator, and chiller capacity. Each heat exchanger circuit has its own compressor. The ANN model was applied to normal and "faulty" test data collected from a 70-ton laboratory air-cooled chiller with screw compressor.

Sreedharan and Haves (2001) compared three chiller models for their ability to reproduce the observed performance of a centrifugal chiller. Although the evaluation was meant to find the most suitable model for chiller FDD, no FDD system was proposed or developed. Two models were based on first principles (from Gordon and Ng [1995] and a modified ASHRAE Primary Toolkit from Bourdouxhe et al. [1997]) and the third was an empirical model. While each model has some distinct advantages and disadvantages, they concluded that the accuracies of all three models were similar. Hydeman et al. (2002) reported that the three models compared by Sreedharan and Haves (2001) were not accurate in predicting the power consumption of chillers with variable condenser water flow and centrifugal chillers operating with variable-speed drives at low loads. They reformulated the Gordon and Ng model and found that it performed better than the three models described above.

Castro (2002) used a physical model developed by Rossi (1995) along with a k-nearest neighbor classifier to detect faults and a rule base to diagnose five different faults (condenser and evaporator fouling, liquid line restriction, and refrigerant under- and overcharge) in a reciprocating chiller. The FDD implementation detected and diagnosed condenser fouling, refrigerant undercharge at faults level of 20% or greater, and evaporator fouling and liquid line restriction at fault levels of 30% or greater.

[1]Refer to Box and Jenkins (1976) for more details on ARX type models.

Air-Handling Units

There are several studies relating to FDD methods for air-handling units (both the airside and the waterside); some of these are summarized in this section (Norford and Little 1993; Glass et al. 1995; Yoshida et al. 1996; Haves et al. 1996; Lee et al. 1996a, 1996b; Lee et al. 1997; Peitsman and Soethout 1997; Brambley et al. 1998; Katipamula et al. 1999; House et al. 1999; Ngo and Dexter 1999; Yoshida and Kumar 1999; Seem et al. 1999; Karki and Karjalainen 1999; Morisot and Marchio 1999; House et al. 2001; Dexter and Ngo 2001; Kumar et al. 2001; Salsbury and Diamond 2001; Carling 2002; Norford et al. 2002; Wang and Chen 2002; Pakanen and Sundquist 2003).

Norford and Little (1993) classify faults in ventilating systems, consisting of fans, ducts, dampers, heat exchangers, and controls. They then review two forms of steady-state parametric models for the electric power used by supply fans and propose a third, that of correlating power with a variable-speed drive control signal. The models are compared based on prediction accuracy, sensor requirements, and their ability to detect faults.

Using the three proposed models, four different types of faults associated with fan systems are detected: (1) failure to maintain supply air temperature, (2) failure to maintain supply air pressure setpoint, (3) increased pressure drop, and (4) malfunction of fan motor coupling to fan and fan controls. Although the paper by Norford and Little (1993) lacks details on how the faults were evaluated, error analysis and associated model fits were discussed. The results indicate that all three models were able to identify at least three of the four faults. The diagnosis of the faults is inferred after the fault is detected.

Glass et al. (1995) use a qualitative model-based approach to detect faults in an air-handling unit. The method uses outdoor, return, and supply air temperatures and control signals for the cooling coil, heating coil, and the damper system. Although Glass et al. (1995) mention that the diagnosis is inferred from the fault conditions, no clear explanation or examples are provided. Detection starts by analyzing the measured variables to verify whether steady-state conditions exist. Then, the controller values are converted to qualitative signal data and, using a model for expected values and measured temperature data, qualitative signals are estimated. Faults are detected based on discrepancies between measured qualitative controller outputs and corresponding model predictions based on the temperature measurements. Examples of qualitative states for the damper signal include "maximum position," "minimum position," "closed," and "in between." When the quantitative value of the damper signal approaches the maximum value, the corresponding qualitative value of "maximum" is assigned to the measured controller output. The results of testing the method on a laboratory AHU were mixed because the method requires steady-state conditions to be achieved before fault detection is undertaken. Fault detection sensitivity and ability to deal with false alarms are not discussed.

Yoshida et al. (1996) use ARX and the extended Kalman filter approach to detect abrupt faults with simulated test data for an AHU. Although the fault diagnosis approach is clearly described, the authors note that diagnosis is not feasible with the ARX method but that the Kalman filter approach could be used for diagnosis. Fault detection sensitivity and ability to deal with false alarms are not discussed.

Haves et al. (1996) use a combination of two models to detect coil fouling and valve leakage in the cooling coil of an AHU. The methodology was tested with data produced by the HVACSIM+ simulation tool (Clark 1985). A radial bias function (RBF) models the local behavior of the AHU and is updated using a recursive gradient-based estimator. The data generated by exercising the RBF over the operating range of the system are used in the estimation of the parameters for the physical model (UA and percent leakage) using a direct search method. Detection is accomplished by comparing estimated parameters to fault-free parameters.

Lee et al. (1996a) used two methods to detect eight different faults (mostly abrupt faults) in a laboratory test AHU. The first method uses discrepancies between measured and expected variables (residuals) to detect the presence of a fault. The expected values are estimated at nominal operating conditions. The second method compares parameters estimated using autoregressive moving average with exogenous input (ARMX) and ARX models with the normal (or expected) parameters to detect faults. The faults evaluated included complete failure of the supply and return fans, complete failure of the chilled-water circulation pump, stuck cooling-coil valve, complete failure of temperature sensors, complete failure of the static pressure sensor, and failure of the supply and return air fan flow stations. Because each of the eight faults has a unique signature, no separate diagnosis is necessary.

Lee et al. (1996b) used an ANN to detect the same faults described previously (Lee et al. 1996a). The ANN was trained using the normal data and data that represented each of the eight faults. Inputs to the ANN were values for seven normalized residuals, and the outputs were nine values that constitute patterns that represent the normal mode and the eight fault modes. Instead of generating the training data with faults, idealized training patterns were specified by considering the dominant symptoms of each fault. For example, supply fan failure implies that the supply fan speed is zero, the supply air pressure is zero, the supply fan control signal is maximum, and the difference between the flow rates in the supply and return ducts is zero. Using similar reasoning, a pattern of dominant training residuals was generated for each fault (see Table 4). A dominant symptom residual is assigned a value of +1 if the residual is positive and –1 if the residual is negative; all other residuals are assigned a value of 0. The ANN was trained using the pattern shown in Table 4. Normalized residuals were calculated for faults that were artificially generated in the laboratory AHU. The normalized residuals vector at each time step was then used with the trained ANN to identify the fault. Although the ANN was successful in detecting the faults from laboratory data, it is not clear how successful this method would be in general because the faults generated in the laboratory setting were severe and without noise.

Lee et al. (1997) extended the previous work described in Lee et al. (1996b). In the 1997 analysis, Lee et al. (1997) used two ANN models to detect and diagnose faults. The AHU is decomposed into various subsystems such as the pressure control subsystem, the flow-control subsystem, the cooling-coil subsystem, and the mixing-damper subsystem. The first ANN model is trained to identify the subsystem in which a fault occurs, while the second ANN model is trained to diagnose the specific cause of a fault at the subsystem level. An approach similar to the one used in Lee et al. 1996b is used to train both ANN models. Lee et al. (1997) note that this two-stage approach simplifies generalization by replacing a single ANN that encompasses all considered faults with a number of less complex ANNs, each one dealing with a subset of the residuals and symptoms. Although 11 faults are identified for detection and diagnosis, fault detection and diagnosis are presented for only one fault in the paper.

Peitsman and Soethout (1997) used several different ARX models to predict the performance of an AHU and compared the predictions to measured values to detect faults. The training data for the ARX models were generated using HVACSIM+. The AHU is modeled at two levels. The first level is the system level, where the complete AHU is modeled with one ARX model. The second level is the component level, where the AHU is subdivided into several subsystems such as the return fan, the mixing box, and the cooling coil. Each component is modeled with a separate ARX model. The first level ARX model is used to detect a problem and the second level models are used to diagnose the problem. Most abrupt faults were correctly identified and diagnosed, while slowly evolving faults were not detected. There is a potential for a conflict between the two levels with this approach; for example, the top-level ARX model could detect a fault with the AHU, while the second-level ARX models do not indicate any faults. Furthermore, there is a potential for multiple diagnoses at the second level. Peitsman and Soethout (1997)

Table 4. Normalized Patterns for AHU Fault Diagnosis Used in ANN Training (Lee et al. 1996b)

	Network Inputs – Residuals																
Fault Diagnosis	**Supply Pressure**	**Difference in Supply and Return Airflow**	**Supply Air Temperature**	**Control Signal to Cooling Coil**	**Supply Fan Speed**	**Return Fan Speed**	**Cooling Coil Valve Position**	**Network Outputs**									
Normal (no fault)	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
Supply Fan	–1	–1	0	1	–1	0	0	0	1	0	0	0	0	0	0	0
Return Fan	0	1	0	0	0	–1	0	0	0	1	0	0	0	0	0	0
Pump	0	0	0	1	0	0	0	0	0	0	1	0	0	0	0	0
Cooling Coil Valve	0	0	0	0	0	0	1	0	0	0	0	1	0	0	0	0
Temperature Sensor	0	0	–1	–1	0	0	0	0	0	0	0	0	1	0	0	0
Pressure Transducer	–1	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
Supply Fan Flow Station	0	–1	0	0	0	0	0	0	0	0	0	0	0	0	1	0
Return Fan Flow Station	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1

indicated that some of this multiple diagnosis could be discriminated by ranking of diagnoses according to their improbability; however, no details were provided on how to implement such a scheme.

House et al. (1999) compared several classification techniques for fault detection and diagnosis of seven different faults in an AHU. The data for the comparison were generated using an HVACSIM+ simulation model. Using the residuals, as defined in Lee et al. (1996a, 1996b), five different classification methods are evaluated and compared for their ability to detect and diagnose faults. The five classification methods include: ANN classifier, nearest neighbor classifier, nearest prototype classifier, a rule-based classifier, and a Bayes classifier.

Based on the performance of classification methods, the Bayes classifier appears to be a good choice for fault detection. For diagnosis, the rule-based method proves to be a better choice for the classification problems considered, where the various classes of faulty operations were well separated and could be distinguished by a single dominant symptom or feature.

Ngo and Dexter (1999) developed a semi-qualitative analysis of measured data using generic fuzzy reference models to diagnose faults with the cooling coil of an AHU. The method uses sets of training data with and without faults to develop generic fuzzy reference models for diagnosing faults in a cooling coil. The faults include leaky valve, waterside fouling, valve stuck closed, valve stuck midway, and valve stuck open. The fuzzy reference models describe in qualitative terms the steady-state behavior of a particular class of equipment with no faults present and when each of the faults has occurred. Measured data are used to identify a partial fuzzy model that describes the steady-state behavior of the equipment at a particular operating point. The partial fuzzy model is then compared to each of the reference models using a fuzzy matching scheme to determine the degree of similarity between the partial model and the reference models. Ngo and Dexter (1999) provide a detailed description of fault detection sensitivity and false alarm rates.

Yoshida and Kumar (1999) evaluated two model-based methods to identify abrupt (sudden) faults in an AHU. They report that both ARX and adaptive forgetting through multiple models (AFMM) seem promising for use in on-line fault detection of AHUs. They report that ARX models require only a minimal knowledge of the system, and the potential limitation of the technique is that it requires long periods to stabilize its parameters. On the other hand, Yoshida and Kumar (1999) report that the AFMM method requires long moving averages to suppress false alarms. When this is done, faults of lesser magnitude cannot be easily detected. Implementation details are not provided, and only one example of fault detection is provided.

Morisot and Marchio (1999) use an ANN-based approach to detect degradation of performance of a cooling coil in an AHU. The ANN network includes an input layer (six inputs), a hidden layer (four nodes), and an output layer (two outputs). The inputs include entering air temperature and humidity, entering and leaving water temperatures, fan-control signal, and cooling-coil-valve-control signal. The outputs are the leaving air temperature and humidity. The authors highlight the difficulties of using ANNs with real measured data, which include a need for an exhaustive training data set and the inability of the ANNs to extrapolate values outside the range of the training data. The proposed alternative is to use a simulation model to generate the training data for the ANN. Using this alternative approach, the authors test the ability of the ANN to detect two faults (air-side fouling and a sensor fault).

Dexter and Ngo (2001) outline a multi-step fuzzy model-based FDD approach to detecting and diagnosing faults with AHUs. This approach involves classifying measured data with fuzzy rules and comparing them to a set of fuzzy reference models for normal and faulty operations. The fuzzy reference models for a specific system are developed from data that are generated from simulations. Each rule is assigned a rule-confidence in the range from zero to one, where zero indicates no confidence and one indicates complete confidence in the rule correctly describing the behavior. Rule-confidence values are estimated from the data. The authors state that this method prevents false alarms because it accounts for major sources of uncertainty. The multi-step approach is shown to be capable of detecting and isolating faults in a cooling coil (leaking valves and fouling).

Kumar et al. (2001) propose a method based on an auto regressive exogenous model and a recursive parameter estimation algorithm to detect faults with AHUs. They conclude that changes in parameter estimates from real data cannot be directly used to detect faults; instead a statistical analysis of the frequency response of the model parameters is needed to detect faults.

Salsbury and Diamond (2001) develop a simplified physical model-based approach to both control and detect faults in AHUs. Results from a field test on a single AHU demonstrate the fault detection capabilities but also highlight some of the practical implementation difficulties including selection of model parameters, reliability of sensor signals, and difficulty in establishing a baseline of "correct" operation of the AHU.

Carling (2002) assesses the performance of three fault detection methods for AHUs: (1) qualitative model-based approach outlined in Glass et al. (1995), (2) rule-based approach outlined in House et al. (2001), and (3) simplified steady-state model-based. The normal and "faulty" data used for the assessment were collected from real systems for an offline analysis. The "faulty data" were collected by introducing artificial faults in the AHU. The qualitative model was easy to set up, generated few false alarms, but also detected fewer faults. The rule-based method detected more faults but required some analysis and customization during setup. The third method detected more faults but also generated more false alarms and took considerable time to set up and customize. It also required installation of additional sensors.

Norford et al. (2002) present results from controlled field tests for detecting and diagnosing faults in AHUs. These tests were part of an ASHRAE research project (RP-1020), which was to demonstrate FDD methods for AHUs. The first FDD method used a first-principles model-based approach, and the second one was based on semi-empirical polynomial correlations of submetered electrical power with flow rates or process control signals generated from historical data. Although data representing faulty operation were based on blind tests, the faults were selected from a predefined set for an agreed set of conditions and magnitudes. The criteria used in the evaluation of the two FDD methods were sensitivity, robustness, the number of sensors required, and ease of implementation.

Both methods were successful in detecting faults but had difficulty in diagnosing the actual cause of the fault. The first principles-based method requires more sensors and more training data and misdiagnosed more often than the semi-empirical method.

CURRENT STATE FOR DIAGNOSTICS IN BUILDINGS

During the 1990s, significant growth occurred in research on the development of fault detection and diagnostic methods for HVAC&R systems. Still, very few commercial FDD products exist today, and the ones that do are very specialized or not fully automated. There are several reasons for lack of widespread availability and deployment of FDD systems: lack of demand by the building operations and maintenance (O&M) community, possibly as a result of insufficient information on the improvements possible from automated FDD, lack of adequate sensors installed on building systems, reliable sensors being too costly, high perceived cost-to-benefit ratio of deploying FDD systems with current sensor technologies, lack of acceptable benchmarks to quantify the potential benefits from deploying FDD systems, lack of easy access to real-time data unless FDD is built directly into building automation systems, and lack of infrastructure to gather data from existing building automation systems (BASs) for add-on applications.

Most papers reviewed for this study did not cover the evaluation and decision stages of a generic O&M support system using FDD; yet to be useful in the field FDD must be embedded in complete building management and decision support systems. Katipamula et al. (1999), Rossi and Braun (1996), and Breuker and Braun (1998b) have addressed the evaluation aspect of the O&M support system, and Katipamula et al. (2002) and Brambley and Katipamula (2003) proposed a decision step for AHUs. Furthermore, many of the FDD methods have only been tested in laboratory or special test environments (Castro et al. 2003). Some FDD tools have been tested in the field (Katipamula et al. 2003; Castro et al. 2003; Braun et al. 2003). The detection sensitivity of the methods and occurrence rates for false alarms have not been thoroughly investigated in real buildings yet. Although the R&D reviewed is focused on methods for automating FDD, most papers do not address the automation itself in sufficient detail. Efficiently and cost-effectively creating the code that implements these methods represents an important aspect of creating usable tools based on these methods.

A significant number of papers address FDD methods based on process history. In most cases, models based on process history are specific to the system from which the training data are collected. In order to make these methods broadly applicable, the models need to be developed in factory settings for equipment model lines or automatically online in an as-installed setting. Automation of the model development process is critical to controlling the costs of FDD systems. Preliminary work on online modeling has been done by Reddy et al. (2001), but more work is needed in this general area.

Another major limitation of most FDD methods developed to date is that they work well when a single dominant fault is present in a system, but if multiple faults occur simultaneously or are present when FDD is done initially, many of the methods fail to properly detect or diagnose the causes of the faults. Braun et al. (2003) extended the previous work by Rossi and Braun (1996) and Breuker and Braun (1998b) to diagnose multiple simultaneous faults. More work is needed in development of methods that can reliably handle multiple faults.

FUTURE FOR AUTOMATED DIAGNOSTICS IN BUILDINGS

The application of automated FDD to building HVAC&R is still in its infancy. Key technical problems still requiring solutions include:

- eliminating the need to handcraft FDD systems
- automating generation of FDD systems
- selecting the best FDD method for each type of HVAC&R application and the constraints applicable to it
- developing the balance of system for operation and maintenance support tools—evaluation and decision support
- development of prognostics to transform HVAC&R maintenance from corrective and preventive to predictive condition-based maintenance
- lowering the cost of obtaining data for FDD and O&M support

To the extent that FDD requires handcrafting for each installation, costs will likely be prohibitive. Three generically different solutions for this problem exist: (1) deploy FDD in service tools with databases sufficient to cover many equipment model lines, (2) deploy FDD as part of on-board equipment control packages, and (3) develop methods for automatically generating FDD tools. The first approach has already been introduced to the market in a hand tool for air-conditioning service providers (Honeywell 2003). More tools of this type, embedding automated FDD, are likely to evolve. The second approach of embedding monitoring and safety controls capabilities in on-board equipment control is already underway to some extent by manufacturers of equipment and equipment control packages (such as chillers for safety reasons but not for system performance). Capabilities deployed to date appear limited and details of methods are difficult to obtain because of their proprietary nature, but FDD deployment is beginning to emerge via this route. The third approach involving rapid generation, possibly in an automated manner, requires further research not only into the methods for FDD but also for automated code generation (in the fields of software development, adaptive systems, genetic systems, etc.).

Additional R&D is needed in the field of FDD itself to further develop fundamental methods for FDD, selection and specialization of methods to the constraints of the built environment (e.g., pressure to keep costs low and a data-poor environment in buildings), application and testing of FDD to the various systems, equipment, and components used in buildings, and development and application of FDD for building systems of the future, which are likely to include integration with on-site electricity generation, management of electric loads, real-time purchasing of electricity, and other interactions with the electric power grid of the future, and transition to new fuels (e.g., energy carriers such as hydrogen). All provide rich areas for research and development that will improve the performance and efficiency of commercial and residential buildings.

Prognostics are critical to transitioning building equipment maintenance as practiced today to condition based so that it accounts for the expected remaining life of equipment and its performance degradation over time. Only with this information can decisions be made regarding the optimal scheduling of maintenance. The field of prognostics presents a rich area of investigation and development for the HVAC&R research community. Little has been published to date on prognostics for HVAC&R.

Beyond research into FDD methodologies and their application to building systems, the HVAC&R field is faced with the opportunity to develop an entirely new class of tools and to add them to building automation systems. FDD methods may provide a core capability for enhanced operation and maintenance support systems of the future, but the balance of those systems must be developed. Packaging is critical to success in the market. Tools must be developed that meet the needs and fit into the environment of building operators and maintenance service providers and provide them value.

Probably the most constraining of all problems facing the application of FDD&P to HVAC&R is the dearth of data. Relatively small numbers of sensors are generally installed in building systems and the quality (accuracy, precision, and reliability) of the sensors that are installed is inadequate for many uses. Sensors frequently fail or drift out of calibration and remain that way for long periods of time until fortuitously discovered. Performance, cost, and durability need to be addressed to promote better sensing in buildings.

With the development of low-cost reliable sensor technology (Kintner-Meyer and Brambley 2002; Kintner-Meyer et al. 2002), a major hurdle to commercial deployment of FDD systems would be overcome. This would potentially speed the deployment of third party FDD tools and integration of FDD into individual equipment controllers and building automation systems to provide continuous monitoring, real-time fault detection and diagnostic information, and recommendations for maintenance service and would lead to much improved maintenance of HVAC&R systems. Ultimately, as networking infrastructure matures, the use of automated FDD systems should enable a small support staff to operate, monitor, and maintain a large number of different systems from a remote, centralized location. Local FDD systems could communicate across a network to provide reports on the health of the equipment that they monitor. Failures that lead to loss of comfort could be identified quickly before significant impacts on comfort or equipment damage occurs. In many cases, degradation faults could be identified well before they lead to loss of comfort or uneconomical operation, allowing more efficient scheduling of (and lower costs for) maintenance service.

At present, no fully automated FDD systems have been integrated into individual controllers for commercial HVAC&R equipment. In general, larger equipment applications (e.g., chillers) can absorb more add-on costs than smaller ones (e.g., rooftop units) and, therefore, automated FDD will probably appear first in larger equipment.

Open communication standards for building automation systems are catching on, and use of Internet and intranet technologies is pervasive. These developments enable FDD systems to be deployed more readily. In addition, the structure of the industry that provides services for the operations and maintenance of buildings is changing; companies are consolidating and offering whole-building operations and maintenance packages. Furthermore, as utilities are deregulated, they will begin to offer new services, including complete facility management. With complete and distributed facility management, the cost-to-benefit of deploying FDD systems will improve because the cost can be spread over a large number of buildings (Katipamula et al. 1999). To benefit from these changes, facility managers, owners, operators, and energy service providers are challenged to acquire or develop new capabilities and resources to better manage this information and, in the end, their buildings and facilities.

Although the incentives for application of FDD systems for HVAC&R and other building systems have never been greater, there still are several obstacles to their development and deployment. Beyond research and development, there is a need to quantify the benefits, to establish benchmarks for acceptable costs, and to provide market information. Assessing and demonstrating value for these technologies is an opportunity for public/private partnerships. Public agencies can help reduce risk to facility owners and operators while promoting and accelerating transition to a more efficient buildings sector by demonstrating the value of these technologies and transforming the market to accelerate adoption where public benefits warrant. FDD&P promises to help transform the buildings sector to a new level of energy and operational performance and efficiency.

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TAC: Electrical

Total Mods for **Electrical** in **Pending Review : 16**

Total Mods for report: 16

Sub Code: Energy Conservation

7

E9994

Date Submitted	02/01/2022	**Section**	403	**Proponent**	Bryan Holland
Chapter	4	**Affects HVHZ**	No	**Attachments**	Yes
TAC Recommendation	Pending Review				
Commission Action	Pending Review				

Comments

General Comments No **Alternate Language No**

Related Modifications

Summary of Modification

This proposed modification adds requirements for economizer fault detection and diagnostics (FDD) for air-cooled unitary direct-expansion units variable refrigerant flow (VRF) units that are equipped with an economizer.

Rationale

Commercial HVAC systems have been shown to have problems with economizer function, control and performance in field studies and utility-sponsored maintenance programs. This results in reduced energy efficiency and potential energy savings from the economizer with fan-only operation. Adding such systems will provide building owners key information regarding the operation of their HVAC systems. Fault Detection and Diagnostics (FDD) technology significantly reduces costs and improves operational efficiency. It incorporates a standard library of fault rules that can be customized to predict equipment failures and advise personnel of preventive actions. Before the emergence of FDD software solutions, many organizations relied on institutional knowledge in order to fix or maintain their wide variety of equipment. After the development of FDD tech, this type of info (the numerous symptoms, causes and recommended actions) that may have only existed in the heads of senior personnel or, if lucky, in print or electronic archives, could now be used in algorithms to help organizations move from reactionary “break/fix” maintenance to more modern, more cost-effective predictive maintenance. Return on investment studies indicate typical ROI within 12 to 18 months following installation. Please see the attached reports from the Lawrence Berkeley National Laboratory and American Society of Heating, Refrigerating and Air-Conditioning Engineers/Pacific Northwest National Laboratory. This proposed modification improves the code and meets the mandate outlined in F.S. 553.886 that states; "the Florida Building Code must facilitate and promote the use of cost-effective energy conservation, energy-demand management, and renewable energy technologies in buildings.

Fiscal Impact Statement

Impact to local entity relative to enforcement of code

This proposed modification will require the local entity to confirm Economizer FDD is included on the construction documents at time of plan review and has been installed and operational at time of inspection.

Impact to building and property owners relative to cost of compliance with code

This proposed modification will increase the cost of compliance with the code but will result in improved HVAC system efficiency and have a return on investment not greater than 18 months from time of installation.

Impact to industry relative to the cost of compliance with code

This proposed modification will increase the cost of compliance with the code for industry. FDD software and hardware is readily available in the marketplace by a multitude of manufacturers. FDD design, installation, and operation requires specialized training.

Impact to small business relative to the cost of compliance with code

Requirements

Has a reasonable and substantial connection with the health, safety, and welfare of the general public

This proposed modification will improve the health and welfare of the general public by improving HVAC system efficacy and reducing operating costs for HVAC economizers.

Strengthens or improves the code, and provides equivalent or better products, methods, or systems of construction

This proposed modification improves the code and meets the mandate outlined in F.S. 553.886 that states; "the Florida Building Code must facilitate and promote the use of cost-effective energy conservation, energy-demand management, and renewable energy technologies in buildings.

Does not discriminate against materials, products, methods, or systems of construction of demonstrated capabilities

This proposed modification does not discriminate against any materials, methods, or systems of constructions.

Does not degrade the effectiveness of the code

This proposed modification improves the effectiveness of the code.

C403.3.5 Economizer fault detection and diagnostics. Air-cooled unitary direct-expansion units listed in the tables in Section C403.2.3 and variable refrigerant flow (VRF) units that are equipped with an economizer in accordance with Sections C403.3 through C403.3.4 shall include a fault detection and diagnostics system complying with the following:

1. The following temperature sensors shall be permanently installed to monitor system operation:

1.1. Outside air.

1.2. Supply air.

1.3. Return air.

2. Temperature sensors shall have an accuracy of ±2°F (1.1°C) over the range of 40°F to 80°F (4°C to 26.7°C).

3. Refrigerant pressure sensors, where used, shall have an accuracy of ±3 percent of full scale.

4. The unit controller shall be configured to provide system status by indicating the following:

4.1. Free cooling available.

4.2. Economizer enabled.

4.3. Compressor enabled.

4.4. Heating enabled.

4.5. Mixed air low limit cycle active.

4.6. The current value of each sensor.

5. The unit controller shall be capable of manually initiating each operating mode so that the operation of compressors, economizers, fans and the heating system can be independently tested and verified.

6. The unit shall be configured to report faults to a fault management application available for access by day-to-day operating or service personnel, or annunciated locally on zone thermostats.

7. The fault detection and diagnostics system shall be configured to detect the following faults:

7.1. Air temperature sensor failure/fault.

7.2. Not economizing when the unit should be economizing.

7.3. Economizing when the unit should not be economizing.

7.4. Damper not modulating.

7.5. Excess outdoor air.

LBNL-2001075

Lawrence Berkeley National Laboratory

Characterization and Survey of Automated Fault Detection and Diagnostic Tools

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Energy Technologies Area
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Disclaimer

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Executive Summary

Background

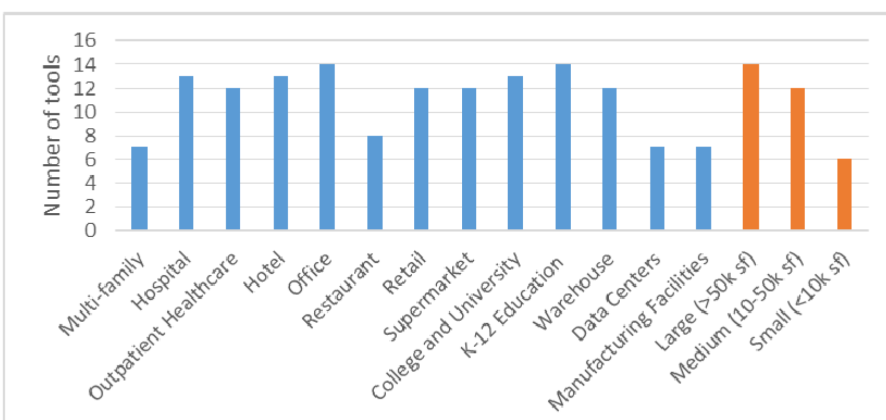
It is estimated that 5%–30% of the energy used in commercial buildings is wasted due to faults and errors in the operation of the control system. Tools that are able to automatically identify and isolate these faults offer the potential to greatly improve performance, and to do so cost effectively. This document characterizes the diverse landscape of these automated fault detection and diagnostic (AFDD) technologies, according to a common framework that captures key distinguishing features and core elements.

Approach

To understand the diversity of technologies that provide AFDD, a framework was developed to capture key elements to distinguish the functionality and potential application of one offering from another. The AFDD characterization framework was applied to 14 currently available technologies, comprising a sample of market offerings. These 14 technologies largely represent solutions that integrate with building automation systems, that use temporary in field measurements, or that are implemented as retrofit add-ons to existing equipment. To characterize them, publicly available information was gathered from product brochures and websites, and from technical papers. Additional information was acquired through interviews and surveys with the developers of each AFDD tool. The study concludes with a discussion of technology gaps, needs for the commercial sector, and promising areas for future development.

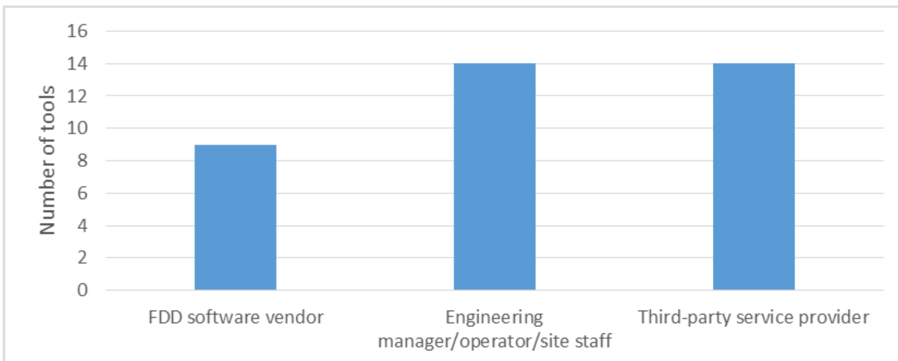
Key Findings

Today's AFDD technologies are being used in nearly all commercial building sectors. Smaller facilities, however, are less commonly served, and when they are it is often through portfolios of small buildings as opposed to single sites.

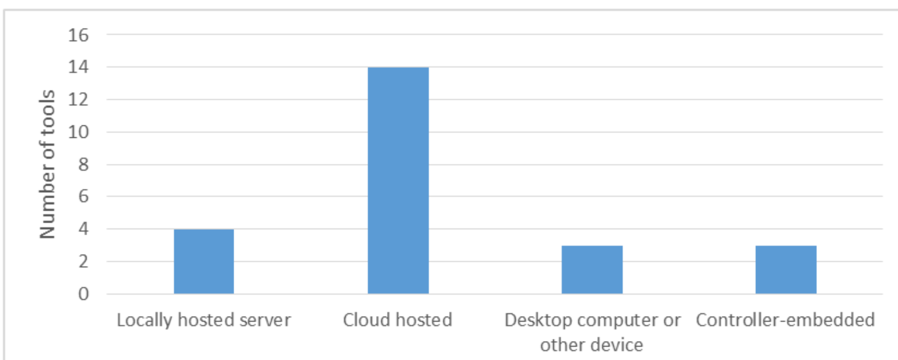


Market presence of surveyed FDD tools

Software-as-a-service models have quickly become the norm for AFDD technologies; even vendors providing on premise and desktop applications also tend to offer SaaS options. A compelling evolution in the industry is seen in the expansion of market delivery of FDD through third-party service providers using the tools as a way to provide value-add to their customers. This expansion offers the potential to increase access to the technology and its associated benefits for a new class of owners who otherwise may not be using it, however third parties' costs may vary significantly and each cost component should be defined in full to be able to compare across delivery options.



Intended users of surveyed AFDD tools



Location of surveyed AFDD tools

While rule-based methodologies to detect and diagnose faults are still heavily used, vendors are beginning to use process history-based techniques. Independent of the FDD methodology used, vendors report a high degree of commonality in the systems and types of faults that their products can cover. That is, coverage of systems and faults is driven more by site data availability than by product offering. Most AFDD tools surveyed accept real-time BAS data and external meters and sensors; many accept historical data from the BAS, and several accept equipment's onboard/ internal measures without going through the BAS. The majority of the AFDD tool vendors surveyed cover major the HVAC systems found in commercial buildings, as well as lighting systems and whole building energy use. Many tools have large libraries that are able to determine at least some types of faults across all systems for whatever data can be provided. Nearly all of the tool vendors surveyed are able to detect faults in the major categories, including: sensors, energy consumption, economizers and ventilation, commercial refrigeration, cooling/heating systems, equipment cycling, scheduling, and lighting or other end uses. Configuration of the technologies does require site-specific tuning. While this is not a fully automated process, some elements of the process may be automated for streamlining.

Distinguishing factors are often associated with the additional features offered to complement the AFDD, and with the available delivery models. The market offers great diversity in additional analytics and reporting capabilities, integration architectures, and purchase models, making it possible to custom fit the technology to the needs of the organization. While custom solutions are desirable for some portions of the buildings market— such as campuses, enterprises, and large or complex facilities—others may benefit from higher degrees of commoditization.

An important theme in interpreting the findings from this survey is that many products are sold with an emphasis on broad-scale applicability, and in analyzing the features and capabilities across all offerings as whole, there is indeed a high degree of similarity. However, it is critical for prospective technology users to probe providers to understand the precisely what is entailed in a given offering's implementation of a feature of interest. For example, there are many ways to prioritize faults and estimate their impacts, and effective prioritization may be dependent on customer input. Similarly, root cause analysis (diagnosis) may be supported for just a subset of faults, or require manual input from operational staff. Analogously, ease of integration with different makes and vintages of BAS is another critical element of implementation for which "the devil is in the details."

Outstanding Needs
FDD technology is seeing increased uptake in the market, and is constantly developing and evolving. Best practice implementations can deliver significant improvements in energy efficiency, utility expenses, operations and maintenance processes, and operational performance—all with rapid return on investment. However, for the full potential to be realized at scale, a core set of interrelated informational, organizational, and technical needs and barriers must be addressed.

The primary informational barriers for prospective users are rooted in interpreting the value proposition of FDD for their facilities, and in accessing best practices in implementation — for example all-in costs and benefits, effective use of contractors and service providers, and integration with higher level energy management practices. Organizationally, successful implementation of AFDD can be slowed by a need to diverge from existing business practices and norms. While the costs are modest compared to capital projects and can be quickly recovered, decision makers must buy in to an increase in operation and maintenance expenses and be willing to manage a certain degree of risk. Finally, from a technical standpoint, IT and data integration represent one of the largest challenges. Even once data is accessible through cross-system integration, it must be interpreted for use in analytic applications. The current lack of common standards in data, metadata, and semantic representation also poses difficulties in scaling. Lastly, today's AFDD offerings can prove difficult and expensive to apply in smaller commercial buildings.

Future Work

AFDD has matured significantly since its first introduction into commercial buildings. Based on information gathered through this survey and discussion with both vendors and users, several opportunities emerge to further advance the technology. Continued development of algorithms that include machine learning and other promising techniques could reduce tuning needs, simplify configuration, and enhance diagnostic power. Following the trends in other industries, there is also potential to move beyond diagnostics into prognostics and predictive maintenance. Machine-to-machine integration presents further opportunity for advancement to realize pervasive "plug-and-play" functionality, thereby enabling tighter coupling of AFDD with computerized maintenance management systems, meter analytics, and operations and asset management tools. Finally, there are gains to be achieved through the development of corrective and adaptive controls, in combination with tool chains that can ensure that operational design intent is correctly implemented and maintained over the duration of the operational stage in the building lifecycle.

1. Overview

Energy Management and Information Systems (EMIS) comprise a broad family of tools and services to analyze, monitor, and control commercial building equipment and energy use. These technologies include, for example, meter analytics or energy information systems (EIS), some types of automated fault detection and diagnostic tools (AFDD), benchmarking and utility bill tracking tools, and building automation systems. These technologies may encompass uses that include monitoring-based and ongoing commissioning, remote audits and virtual assessments, enterprise monitoring and asset tracking, continuous savings estimation, and energy anomaly detection. There are a wide a wide variety of EMIS products available on the commercial market, and they are increasingly heavily marketed to the energy management community.

It is estimated that 5%–30% of the energy used in commercial buildings is wasted due to faults and errors in the operation of the control system[1, 2, 3]. Tools that are able to automatically identify and isolate these faults offer the potential to greatly improve performance, and to do so cost effectively.

This document characterizes the diverse landscape of technologies that offer AFDD functionality, according to a common framework that captures key distinguishing features and core elements. These technologies can reside on local servers or in the cloud, as well as at the network edge within equipment or controller-embedded solutions.

The primary audience for this document is building owners and operators, who are seeking an understanding of the functionality available in AFDD products and services to inform piloting and procurement decisions. It also may be useful to utility energy efficiency program stakeholders who are interested in emerging technologies to test and pilot for incentive programs. A secondary audience includes developers of AFDD solutions who are looking for information to inform and target their efforts.

In the following sections of this review we present a general overview of FDD and other analytics technology types, followed by a common framework to distinguish among various types of AFDD tools. We then apply this framework to evaluate a sampling of AFDD tools and discuss the findings. The evaluation focused primarily on solutions that integrate with building automation systems, that use temporary in-field measurements, or that are implemented as retrofit add-ons to existing equipment; it did not include OEM-embedded AFDD offerings (although in a few instances these variants are available through the AFDD vendor). We conclude with a discussion of technology gaps, needs for the commercial sector, and promising areas for future development.

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[1] Roth, K. W., D. Westphalen, M. Y. Feng, P. Llana, and L. Quartararo. *Energy Impact of Commercial Building Controls and Performance Diagnostics: Market Characterization, Energy Impact of Building Faults and Energy Savings Potential.* 2005. Report prepared by TIAC LLC for the U.S. Department of Energy.

[2] Katipamula, S., and M. Brambley. 2005. "Methods for fault detection, diagnostics, and prognostics for building systems – a review, part 1." *HVAC&R Research* 11(1): 3–25.

[3] Fernandez, N., et al. 2017. *Impacts on commercial building controls on energy savings and peak load reduction.* Pacific Northwest National Laboratory. PNNL Report Number PNNL-25985.

2. Introduction to Fault Detection and Diagnostics

FDD is the process of identifying (detecting) deviations from normal or expected operation (faults) and resolving (diagnosing) the type of problem or its location. FDD has been used for decades to great success in industries that include aerospace, nuclear, and industrial applications, and its use in building operation and control applications is growing. In practice, FDD in buildings is most commonly conducted for heating, ventilation, and air conditioning (HVAC) systems, however as a process, FDD is applicable to all systems in the building. Although currently underutilized, FDD is a powerful approach to ensuring efficient building operations.

As further detailed in the characterization framework that follows, AFDD technology may be delivered through a variety of implementation models. The FDD code may be integrated into either server-based software, desktop software, or software that is embedded in an equipment controller. The AFDD algorithms may rely on historical or near-real time data from building automation systems (BAS), from data local to the equipment or controller, from external sensors and meters, or from some combination of these data sources. AFDD software may be used by the building operator or energy manager, or may be delivered through analysis-as-a-service contracts that do not require direct “in-house” use of the technology.

The software tools that offer AFDD may include additional functionality such as energy consumption monitoring and analytics, visualization, benchmarking, reporting of key performance indicators, or fault prioritization and impact assessment. The server-based offerings rely on continuous data acquisition and analysis; these types of AFDD tools are commonly considered part of the broader family of tools called Energy Management and Information Systems (EMIS). Although not within the scope of this document, other EMIS technologies such as meter analytics or energy information systems, automated (HVAC) system optimization, and building automation systems are powerful tools for ensuring persistent low-energy commercial building operations—both at the facility and enterprise levels.

3. FDD Technology Characterization Framework

To understand the diversity of technologies that provide AFDD, a characterization framework was developed to capture key elements that can be used to distinguish the functionality and potential application of one offering from another. Content contained in this framework was developed through review with a subset of providers, and is based on the authors’ collective subject matter expertise, knowledge of AFDD technology and its use in commercial building energy management applications. The categories in the framework are defined in the following sections, with characteristics spanning delivery to market, technical capabilities, and additional software functionality.

3.1 Delivery to Market

Company or institution name: The developer of the AFDD technology.

Tool name: The name of the AFDD software or service offering.

Software type: Whether the AFDD is offered as a commercial product or service, or as open source code.

Availability to market: Whether the AFDD is commercially available or still being researched (pre-commercial).

Current markets served: What markets are currently served in terms of:

- Building type (multi-family, hospital, outpatient healthcare, hotel, office, restaurant, retail, supermarket, college and university, K–12 education, warehouse).
- Building size (large [> 50k square feet (sf)], medium [10–50k sf], small [< 10k sf]).

Software location: Whether the AFDD software is cloud hosted, locally hosted on an "on-site" server, located on a desktop computer or other device, or controller-embedded.

Purchase model: Whether the AFDD software is a one-time purchase, software as a service (with monthly or annual fee), or other. Additionally, whether the AFDD software comes with updates and/or periodic maintenance in the initial offering costs, or whether additional purchase is required.

Intended users: Whether the AFDD software is intended for use by the vendor (for analysis-as-a-service), an engineering manager/operator/site staff, and/or a third-party service provider.

Software configuration: Whether the party typically responsible for the AFDD software installation and configuration is the software vendor; an integrator, distributor, or third-party service provider; or an engineering manager/operator/site staff.

Data sources: Whether the AFDD software relies upon data from BAS real-time data (i.e., live, continuous), from BAS historical data (e.g., trend logs, csv, xls), from on-board or internal equipment measures, or from external meters and sensors.

Data ownership: Whether the owner(s) of the AFDD software tool inputs and outputs is the end-customer, the FDD software vendor, and/or a third-party service provider.

FDD method tailoring: Whether the AFDD software requires tailoring of the tuning algorithm parameters and associated thresholds manually or automatically, or whether it is not applicable or unnecessary.

Notification of findings: Whether the AFDD software tool delivers results through a software user interface with fault findings, through a service to the user that includes periodic reports of fault findings, and/or through automated notifications, e.g., via email or text.

3.2 Technical Capabilities

Systems covered: Whether the FDD software has existing libraries and rules for the following systems: air conditioners/heat pumps (including packaged rooftop units), chillers and towers, air handler units (AHUs) and variable air volumes (VAVs), fan coil units (FCUs), commercial refrigeration, lighting, boilers/furnaces, water heaters, and/or whole-building.

Categories of faults detectable: These are broad categories of faults that the AFDD tool is able to detect and potentially diagnose. The fault categories included in this framework include:

- Sensor errors/faults
- Energy consumption (explicit energy use fault)
- Economizers and ventilation
- Control-related pressurization issues
- Commercial refrigeration (related to vapor/compression)
- Space cooling/heating (related to vapor/compression)
- Heating system (boiler, heat exchanger, furnace, etc.)
- Cooling system (chillers, towers, etc.)
- Equipment cycling
- Pump and fan systems
- Scheduling (too little, too long, wrong time, etc.)
- Simultaneous heating and cooling
- Lighting or other end uses

Note that problems such as mechanical failures and departures from setpoint or intended sequences may be included under multiple fault categories in the list above.

Methods/algorithms: These are the categories of analytical methods used in the AFDD software. The schematic diagram below depicts the definition of algorithm types that are used in this framework.

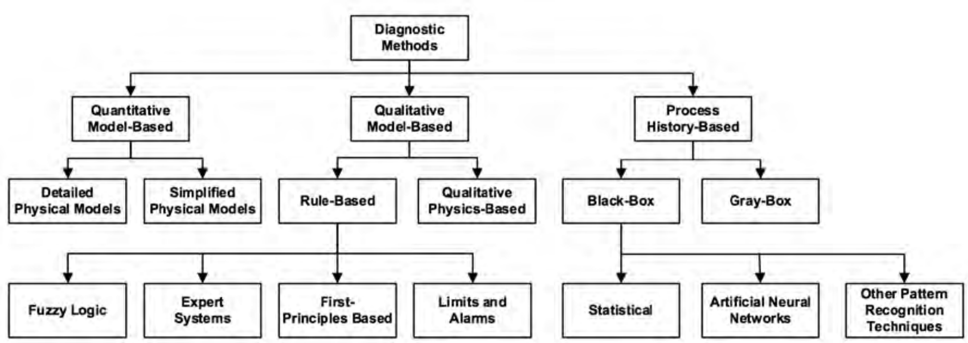

Figure 1. Depiction of algorithm types used in this framework, from Katipamula and Brambley, 2005[2]

As illustrated in Figure 1, FDD methods may be model-based or based purely on process history data. The model-based methods rely upon knowledge of the underlying physical processes and first principles governing the system(s) being analyzed. Quantitative model-based approaches are not yet frequently employed in commercial AFDD tool offerings, however qualitative model-based approaches which include rule-based FDD, have been extensively used in the industry and provide intuitive representations of engineering principles. The process history-based (data-driven) approaches do not rely upon knowledge of first principles, but may leverage some degree of engineering knowledge; they rely upon data from the system in operation. These include statistical regression models, neural networks, and other methods. Process history-based AFDD algorithms are increasingly being explored for use in commercial tool offerings. Although the distinctions between these method types may become blurry (even to developers), AFDD users may have interest in understanding whether a technology uses rules-based techniques versus newer data driven approaches, or less commonly employed first principles – or a combination of several approaches.

Detection and diagnosis capabilities: Whether the AFDD tool is capable of identifying fault presence (reporting a fault without specification of the physical location, severity, or root cause), fault location, fault severity (degree of faultiness as opposed to impact on energy or dollars, which is covered in "additional functionality"), root cause, and/or estimated costs of resolution and payback.

3.3 Additional Functionality

Other features: Additional features of the AFDD tool that are not represented above, and may include:

- Detection of equipment degradation
- Fault prioritization
- Automated work order request system integration
- Assessment of energy impacts
- Conversion of energy impacts to cost impacts
- Assessment of cost impacts other than energy cost, e.g., reduced equipment life
- Meter data analytics
- Time series visualization and plotting
- Key performance indicator (KPI) tracking and reporting
- Longitudinal and cross-sectional benchmarking (within a given portfolio or via ENERGY STAR Portfolio Manager)

4. Technology Characterization Findings

The AFDD characterization framework was applied to 14 currently available technologies, comprising a sample of market offerings (see the Appendix for a list of those surveyed). These technologies were identified based on factors including:

- Diversity across defining characteristics to illustrate market breadth
- Known use in commercial buildings based on the authors' knowledge of the market and engagement with the community of AFDD users
- Vendor or developer willingness and ability to share information necessary for a full characterization

It is important to emphasize that inclusion in this survey does not indicate endorsement, and conversely, absence from the survey does not indicate non-endorsement.

To characterize the technologies, publicly available information was gathered from product brochures and websites, and from technical papers. Additional information was acquired through interviews and surveys with the vendors and developers of each AFDD tool. The information that was acquired was therefore based on self-reporting from the technology provider. It was not within the scope of this effort to independently verify reported functionality and characteristics of each technology that is included. Moreover, as the market is constantly evolving and technologies are continuously modified, these market findings represent a snapshot in time. Although specific offerings may evolve, it is expected that the characterization framework itself will remain a viable tool to distinguish key AFDD technology elements well into the future.

The tables in the Appendix provide a summary of the capability of each tool surveyed, with respect to each category in the characterization framework.

4.1 Delivery to Market

All tool vendors surveyed offered proprietary, commercially available software and/or hardware. However, several of the software vendors noted that they provide an open application programming interface (API) to support integration with third-party applications.

The markets currently served by the AFDD tool vendors are represented in Figure 2. Multi-family, restaurant, data centers, and manufacturing facilities are less commonly served, with a mostly even coverage of other sectors. In addition to the market segments shown in the figure, several tool vendors noted additional facility types such as industrial subsectors, arenas, multi-event facilities, and correctional facilities. The technologies are commonly used in large and medium facilities, with less penetration in smaller buildings. Several tool vendors also noted that they do not serve a particular building size and that their product would be applicable to any size building.

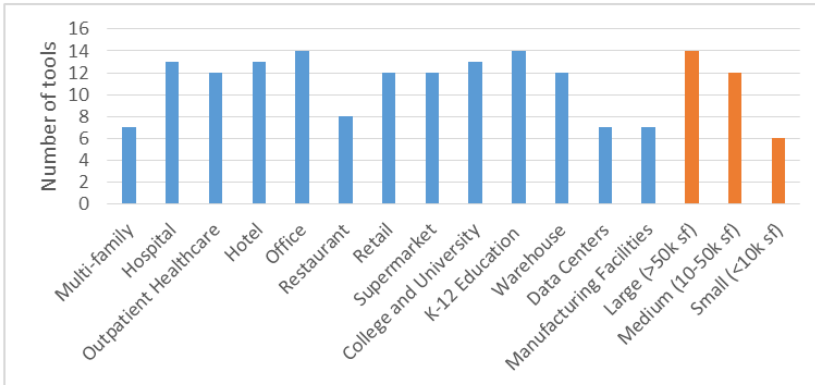

Figure 2.Market presence of surveyed FDD tools

As shown in Figure 3, the software for all 14 tool vendors can be cloud hosted; eight of them offer that as the only option. Additionally, four AFDD tools can be installed on a locally hosted on-site server, and three can be located on a desktop computer or other device (such as a handheld device). Three can be controller-embedded, reflecting emerging variants in software delivery that can entail relationships with OEMs.

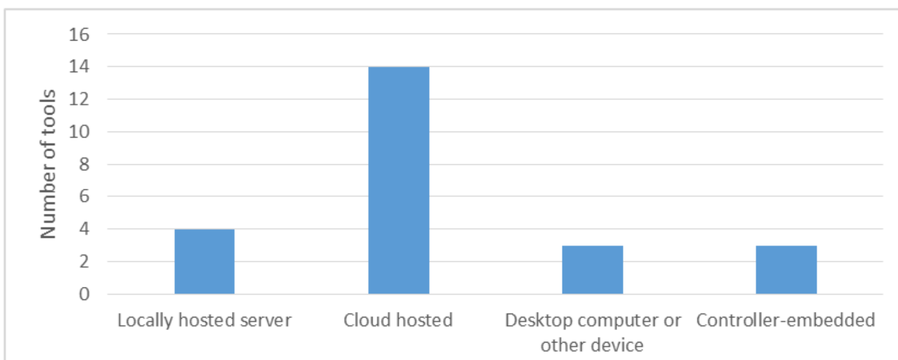

Figure 3. Software location

AFDD tool vendors offer a wide range of variability in purchase models. Many vendors noted that there is no standard, and that often the purchase model is tailored to what the customer wants. Typically tools that are hosted on the cloud offer a software-as-a-service (SaaS) model with ongoing updates and maintenance included for either an annual or a monthly fee. Maintenance and updates may come bundled or optionally in an upfront fee, or can be deferred for later purchase.

As reflected in the tallies in Figure 4, all of the AFDD tool vendors surveyed have multiple intended users. The traditional model of in-house technology used by the end customer is still prevalent—all vendors surveyed listed engineering manager/operator/site staff as an intended user. However, tools are increasingly being used by and resold by third-party service providers as a value-add to customers, with all of the AFDD tool vendors surveyed also listing a third-party service provider as an intended user. Nine vendors provide analysis-as-a-service directly to their clients and are therefore an intended user of the tool. This is expected to grow as the market matures and alternative business models are explored by the industry.

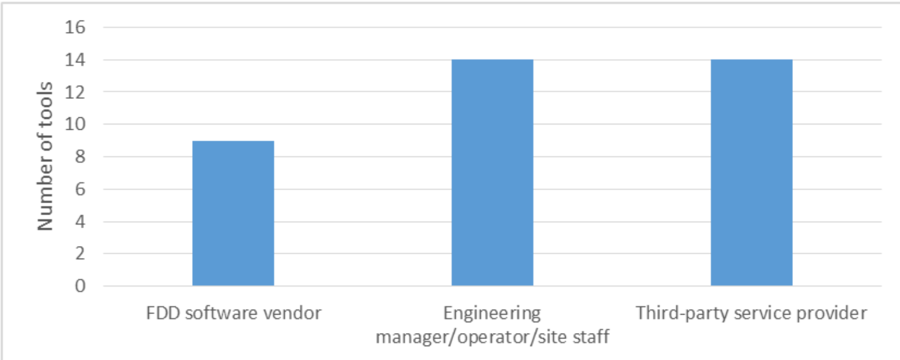

Figure 4. Intended Users

The majority of the AFDD tools are installed and configured by some combination of the software vendor, an integrator/distributor/third-party service provider, and the engineering manager/operator/site staff, as shown in Figure 5. In most cases, the vendor plus a third party do the configuration, working from owner requirements. In some cases multiple parties are required for the installation, and in some cases the vendor offers several options for who does the installation.

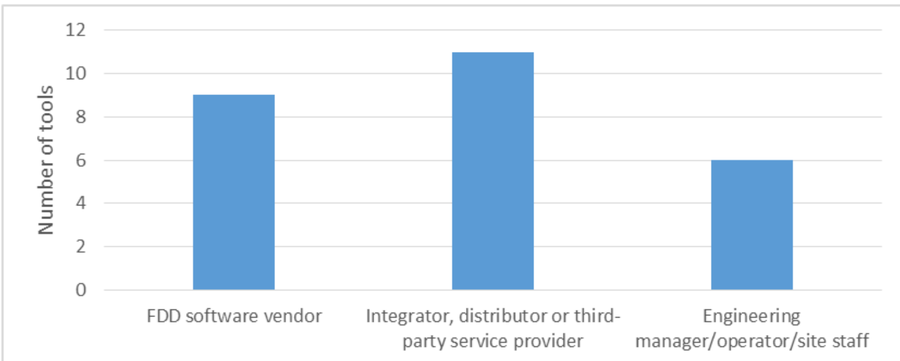

Figure 5. Parties involved in software configuration

There is a range of input data that are required by AFDD tools and a range of data that they can accept, as shown in Figure 6. Most of the tools take in real-time BAS data, which would be expected, given the large number of cloud-based solutions that serve as a BAS overlay. Eleven tools are also able to utilize historical data from the BAS. Most of the tools are also able to utilize external meters and sensors. Three tools are able to utilize equipment's onboard/ internal measures without going through the BAS. Typically not all of the data points that *can* be processed by the tool are required, and the technologies operate based on the data that are available. Though the tool vendor may have a short list of critical points, additional data are used to enhance the spectrum of diagnostics that can be performed.

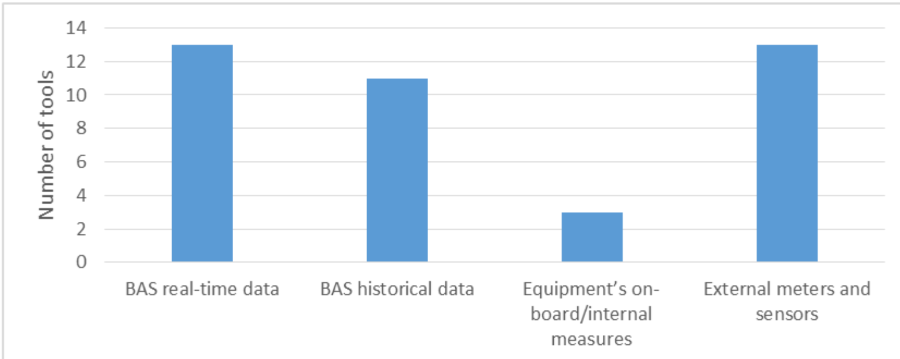

Figure 6. Data sources for surveyed FDD tools

All AFDD tool vendors note that primarily, the customer owns the data. Additionally, two vendors noted that they themselves also have ownership over the data and one other tool vendor noted that a third-party service provider has ownership over the data. Several tool vendors noted that they retain the right to use aggregate and anonymous data for benefit of all their users; for example, to provide peer benchmarking analyses.

All 14 tools require some degree of tuning or tailoring algorithm configuration and implementation. While none offer fully automated tuning, six vendors noted that they provide automated routines and/or GUIs to streamline the process. At least one tool comes with a fault library with default thresholds, with which the customer may subsequently tune parameters or hire consultants to help.

All of the AFDD tool vendors provide access and viewing of fault findings through a software interface, as shown in Figure 7. In addition to user-facing GUIs, the majority of offerings surveyed also provide services to periodically output reports of fault findings. All but two of the tools provide automated notifications via text, e-mail, or even other novel communications options such as tweets. Several tool vendors have the capability to have reports sent via e-mail at user-defined intervals (daily, weekly, monthly) and on customer demand.

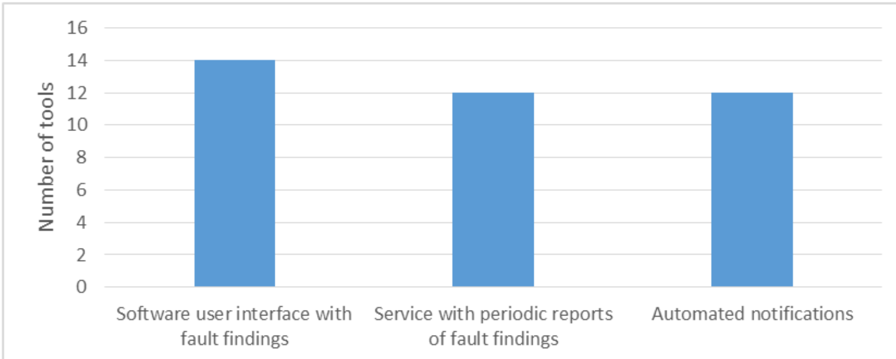

Figure 7. Notification of findings

4.2 Technical Capabilities

As seen in Figure 8, the majority of the AFDD tool vendors surveyed cover most of the systems that were included in the survey (AC/heat pump which includes packaged rooftop units, chillers and towers, AHU and VAV, FCUs, commercial refrigeration, lighting, boilers/furnaces, water heaters, and whole-building). Many tools have large libraries that are able to determine at least some types of faults across all systems for whatever data can be provided. Several vendors reported that they additionally include energy recovery ventilators (ERVs), other terminal units besides VAV boxes, solar panels, industrial processes, variable refrigerant flow (VRF) systems, BAS controls, cogeneration, and manufacturing equipment.

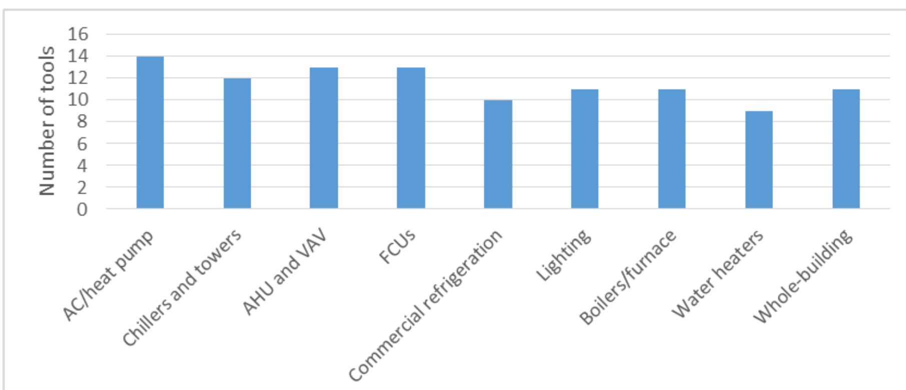

Figure 8. Systems covered

Nearly all of the tool vendors surveyed are able to detect faults in the majority of the fault categories in the survey: sensor errors/faults, energy consumption, economizers and ventilation, control-related pressurization issues, commercial refrigeration, space cooling/heating, heating system, cooling system, equipment cycling, pump and fan systems, scheduling, simultaneous heating and cooling, and lighting or other end uses. Many tools have large libraries that are able to determine at least some types of faults for whatever data can be provided. See Figure 9 for details.

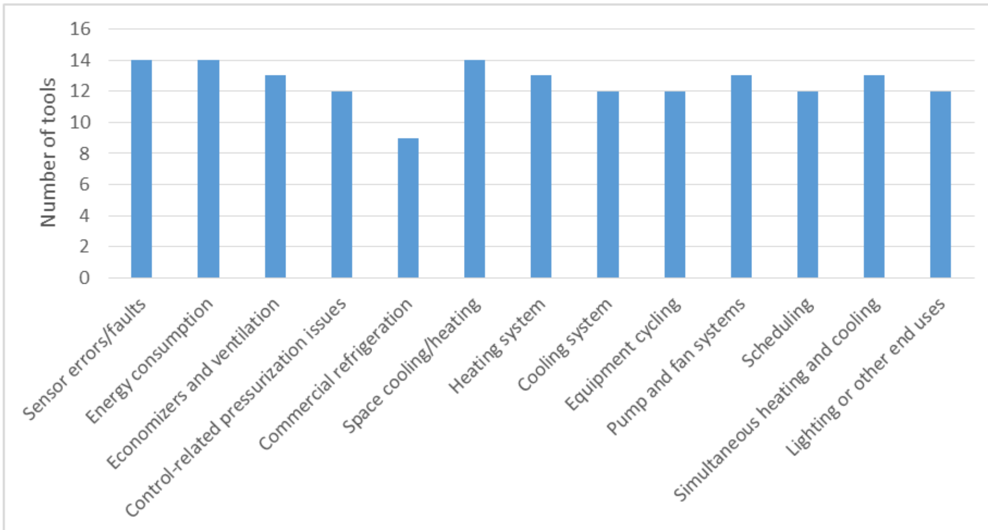

Figure 9. Categories of detectable faults

Most of the tools (12 out of 14) use rule-based algorithms, the majority of which apply some combination of expert systems, first principles-based, and limits and alarms. Many of the rule-based tools are supplemented with other approaches, and in one case the offering is a platform that is most commonly programmed and configured to deliver rule-based algorithms, but also includes machine learning functions. Three tools use black-box process history-based approaches; one of these also uses a gray-box approach. Two tools use quantitative model-based approaches. Figure 10 illustrates these findings graphically—dark shading indicates approaches used by ten or more tools, medium shading indicates approaches used by two or three tools, and light shading indicates approaches used by one or no tools.

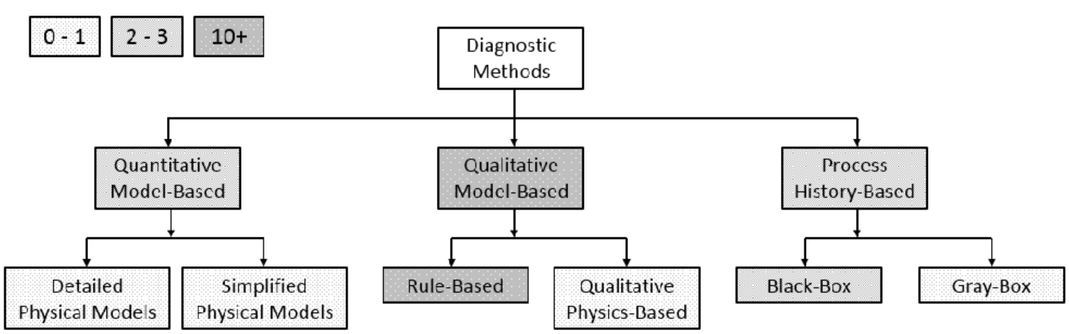

Figure 10. Methods and algorithms

As shown in Figure 11, all vendors surveyed reported the ability to identify fault presence as well as physical fault location. All but one tool is able to identify potential root causes. Depending on the specific fault identified, root case identification may be more or less precise, or in some cases, not possible. In addition, all but one reported some quantification of fault severity, e.g., degree of leakage. The degree of faultiness may be determined based on the frequency of a fault, fault magnitude (e.g., how far a point is away from setpoint), and fault duration. Several tools associate fault severity with assessment of the degree to which energy, energy cost, comfort, and maintenance costs are affected. At least one of these tools prioritizes the faults, then displays only one fault at a time to the user.

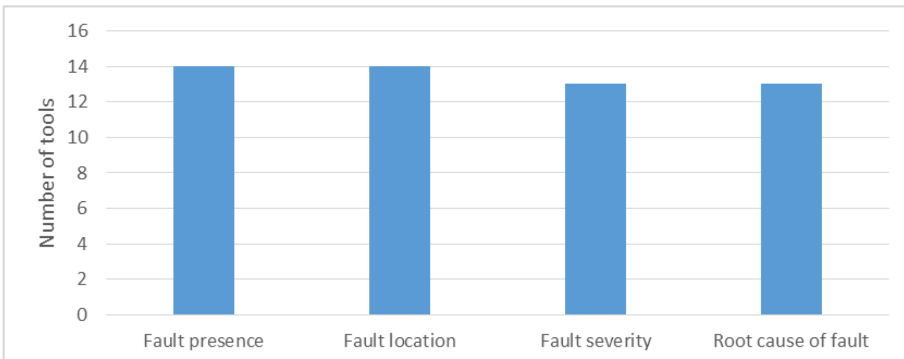

Figure 11. Detection and diagnosis capabilities

4.3 Additional Functionality

AFDD tools are commonly delivered with many supplementary features. Out of the tools surveyed, the most common features were time series visualization and plotting, quantification of energy impacts, and fault prioritization, as shown in Figure 12. Other very common features were equipment degradation, conversion of energy impacts to cost impacts, KPI tracking and reporting, automated work order request system integration, and meter data analytics. Less common but still prevalent features were cost impacts other than energy cost (such as the cost of pending equipment failure), longitudinal and cross-sectional benchmarking, and estimated cost of fault resolution and payback.

In addition, tool vendors noted a number of other features, including feedback for load management and demand response applications, verification of corrective actions, savings measurement and verification (M&V), equipment level M&V, asset data and service history, and issue-tracking systems. These other features were not exhaustively reviewed in the survey (or Tabulated findings in the Appendix) but are important complements to the AFDD capabilities.

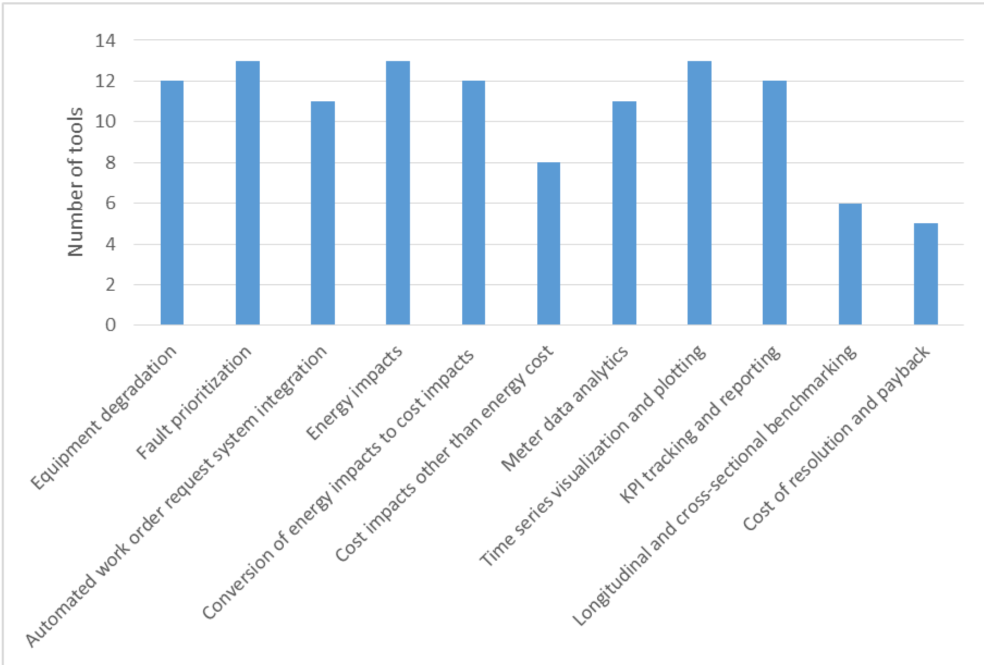

Figure 12. Relative frequency of a selected set of additional features of AFDD tools

5. Industry Needs and Future Development

This survey focused on AFDD solutions that integrate with building automation systems, that use temporary in-field measurements, or that are implemented as retrofit add-ons to existing equipment. As indicated in the findings, today's AFDD technologies are being used in nearly all commercial building sectors. Smaller facilities, however, are less commonly served, and when they are it is often through portfolios of small buildings as opposed to single sites. Cost effectiveness and complexity of implementation may vary as the technology is applied to different sectors and building sizes. For example, with a historic emphasis on HVAC systems and larger buildings, solutions for built-up systems may be simultaneously more developed, yet also more complex than those for packaged systems.

Software-as-a-service models have quickly become the norm for AFDD technologies; even vendors providing on-premise and desktop applications also tend to offer SaaS options. A compelling evolution in the industry is seen in the expansion of market delivery of FDD through third-party service providers using the tools as a way to provide value-add to their customers. Illustrated in Figure 13, these third-party services may cover a spectrum of activities. This is in contrast to earlier models that relied on in-house direct organizational use, and also from analysis-as-a-service provided by the AFDD vendor. This expansion offers the potential to increase access to the technology and its associated benefits for a new class of owners who otherwise may not be using it, however third parties' costs may vary significantly and each cost component should be defined in full to be able to compare across delivery options.

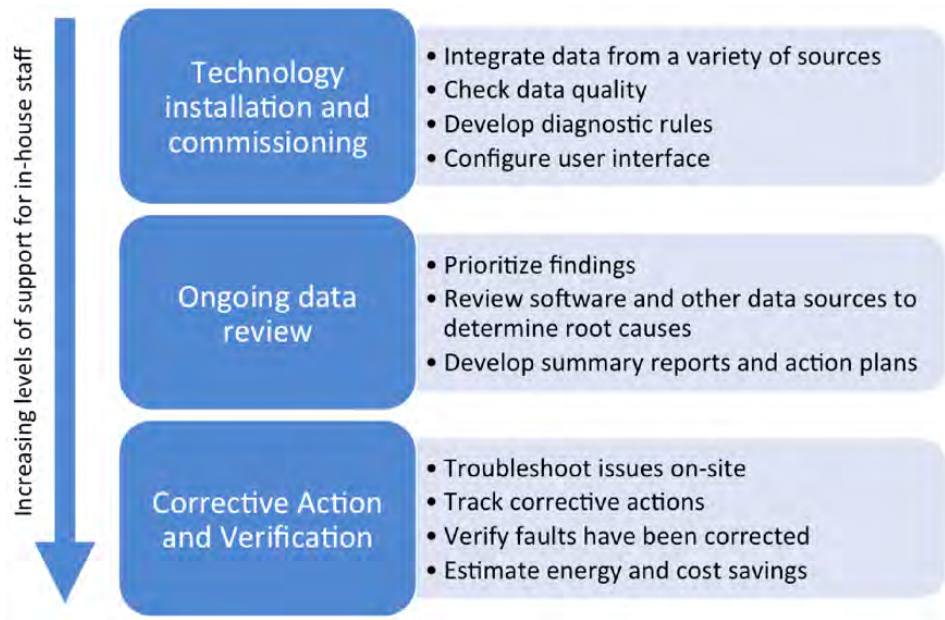

Figure 13. A spectrum of analytics-focused activities that service providers may offer their customers

While rule-based methodologies to detect and diagnose faults are still the norm, vendors are beginning to use process history-based techniques. Independent of the FDD methodology used, vendors report a high degree of commonality in the systems and types of faults that their products can cover. That is, coverage of systems and faults is driven more by site data availability than by product offering. Configuration of the technologies does require site-specific tuning, which may be conducted by vendors and service providers with varying degrees of involvement from site staff. While this is not a fully automated process, some elements of the process may be automated for streamlining.

Distinguishing factors are often associated with the additional features offered to complement the AFDD, and with the available delivery models. The market offers great diversity in additional analytics and reporting capabilities, integration architectures, and purchase models, making it possible to custom fit the technology to the needs of the organization. While custom solutions are desirable for some portions of the buildings market— such as campuses, enterprises, and large or complex facilities—other portions of the market may benefit from higher degrees of commoditization.

An important theme in interpreting the findings from this survey is that many products are sold with an emphasis on broad-scale applicability, and in analyzing the features and capabilities across all offerings as whole, there is a high degree of similarity. However, actual implementation needs can differ widely from one application case to another. Moreover, it is critical for prospective technology users to probe providers to understand the precisely what is entailed in a given offering's implementation of a feature of interest. For example, there are many ways to prioritize faults and estimate their impacts, ranging from those that rely upon static assumptions of fault persistence versus intermittence, to those that rely upon more dynamic calculations of concurrent operational conditions – and effective prioritization may be dependent on customer input. Similarly, root cause analysis (diagnosis) may be supported for just a subset of faults, or require manual input from operational staff. Analogously, ease of integration with different makes and vintages of BAS is another critical element of implementation for which "the devil is in the details."

FDD technology is seeing increased uptake in the market, and is constantly developing and evolving. Best practice implementations can deliver significant improvements in energy efficiency, utility expenses, operations and maintenance processes, and operational performance—all with rapid return on investment (see the Smart Energy Analytics Campaign Year 1 Report[4] for a snapshot of EIS, FDD and ASO performance and cost). However, for the full potential to be realized at scale, a core set of interrelated informational, organizational, and technical needs and barriers must be addressed.

Informational:

1. Prospective users remain challenged in interpreting the value proposition of FDD for their facilities. Common questions include: what will it really take to make this work for my buildings? What will the all-in costs and benefits be, up-front, and in the long-term? How do I navigate this developing market with numerous evolving players and product options?
2. Prospective users also face more specific implementation questions such as: What is the distinction between automated fault detection and diagnostics (AFDD) and BAS alarms, and which products support one versus the other? What are best practices for tuning and avoidance of false positives? What is the benefit of integrating AFDD within higher-level energy management practices such as strategic energy management and ongoing monitoring-based commissioning? How do I best integrate the support of contractors and service providers with in-house activities?

[4] Smart Energy Analytics Campaign. Synthesis of year 1 outcomes in the Smart Energy Analytics Campaign [Internet]. 2017 [accessed on September 25, 2017]. Available from: https://smart-energy-analytics.org/

Organizational:

3. Successful implementation of AFDD can be slowed by a need to diverge from existing business practices and norms. While the costs are modest compared to capital projects and can be quickly recovered, decision makers must buy in to an increase in operation and maintenance expenses and be willing to manage a certain degree of risk. Translation of information into action requires allocation of resources for staff time and training to act upon on identified fixes; it also requires effective operational response processes.

Technical:

4. While improving, IT and data integration represent one of the largest barriers to scale. It is complex, expensive and crosses organizational business units, and communications infrastructures are not easily leveraged for installation of analytics technologies.
5. Once data is accessible through cross-system integration, it must be interpreted for use in analytic applications. The current lack of common standards in data, metadata, and semantic representation also poses difficulties in scaling.
6. Similar to many efficiency solutions, today's AFDD offerings can be difficult and expensive to apply in smaller commercial buildings. Smaller facilities do not commonly have building automation systems or energy management staff and present much tighter payback constraints due to smaller energy expenditures.

A number of academic, industry, utility, and federal efforts are seeking to address these barriers. These collective efforts are far too varied and numerous to comprehensively describe, however, a few examples from current work sponsored by the U.S. Department of Energy (DOE) are provided as an illustration.

- The University of New Haven is conducting a public-facing field evaluation[5] of approximately 10 AFDD solutions to quantify technology costs and benefits, and is partnering with the utility community to inform the development of incentive programs for scaled regional deployment.
- The National Renewable Energy Laboratory (NREL) is conducting early-stage development of AFDD solutions for small commercial facilities that are based on simulation modeling and smart meter data.[6]
- Lawrence Berkeley National Laboratory (LBNL) is administering the Smart Energy Analytics Campaign[7] to provide technical assistance to AFDD and other analytics users, track gaps and benefits, and synthesize barriers.

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[5] U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy. Department of Energy announces scaling up the next generation of building efficiency packages funding awards [Internet]. 2017 [accessed on August 29, 2017]. Available from: https://energy.gov/eere/buildings/articles/department-energy-announces-scaling-next-generation-building-efficiency

[6] Frank, S., et al. 2016. Hybrid model-based and data-driven fault detection and diagnostics for commercial buildings. *Proceedings of the 2016 ACEEE Summer Study on Energy Efficiency in Buildings.*

[7] Smart Energy Analytics Campaign. Smart Energy Analytics Campaign [Internet]. 2017 [accessed on August 29, 2017]. Available from: https://smart-energy-analytics.org/

- LBNL and NREL are conducting public-facing multi-site field evaluations of technologies for rooftop unit AFDD and combined FDD/HVAC optimization.[8] Performance results are intended to inform the market at large, with a particular focus on public and private sector portfolio owners.

AFDD has matured significantly since its first introduction into commercial buildings. Based on information gathered through this survey and discussion with both vendors and users, several opportunities emerge to further advance the technology. Some of these are technical development challenges, and some strongly tied to the interplay between market demand and business choices concerning standardization and interoperability.

Continued development of algorithms that include machine learning and other promising techniques could reduce tuning needs, simplify configuration, and enhance diagnostic power. Following the trends in other industries, there is also potential to move beyond fault diagnostics into controls optimization, prognostics, and predictive maintenance. Integration of physics-based models to complement data-driven approaches holds promise to increase diagnostic power and support predictive analytics.

Machine-to-machine integration presents further opportunity for advancement. For example, truly pervasive “plug-and-play” functionality is still being developed, as are solutions to automatically extract and semantically interpret data across diverse systems and data types. The ability to interface AFDD tools with computerized maintenance management systems (CMMS) is just beginning to be explored, and will streamline the process of operationalizing action-taking based on the findings from analytics tools. Similarly, the practice of energy management will be enhanced through an ability to more tightly couple today’s disparate systems and platforms with more pervasive data and connectivity for controls optimization, FDD, site and portfolio meter analytics, and operations and asset management. While an “all in one” tool is not likely, nor necessarily optimal, some convergence for users would be beneficial.

Finally, there are gains to be achieved through the development of corrective and adaptive controls, in combination with tool chains that can ensure that operational design intent is correctly implemented and maintained over the duration of the operational stage in the building lifecycle.

[8] U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy. BuildingIQ Inc: Predictive Energy Optimization [Internet]. 2017 [accessed on August 29, 2017]. Available from: https://energy.gov/eere/buildings/downloads/buildingiq-inc-predictive-energy-optimization

Appendix

Table 1 summarizes aspects of market delivery for each tool surveyed, and Table 2 summarizes their AFDD technical capabilities and additional software features.

Table 1. Market delivery aspects of each tool surveyed

Tool name	Company	Building type of markets served	Building size of markets served	Software location	Purchase model	Intended users	Software configuration	Data sources	Data ownership	FDD method tailoring	Notification of findings
SkySpark (platform)	SkyFoundry	Hospital, Outpat. Health., Hotel, Office, Restaurant, Retail, Supermarket, College and Univ, K-12 Ed, Warehouse	Large, Medium, Small	Cloud hosted, Desktop computer or other device, Controller-embedded	One time purchase with maintenance included; SaaS through partners	FDD vendor, Site staff, Third-party provider	Third-party provider; Site staff	BAS real-time and historical data, Equipment on-board/internal measures, External meters and sensors	End-customer	Manual	Software user interface, Service with periodic reports, Automated notifications
SkySpark (implementn.)	CBRE|ESI	Hospital, Office, Retail, Supermarket, College and Univ, K-12 Ed	Large, Medium	Locally hosted server, Cloud hosted	SaaS. Optional updates and maintenance after first year	Site staff, Third-party provider	Third-party provider	BAS real-time and historical data, External meters and sensors	End-customer, FDD vendor, Third-party provider	Manual	Software user interface, Service with periodic reports, Automated notifications
True Analytics	Ecorithm	Multi-fam., Hospital, Hotel, Office, College and Univ, K-12 Ed, Warehouse	Large	Cloud hosted	SaaS. Updates and maintenance included	Site staff, Third-party provider	FDD vendor, Third-party provider	BAS real-time and historical data	End-customer	Manual and Automated	Software user interface, Service with periodic reports
Clockworks	KGS	Multi-fam., Hospital, Outpat. Health., Hotel, Office, Retail, Supermarket, College and Univ, K-12 Ed, Warehouse	Large, Medium	Cloud-hosted (via platform-as-a-service)	SaaS. Updates and maintenance included	FDD vendor, Site staff, Third-party provider	FDD vendor, Third-party provider	BAS real-time and historical data, External meters and sensors	End-customer	Manual	Software user interface, Service with periodic reports, Automated notifications

Tool name	Company	Building type of markets served	Building size of markets served	Software location	Purchase model	Intended users	Software configuration	Data sources	Data ownership	FDD method tailoring	Notification of findings
Kaizen	CopperTree Analytics	Multi-fam., Hospital, Outpat. Health., Hotel, Office, Restaurant, Retail, Supermarket, College and Univ, K-12 Ed, Warehouse	Large, Medium, Small	Cloud hosted	SaaS. Use partners as value-added resell distributers Updates and maintenance included	FDD vendor, Site staff, Third-party provider	FDD vendor, Third-party provider	BAS real-time and historical data, External meters and sensors	End-customer	Manual and Automated	Software user interface, Service with periodic reports, Automated notifications
BuildPulse	BuildPulse Inc.	Hospital, Outpat. Health., Hotel, Office, Retail, College and Univ, K-12 Ed	Large, Medium	Cloud hosted	SaaS. Updates and maintenance included	FDD vendor, Site staff, Third-party provider	Third-party provider, Site staff	BAS real-time data, External meters and sensors	End-customer	Manual and Automated	Software user interface, Service with periodic reports, Automated notifications
Analytika	Cimetrics	Hospital, Outpat. Health., Hotel, Office, Supermarket, College and Univ, K-12 Ed, Warehouse, Mfg Facilities	Large, Medium	Cloud hosted	SaaS. Updates and maintenance included	FDD vendor, Site staff, Third-party provider	FDD vendor	BAS real-time and historical data, External meters and sensors	End-customer	Manual and Automated	Software user interface, Service with periodic reports, Automated notifications
Niagara Analytics 2.0	Tridium	Multi-fam., Hospital, Outpat. Health., Hotel, Office, Restaurant, Retail, Supermarket, College and Univ, K-12 Ed, Warehouse, Data Centers, Mfg Facilities	Large, Medium, Small	Locally hosted server, Cloud hosted, Controller-embedded	One time purchase with optional updates and maintenance	FDD vendor, Site staff, Third-party provider	FDD vendor, Third-party provider	BAS real-time and historical data, Equipment on-board/internal measures, External meters and sensors	End-customer	Manual and Automated	Software user interface, Automated notifications
IntelliCommand	JLL	Hospital, Outpat. Health., Hotel, Office, Retail, Supermarket, College and Univ, K-12 Ed, Warehouse, Data Centers, Mfg Facilities	Large, Medium	Cloud hosted	SaaS. Updates and maintenance included	Site staff, Third-party provider	FDD vendor	BAS real-time and historical data, External meters and sensors	End-customer	Manual	Software user interface, Service with periodic reports, Automated notifications

Tool name	Company	Building type of markets served	Building size of markets served	Software location	Purchase model	Intended users	Software configuration	Data sources	Data ownership	FDD method tailoring	Notification of findings
Balance	EEI	Multi-fam, Hospital, Outpat. Health., Hotel, Office, Restaurant, Retail, Supermarket, College and Univ, K-12 Ed, Warehouse, Data Centers, Mfg Facilities	Large, Medium	Cloud hosted	SaaS. Updates and maintenance included.	FDD vendor, Site staff, Third-party provider	FDD vendor, Third-party provider, Site staff	BAS real-time and historical data, External meters and sensors	End-customer, FDD vendor	Manual	Software user interface, Service with periodic reports
Facility Analytix	ICONICS	Hospital, Outpat. Health., Hotel, Office, Restaurant, Retail, Supermarket, College and Univ, K-12 Ed, Warehouse, Data Centers, Mfg Facilities	Large	Locally hosted server, Cloud hosted	One-time purchase or SaaS. Maintenance included, updates optional	Site staff, Third-party provider	FDD vendor, Third-party provider, Site staff	BAS real-time and historical data, External meters and sensors	End-customer	Manual	Software user interface, Service with periodic reports, Automated notifications
eIQ	Transformative Wave	Hospital, Outpat. Health., Hotel, Office, Restaurant, Retail, Supermarket, College and Univ, K-12 Ed, Warehouse, Data Centers, Mfg Facilities	Large, Medium, Small	Cloud hosted	SaaS. Updates and maintenance included	FDD vendor, Site staff, Third-party provider	FDD vendor, Third-party provider, Site staff	BAS real-time and historical data, External meters and sensors	End-customer	Manual	Software user interface, Automated notifications
ClimaCheck Onsite/ ClimaCheck Online	ClimaCheck	Multi-fam, Hospital, Outpat. Health., Hotel, Office, Restaurant, Retail, Supermarket, College and Univ, K-12 Ed, Warehouse, Data Centers, Mfg Facilities	Large, Medium, Small	Locally hosted server, Cloud hosted, Desktop computer or other device	Onsite: One-time purchase. Optional updates Online: Updates and maintenance included.	FDD vendor, Site staff, Third-party provider	Third-party provider, Site staff	BAS real-time data, External meters and sensors	End-customer	Manual and Automated	Software user interface, Service with periodic reports, Automated notifications
HVAC Service Assistant, SA Mobile, Onboard controller	Field Diagnostic Services	Multi-fam, Outpat. Health., Hotel, Office, Restaurant, Retail, Supermarket, K-12 Ed, Warehouse, Data Centers	Large, Medium, Small	Cloud hosted, Desktop computer or other device, Controller-embedded	One-time purchase or SaaS. Updates included	Site staff, Third-party provider		Equipment on-board/internal measures, External meters and sensors	End-customer	Manual	Software user interface, Service with periodic reports, Automated notifications

Table 2. Technical capabilities and additional features of each tool surveyed

Tool name	Company	Systems covered	Categories of faults detectable	Methods/algorithms	Detection and diagnosis capabilities	Additional functionality
SkySpark	SkyFoundry	AC/HP, Chillers & towers, AHU & VAV, FCU, Com. refrig., Lighting, Boilers/furnace, Water heaters, Whole-building	Sensor errors, Energy consumption, Econ. & vent., Pressurization issues, Com. refrig., Space Clg./Htg., Htg. system, Clg. system, Equip cycling, Pump & fan systems, Scheduling, Sim. htg. & clg., Lighting or other end uses	Rule-based. Platform supports full programmability of rules and includes machine learning functions for use in FDD algorithms.	Fault presence, location, severity, root cause	Equip degradation, Fault prioritization, Auto work order, Energy impacts, Energy cost impacts, Other cost impacts, Meter data analytics, Time series visualization, KPI tracking and reporting, Benchmarking, Cost of resolution and payback
SkySpark (implementn.)	CBRE|ESI	AC/HP, Chillers & towers, AHU & VAV, FCU, Lighting, Boilers/furnace, Whole-building	Sensor errors, Energy consumption, Econ. & vent., Pressurization issues, Space Clg./Htg., Htg. system, Clg. system, Equip cycling, Pump & fan systems, Scheduling, Sim. htg. & clg., Lighting or other end uses	Rule-based	Fault presence, location, severity, root cause	Equip degradation, Fault prioritization, Auto work order, Energy impacts, Energy cost impacts, Meter data analytics, Time series visualization, KPI tracking and reporting, Benchmarking, Cost of resolution and payback
True Analytics	Ecorithm	AC/HP, Chillers & towers, AHU & VAV, FCU, Com. refrig., Lighting, Boilers/furnace, Water heaters, Whole-building	Sensor errors, Energy consumption, Econ. & vent., Pressurization issues, Com. refrig., Space Clg./Htg., Htg. system, Clg. system, Equip cycling, Pump & fan systems, Scheduling, Sim. htg. & clg., Lighting or other end uses	Qual. Model-based, Rule-based, Expert Systems, First Principles-based, Machine learning techniques, fast-sampling algorithms, and the spectral method.	Fault presence, location, severity, root cause	Equip degradation, Fault prioritization, Energy impacts, Meter data analytics, Time series visualization, KPI tracking and reporting, Benchmarking
Clockworks	KGS	AC/HP, Chillers & towers, AHU & VAV, FCU, Com. refrig., Lighting, Boilers/furnace, Water heaters, Whole-building	Sensor errors, Energy consumption, Econ. & vent., Pressurization issues, Com. refrig., Space Clg./Htg., Htg. system, Clg. system, Equip cycling, Pump & fan systems, Scheduling, Sim. htg. & clg., Lighting or other end uses	Simplified Physical Models, Expert Systems, First Principles-based, Limits and Alarms, Statistical	Fault presence, location, severity, root cause	Equip degradation, Fault prioritization, Auto work order, Energy impacts, Energy cost impacts, Meter data analytics, Time series visualization, KPI tracking and reporting, Benchmarking

Tool name	Company	Systems covered	Categories of faults detectable	Methods/algorithms	Detection and diagnosis capabilities	Additional functionality
Kaizen	CopperTree Analytics	AC/HP, Chillers & towers, AHU & VAV, FCU, Com. refrig., Lighting, Boilers/furnace, Water heaters, Whole-building	Sensor errors, Energy consumption, Econ. & vent., Pressurization issues, Com. refrig., Space Clg./Htg., Htg. system, Clg. system, Equip cycling, Pump & fan systems, Scheduling, Sim. htg. & clg., Lighting or other end uses	Rule-based. Includes an open library of rules for users to download, publish and share	Fault presence, location, severity, root cause	Equip degradation, Fault prioritization, Auto work order, Energy impacts, Energy cost impacts, Other cost impacts, Meter data analytics, Time series visualization, KPI tracking and reporting
BuildPulse	BuildPulse Inc.	AC/HP, Chillers & towers, AHU & VAV, FCU, Lighting, Boilers/furnace, Water heaters, Whole-building	Sensor errors, Energy consumption, Econ. & vent., Pressurization issues, Space Clg./Htg., Htg. system, Clg. system, Equip cycling, Pump & fan systems, Scheduling, Sim. htg. & clg., Lighting or other end uses	Rule-based, Qualitative model	Fault presence, location, severity, root cause	Equip degradation, Fault prioritization, Auto work order, Energy impacts, Energy cost impacts, Other cost impacts, Meter data analytics, Time series visualization, KPI tracking and reporting, Benchmarking, Cost of resolution and payback
Analytika	Cimetrics	AC/HP, Chillers & towers, AHU & VAV, FCU, Com. refrig., Lighting, Boilers/furnace, Water heaters, Whole-building	Sensor errors, Energy consumption, Econ. & vent., Pressurization issues, Com. refrig., Space Clg./Htg., Htg. system, Clg. system, Equip cycling, Pump & fan systems, Scheduling, Sim. htg. & clg., Lighting or other end uses	Quant. Model-based, Qual. Model-based, Rule-based, Expert Systems, First Principles-based, Limits and Alarms, Process History-based, Black Box, Statistical, Gray Box	Fault presence, location, severity, root cause	Equip degradation, Fault prioritization, Auto work order, Energy impacts, Energy cost impacts, Other cost impacts, Meter data analytics, Time series visualization, KPI tracking and reporting, Benchmarking
Niagara Analytics 2.0	Tridium	AC/HP, Chillers & towers, AHU & VAV, FCU, Com. refrig., Lighting, Boilers/furnace, Water heaters, Whole-building	Sensor errors, Energy consumption, Econ. & vent., Pressurization issues, Com. refrig., Space Clg./Htg., Htg. system, Clg. system, Equip cycling, Pump & fan systems, Scheduling, Sim. htg. & clg., Lighting or other end uses	Rule-based, Limits and Alarms	Fault presence, location, severity, root cause	Equip degradation, Fault prioritization, Auto work order, Energy impacts, Energy cost impacts, Other cost impacts, Meter data analytics, Time series visualization, KPI tracking and reporting, Cost of resolution and payback
IntelliCommand	JLL	AC/HP, Chillers & towers, AHU & VAV, FCU, Com. refrig., Lighting, Boilers/furnace, Whole-building	Sensor errors, Energy consumption, Econ. & vent., Pressurization issues, Space Clg./Htg., Htg. system, Clg. system, Equip cycling, Pump & fan systems, Scheduling, Sim. htg. & clg., Lighting or other end uses	Rule-based, Limits and Alarms, Statistical, Other Pattern Recognition Techniques	Fault presence, location, severity, root cause	Equip degradation, Fault prioritization, Auto work order, Energy impacts, Energy cost impacts, Other cost impacts, Meter data analytics, Time series visualization, KPI tracking and reporting

Tool name	Company	Systems covered	Categories of faults detectable	Methods/algorithms	Detection and diagnosis capabilities	Additional functionality
Balance	EEI	AC/HP, Chillers & towers, AHU & VAV, FCU, Com. refrig., Lighting, Boilers/furnace, Water heaters, Whole-building	Sensor errors, Energy consumption, Econ. & vent., Pressurization issues, Com. refrig., Space Clg./Htg., Htg. system, Clg. system, Equip cycling, Pump & fan systems, Scheduling, Sim. htg. & clg., Lighting or other end uses	Rule-based, Expert Systems, First-Principles Based	Fault presence, location, severity	Equip degradation, Fault prioritization, Auto work order, Energy impacts, Energy cost impacts, Other cost impacts, Meter data analytics, Time series visualization, KPI tracking and reporting, Cost of resolution and payback
Facility Analytix	ICONICS	AC/HP, Chillers & towers, AHU & VAV, FCU, Com. refrig., Lighting, Boilers/furnace, Water heaters, Whole-building	Sensor errors, Energy consumption, Econ. & vent., Pressurization issues, Com. refrig., Space Clg./Htg., Htg. system, Clg. system, Equip cycling, Pump & fan systems, Scheduling, Sim. htg. & clg., Lighting or other end uses	Rule-based, First Principles-based, Limits and Alarms	Fault presence, location, severity, root cause	Fault prioritization, Auto work order, Energy impacts, Energy cost impacts, Other cost impacts, Meter data analytics, Time series visualization, KPI tracking and reporting
eIQ	Transformative Wave	AC/HP	Sensor errors, Energy consumption, Econ. & vent., Pressurization issues, Space Clg./Htg., Htg. system, Pump & fan systems, Sim. htg. & clg.	Rule-based, Expert Systems, Limits and Alarms	Fault presence, location, root cause	Fault prioritization, Energy impacts, Energy cost impacts, Time series visualization
ClimaCheck Onsite/ ClimaCheck Online	ClimaCheck	AC/HP, Chillers & towers, AHU & VAV, FCU, Com. refrig.	Sensor errors, Energy consumption, Econ. & vent., Com. refrig., Space Clg./Htg., Htg. system, Clg. system, Equip cycling, Pump & fan systems, Scheduling, Sim. htg. & clg., Lighting or other end uses	Thermodynamic Evaluation, Energy Signatures	Fault presence, location, severity, root cause	Equip degradation, Energy impacts, Energy cost impacts, Time series visualization, KPI tracking and reporting
HVAC Service Assistant, SA Mobile, Onboard controller	Field Diagnostic Services	AC/HP, AHU & VAV, FCU	Sensor errors, Energy consumption, Space Clg./Htg.		Fault presence, location, severity, root cause	Equip degradation, Fault prioritization, Auto work order

REVIEW ARTICLE

Methods for Fault Detection, Diagnostics, and Prognostics for Building Systems— A Review, Part II

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This paper is the second of a two-part review of methods for automated fault detection and diagnostics (FDD) and prognostics whose intent is to increase awareness of the HVAC&R research and development community to the body of FDD and prognostics developments in other fields as well as advancements in the field of HVAC&R. The first part of the review focused on generic FDD and prognostics, provided a framework for categorizing methods, described them, and identified their primary strengths and weaknesses (Katipamula and Brambley 2005). In this paper we address research and applications specific to the fields of HVAC&R, provide a brief discussion on the current state of diagnostics in buildings, and discuss the future of automated diagnostics in buildings.

INTRODUCTION

Poorly maintained, degraded, and improperly controlled equipment wastes an estimated 15% to 30% of energy used in commercial buildings. Much of this waste could be prevented with widespread adoption of automated condition-based maintenance. Automated fault detection and diagnostics (FDD) along with prognostics provide a cornerstone for condition-based maintenance of engineered systems. Although FDD has been an active area of research in other fields for more than a decade, applications for heating, ventilating, air conditioning, and refrigeration (HVAC&R) and other building systems have lagged those in other industries. Nonetheless, over the last decade there has been considerable research and development targeted toward developing FDD methods for HVAC&R equipment. Despite this research, there are still only a handful of FDD tools that are deployed in the field.

This paper, which is the second of two parts, provides a review of fault detection, diagnostics, and prognostics (FDD&P) research in the HVAC&R field and concludes with discussions of the current state of applications for buildings and likely contributions to operating and maintaining buildings in the future. In the first paper (Katipamula and Brambley 2005), we provided an overview of FDD&P, starting with descriptions of the fundamental processes and some important definitions, and then identified the strengths and weaknesses of methods across the broad spectrum of approaches.

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FDD RESEARCH IN HVAC&R

In this section we review FDD research relating to refrigerators, air conditioners, chillers, and air-handling units (AHUs), which represent most of the HVAC&R FDD research completed to date. This review is an update to the review previously published by Katipamula et al. (2001) and includes recent FDD publications. For information on FDD for other building systems refer to Pape et al. (1990), Dexter and Benouarets (1996), Georgescu et al. (1993), Jiang et al. (1995), and Han et al. (1999) for HVAC&R plants; Fasolo and Seborg (1995) for HVAC&R control systems; Li et al. (1996, 1997) for heating systems; Isermann and Nold (1988) and Dalton et al. (1995) for pumps; Noura et al. (1993) for large thermal plants; Isermann and Ballé (1997) for applications for motors; and Dodier and Kreider (1999) for whole-building systems.

Refrigerators

One of the early applications of FDD was to vapor-compression-cycle-based refrigerators (McKellar 1987; Stallard 1989). Although McKellar (1987) did not develop an FDD system, he identified common faults for a refrigerator based on the vapor-compression cycle and investigated the effects of the faults on the thermodynamic states at various points in the cycle. He concluded that the suction pressure (or temperature), discharge pressure (or temperature), and the discharge-to-suction pressure ratio were sufficient for developing an FDD system. The faults considered were compressor valve leakage, fan faults (condenser and evaporator), evaporator frosting, partially blocked capillary tubes, and improper refrigerant charge (under and over charge).

Building upon McKellar's work, Stallard (1989) developed an automated FDD system for refrigerators. A rule-based expert system was used with simple limit checks for both detection and diagnosis. Condensing temperature, evaporating temperature, condenser inlet temperature, and the ratio of discharge-to-suction pressure were used directly as classification features. Faults were detected and diagnosed by comparing the change in the direction of the measured quantities with expected values and matching the changes to expected directional changes associated with each fault.

Air Conditioners and Heat Pumps

There are many applications of FDD to air conditioners and heat pumps based on the vapor-compression cycle. Some of these studies are discussed below (Yoshimura and Ito 1989; Kumamaru et al. 1991; Inatsu et al. 1992; Wagner and Shoureshi 1992; Rossi 1995; Rossi and Braun 1996, 1997; Breuker 1997; Breuker and Braun 1998b; Ghiaus 1999; Chen and Braun 2000). Breuker and Braun (1998a) summarized common faults in air conditioners and their impact on performance. In addition, the frequency of fault occurrence and the relative cost of service for various faults were estimated from service records.

Yoshimura and Ito (1989) used pressure and temperature measurements to detect problems with condenser, evaporator, compressor, expansion valve, and refrigerant charge on a packaged air conditioner. The differences between measured values and expected values were used to detect faults. Expected values were estimated from manufacturers' data, and the thresholds for fault detection were experimentally determined in the laboratory. Both detection and diagnosis were conducted in a single step. No details were provided as to how the thresholds for detection were selected.

Wagner and Shoureshi (1992) developed two different fault detection methods and compared their abilities to detect five different faults in a small heat pump system in the laboratory. The five faults included abrupt condenser and evaporator fan failures, capillary tube blockage, compressor piston leakage, and seal system leakage. The first method was based on limit and trend

Table 1. Symptom Patterns for Selected Faults (Grimmelius et al. 1995)

Fault Modes	Compressor Suction Pressure	Compressor Suction Temperature	Compressor Discharge Pressure	Compressor Discharge Temperature	Compressor Pressure Ratio	Oil Pressure	Oil Temperature	Oil Level	Crankcase Pressure	Compressor Electric Power	Subcooling of Refrigerant	ΔT Refrigerant and Cooling Water	ΔT Cooling Water	Inlet Temperature at Expansion Valve	Filter Pressure Drop	Evaporator Outlet Pressure	Superheat	ΔT Chilled Water	Evaporator Outlet Temperature	Number of Acting Cylinders
Compressor, Suction Side, Increase in Flow Resistance	↓	→	→	→	→	↓	→	→	↓	↓	→	→	→	→	→	↑	↑	↓	→	→
Compressor, Discharge Side, Increase in Flow Resistance	↑	→	↑	→	→	↑	→	→	↑	→	→	→	→	→	→	↑	↑	↓	→	→
Condenser, Cooling Water Side, Increase in Flow Resistance	→	→	↑	→	→	→	→	→	→	↑	↓	→	↑	→	→	→	→	→	→	→
Fluid Line Increase in Flow Resistance	→	→	→	→	→	→	→	→	→	↓	→	→	→	↓	→	→	↑	↑	→	→
Expansion Valve, Control Unit, Power Element Loose from Pipe	↑	→	→	→	→	↑	→	→	↑	↑	→	→	→	→	→	↑	↓	↑	→	→
Evaporator, Chilled Water Side, Increase in Flow Resistance	↓	→	→	→	→	↓	→	→	↓	↓	→	→	→	→	→	↓	↑	↑	→	→

checking (qualitative model-based), and the second method was a simplified physical model-based approach. In the second approach, differences between predictions from a simplified physical model and the monitored observations are transformed into useful statistical quantities for hypothesis testing. The transformed statistical quantities are then compared to predetermined thresholds to detect faults.

The two fault detection strategies were operated in parallel on a heat pump in a psychrometric room. The qualitative method was able to detect four of five faults that were introduced abruptly, while the simplified physical model-based method was successful in only detecting two faults. Because the selection of thresholds for both methods is critical in avoiding false alarms and reduced sensitivity, Wagner and Shoureshi (1992) provide a brief discussion of how to trade off diagnostic sensitivity against false alarms. Their implementation is only capable of detecting faults and does not include diagnosis, evaluation, and decision making.

Rossi (1995) described the development of a statistical rule-based fault detection and diagnostic method for air-conditioning equipment with nine temperature measurements and one humidity measurement. The FDD method is capable of detecting and diagnosing condenser fouling, evaporator fouling, liquid-line restriction, compressor valve leakage, and refrigerant leakage. In addition to the detection and diagnosis, Rossi and Braun (1996) also describe an implementation of fault evaluation. A detailed explanation of the fault evaluation method can be found in Rossi and Braun (1997). The methods were demonstrated in limited testing with a rooftop air conditioner in the laboratory.

Breuker (1997) performed a more detailed evaluation of the methods developed by Rossi (1995). The detailed evaluation relied on steady-state and transient tests of a packaged air conditioner in a laboratory over a range of conditions and fault levels (Breuker and Braun 1998b). Seven polynomial models (ranging from first to third order) were developed to characterize the performance of the air conditioner (evaporating, condensing, and compressor outlet temperatures, suction line superheat, liquid line subcooling, temperature rise across the condenser, and temperature drop across the evaporator) using steady-state data representing normal (unfaulted) operations. The steady-state normal data are also used to determine the statistical thresholds for fault detection, while transient data with faults were used to evaluate FDD performance. Breuker and Braun (1998b) concluded that refrigerant leakage, condenser fouling, and liquid line restriction were detected and diagnosed before 8% reduction in capacity or COP occurred. The technique, however, was less successful in detecting evaporator fouling and compressor valve leakage. The authors also concluded that increasing the measurements from 6 (2 inputs and 4 outputs) to 10 (3 inputs and 7 outputs) and using higher order polynomial models improved the performance by a factor of two.

Ghiaus (1999) presented a bond-graph model for a direct-expansion vapor-compression system and applied it to diagnosing two faults in an air conditioner. The author states that this qualitative approach of modeling faults does not need *a priori* knowledge of possible faults as long as the bond model is complete and accurate.

Chillers

Several researchers have applied FDD methods to detect and diagnose faults in vapor-compression-based chillers; some of the studies are summarized below (Grimmelius et al. 1995; Gordon and Ng 1994, 1995; Stylianou and Nikanpour 1996; Tsutsui and Kamimura 1996; Peitsman and Bakker 1996; Stylianou 1997; Bailey 1998; Sreedharan and Haves 2001; Castro 2002). Comstock et al. (1999) and Reddy et al. (2001) provide a detailed review of FDD literature relating to chiller systems up to their respective times. Comstock et al. (2002) presented a list of common chiller faults and their impacts on performance.

Grimmelius et al. (1995) developed a fault diagnostic system for a chiller, in which fault detection and diagnostics are carried out in a single step. The FDD method uses a reference model based on multivariate linear regression that was developed with data from a properly operating chiller to estimate values for process variables for a healthy (unfaulted) chiller. These estimates are subsequently used to generate residuals (i.e., differences between actual measured values and the values from the reference model). Patterns of these residuals are compared to characteristic patterns corresponding to faulted conditions, and scores are assigned indicating the degree to which the patterns match the pattern corresponding to each fault mode. Fault modes with good fits (high scores) are judged as probably existing in the chiller. Fault modes with poor fits (low scores) are judged as unlikely to exist in the chiller, and faults with intermediate scores are labeled as possibly existing. Twenty different measurements are used including

Table 2. Scoring of Fault Modes for a Highly Idealized Example

Fault Mode/ Score	Symptom 1	Symptom 2	Symptom 3	Symptom 4	Total Score	Normalized Score
F1	↓	→	↓	↑		
Scores	10	10	10	10	40	1.0
F2	↑	→	↑	→		
Scores	0	9	0	3	12	0.3
Measurement-Based Pattern	↓	→	↓	↑		

temperatures, pressures, power consumption, and compressor oil level. In addition to the measured variables, some derived variables, such as liquid subcooling, superheat, and pressure drop, are used. The inputs to the model also include the outdoor ambient temperature and load conditions.

To identify potential fault modes, the chiller is classified into seven components: compressor, condenser, evaporator, expansion valve, liquid line immediately downstream of the condenser and including a filter drier, liquid line with solenoid and sight glass between the other liquid line and the evaporator, and the crankcase heater. Fault modes are associated with any component that is serviceable, which leads to 58 different fault modes. A cause and effect study of the 58 fault modes helped establish the expected influence of the faults on the components, measured variables, and subsequent chiller behavior. Symptoms are defined as a difference in any measured or derived variable from its expected value for normal unfaulted operation (i.e., the value given by the reference model). Symptoms associated with all 58 fault modes were generated and arranged into symptom patterns. Fault modes having identical symptom patterns were aggregated into a single fault mode, reducing the total number of fault modes from 58 to 37. These symptom patterns are arranged in a symptom matrix as shown in Table 2, with each row giving the symptom pattern associated with a particular fault. A symptom (cell in the matrix) shown by an arrow pointing up, ↑, indicates a value for the variable greater than that given by the reference model. Likewise, an arrow pointing down, ↓, indicates a symptom corresponding to a value for the variable less than the value from the reference model, and a horizontal arrow, →, indicates the fault has no effect on the corresponding variable.

To diagnose a fault, a symptom pattern corresponding to a set of measurements is compared to the symptom patterns for all of the fault modes. Scores are assigned to each fault mode indicating the probability that its symptom pattern matches the measured symptom pattern as follows. For each fault mode, each symptom is compared to its corresponding measured symptom and assigned a score between 0 and 10. If the symptom for the fault mode matches the measured symptom very well, it is assigned a high score (close to 10). If it weakly matches, it is assigned a score around 5, and if it does not match well at all, it is assigned a score close to zero. A total score for each fault mode is generated by adding the individual scores of all symptoms and dividing the total by the maximum possible score per pattern (i.e., the number of symptoms in the pattern multiplied by 10) to obtain a normalized score. These normalized scores are then classified into three categories. A normalized score of 0.9 or higher indicates a probable fault, a score between 0.5 and 0.9 indicates a possible fault, and scores lower than 0.5 indicate that the fault is likely not present.

A highly simplified example is shown in Table 2. Symptom patterns for two faults, F1 and F2, are shown along with a symptom pattern derived from measurements. Each pattern consists of symptoms based on four variables. Scores have been assigned to the symptoms in each pattern based on how well the symptom shown in the symptom matrix corresponds to the symptom based on measurements. For example, Symptom 1 for fault mode F1 corresponds identically to Symptom 1 in the pattern derived from measurements, so it is assigned a score of 10. The normalized scores in this example lead to the conclusion that fault F1 with a score of 1.0 probably exists in this system and fault F2 with a score of 0.3 is likely not present. In actual implementation, this methodology accounts for uncertainty in measurements by establishing threshold bands around numerical values of measured and derived variables and using the proximity to them in assigning scores to symptoms. The exact algorithm for assigning numerical scores, however, is not available in the paper.

Although the method proved effective in identifying faults in systems before the chiller system failed completely, faults with only a few symptoms tended to get high scores more often. Because the reference model is a simple regression model developed with data from a specific test chiller, the same model cannot be used on other chillers but instead new models would need to be developed for each chiller. Nonetheless, this generic approach provided a foundation for diagnostic work that followed.

Stylianou and Nikanpour (1996) used the universal chiller model developed by Gordon and Ng (1995) and the pattern matching approach outlined by Grimmelius et al. (1995) as part of their FDD system. Like Grimmelius et al. (1995), Stylianou and Nikanpour also perform detection and diagnosis in a single step. The methods used in the FDD system included a thermodynamic model for fault detection and pattern recognition from expert knowledge for diagnosis of selected faults. The diagnoses of the faults are performed by an approach similar to that outlined by Grimmelius et al. (1995). Seventeen different measurements (pressures, temperatures, and flow rates) were used to detect four different faults: refrigerant leak, refrigerant line flow restriction, condenser water-side flow resistance, and evaporator water-side flow resistance.

The FDD system is subdivided into three parts: one used to detect problems when the chiller is off, one used during chiller start-up, and one used at steady-state conditions. The off-cycle module is deployed when the chiller is turned off and is primarily used to detect faults in the temperature sensors. The temperature sensor readings at different locations on the system are compared to one another after the chiller is shut down and reaches steady state (under the assumption that the temperature of refrigerant will reach equilibrium conditions and reach the ambient state when the chiller is shut down overnight). The differences are then compared to the difference observed during commissioning (if the sensors are calibrated during commissioning, the differences should be zero). The monitored rate of change of a sensor value is used to check whether a particular sensor has reached steady state or not before comparing measurements across sensors.

The start-up module is deployed during the first 15 minutes after the chiller is started. The module uses four measured inputs (discharge temperature, crankcase oil temperature, and refrigerant temperatures entering and leaving the evaporator) scanned at five-second intervals to detect refrigerant flow faults, which are easier to detect before the system reaches steady state. To detect faults, the transient trends in measured variables during start-up are compared to the baseline trend from normal start-up. For example, a shift (in time or magnitude) in the peak of the discharge temperature may indicate liquid refrigerant flood back, refrigerant loss, or a refrigerant line restriction. Because ambient conditions affect the baseline response, the baseline response has to be normalized before a comparison is made.

The steady-state module is deployed after the chiller reaches steady state (steady-state condition is established by monitoring the rate of change of the sensor values just as in off-cycle analysis) and stays deployed until the chiller is turned off. In this mode, the module performs two functions: (1) verifies performance of the system and (2) detects and diagnoses selected faults.

Table 3. Fault Patterns Used in the Diagnostic Module (Stylianou and Nikanpour 1996)

Fault	Discharge Temperature	High Pressure Liquid Line Temperature	Discharge Pressure	Low Pressure Liquid Line Temperature	Suction Line Temperature	Suction Pressure	ΔT_{cond}	ΔT_{Evap}
Restriction in Refrigerant Line	↑	↓	↓	↓	↑	↓	↓	↑
Refrigerant Leak	↑	↓	↓	↓	↑	↓	↓	↑
Restriction in Cooling Water	↑	↑	↑	↓	↓	↓	↑	↓
Restriction in Chilled Water	↑	↓	↓	↓	↓	↓	↓	↓

Performance is verified using the thermodynamic models developed by Gordon and Ng (1995). For fault diagnostics, linear regression models are used to generate estimates of pressure and temperature variables that are then compared to actual measurements in an approach similar to that described by Grimmelius et al. (1995). The estimated variables are compared to the measured values, and the residuals are matched to predefined patterns corresponding to the various faults using a rule-base (as shown in Table 3).

Although Stylianou and Nikanpour (1996) extended the previous work of Gordon and Ng (1995) and Grimmelius et al. (1995), their evaluation of the FDD systems was not comprehensive and lacked several key elements including sensitivity and rate of false alarms. In addition, it is not clear whether the start-up module can be generalized easily.

Stylianou (1997) replaced the rule-based model used to match the patterns shown in Table 3 with a statistical pattern recognition algorithm. This algorithm uses the residuals generated from comparison of predicted (using linear regression models) and measured pressures and temperatures to generate patterns that identify faults. Because this approach relies on the availability of training data for both normal and faulty operation, it may be difficult to implement in the field. Only limited testing of the method was presented in the paper.

Tsutsui and Kamimura (1996) developed a model based on a topological-case-based reasoning (TCBR) technique and applied it to an absorption chiller. Case-based reasoning is a knowledge-based problem-solving technique that solves new problems by adapting old solutions. It is based on defining neighborhoods that provide the needed measure of similarity between cases. In contrast, TCBR defines "the neighborhood theoretically, based on the assumption that the input/output relationship is locally continuous" (Tsutsui and Kamimura 1996). Tsutsui and Kamimura (1996) also compared the diagnostic capabilities of TCBR with a linear regression model. The authors state that although the linear regression model had a better overall modeling error (mean error) than the TCBR model, the TCBR model was better at identifying abnormal conditions.

Peitsman and Bakker (1996) used two types of black-box models (artificial neural networks [ANNs] and auto regressive with exogenous inputs [ARX[1]]) to detect faults in the system and at the component level of a reciprocating chiller system. The inputs to the system models included condenser supply water temperature, evaporator supply glycol temperature, instantaneous power of the compressor, and flow rate of cooling water entering the condenser (for the ANN only). The choice of the inputs was limited to those that are commonly available in the field. Using these inputs with both the ANN and ARX models, 14 outputs were estimated. For the ANN models, inputs from the current and the previous time step and outputs from two previous time steps were used.

Peitsman and Bakker (1996) compared diagnostic capabilities of two types of models—a multiple input/output ARX model and ANN models. They used a two-level approach in which system-level models were used to detect "faulty" operation and component-level models were used to diagnose the cause of the fault. They developed 14 system-level models and 16 component-level models to detect and diagnose faults in a chiller; however, only one example (air in the system) is described in their paper. ANN models appeared to have a slightly better performance than the ARX models in detecting faults at both the system and the component levels. The authors also note that it is critical to find a global minimum when using ANN models. If an incorrect initial state is chosen, it may lead to a local minimum rather than the global minimum.

Bailey (1998) also used an ANN model to detect and diagnose faults in an air-cooled chiller with a screw compressor. The detection and diagnosis were carried out in a single step. The faults evaluated included refrigerant under- and overcharge, oil under- and overcharge, condenser fan loss (total failure), and condenser fouling. The measured data included superheat for heat exchanger circuits 1 and 2, subcooling from circuits 1 and 2, power consumption, suction pressure for circuits 1 and 2, discharge pressures for circuits 1 and 2, chilled water inlet and outlet temperatures from the evaporator, and chiller capacity. Each heat exchanger circuit has its own compressor. The ANN model was applied to normal and "faulty" test data collected from a 70-ton laboratory air-cooled chiller with screw compressor.

Sreedharan and Haves (2001) compared three chiller models for their ability to reproduce the observed performance of a centrifugal chiller. Although the evaluation was meant to find the most suitable model for chiller FDD, no FDD system was proposed or developed. Two models were based on first principles (from Gordon and Ng [1995] and a modified ASHRAE Primary Toolkit from Bourdouxhe et al. [1997]) and the third was an empirical model. While each model has some distinct advantages and disadvantages, they concluded that the accuracies of all three models were similar. Hydeman et al. (2002) reported that the three models compared by Sreedharan and Haves (2001) were not accurate in predicting the power consumption of chillers with variable condenser water flow and centrifugal chillers operating with variable-speed drives at low loads. They reformulated the Gordon and Ng model and found that it performed better than the three models described above.

Castro (2002) used a physical model developed by Rossi (1995) along with a k-nearest neighbor classifier to detect faults and a rule base to diagnose five different faults (condenser and evaporator fouling, liquid line restriction, and refrigerant under- and overcharge) in a reciprocating chiller. The FDD implementation detected and diagnosed condenser fouling, refrigerant undercharge at faults level of 20% or greater, and evaporator fouling and liquid line restriction at fault levels of 30% or greater.

[1]Refer to Box and Jenkins (1976) for more details on ARX type models.

Air-Handling Units

There are several studies relating to FDD methods for air-handling units (both the airside and the waterside); some of these are summarized in this section (Norford and Little 1993; Glass et al. 1995; Yoshida et al. 1996; Haves et al. 1996; Lee et al. 1996a, 1996b; Lee et al. 1997; Peitsman and Soethout 1997; Brambley et al. 1998; Katipamula et al. 1999; House et al. 1999; Ngo and Dexter 1999; Yoshida and Kumar 1999; Seem et al. 1999; Karki and Karjalainen 1999; Morisot and Marchio 1999; House et al. 2001; Dexter and Ngo 2001; Kumar et al. 2001; Salsbury and Diamond 2001; Carling 2002; Norford et al. 2002; Wang and Chen 2002; Pakanen and Sundquist 2003).

Norford and Little (1993) classify faults in ventilating systems, consisting of fans, ducts, dampers, heat exchangers, and controls. They then review two forms of steady-state parametric models for the electric power used by supply fans and propose a third, that of correlating power with a variable-speed drive control signal. The models are compared based on prediction accuracy, sensor requirements, and their ability to detect faults.

Using the three proposed models, four different types of faults associated with fan systems are detected: (1) failure to maintain supply air temperature, (2) failure to maintain supply air pressure setpoint, (3) increased pressure drop, and (4) malfunction of fan motor coupling to fan and fan controls. Although the paper by Norford and Little (1993) lacks details on how the faults were evaluated, error analysis and associated model fits were discussed. The results indicate that all three models were able to identify at least three of the four faults. The diagnosis of the faults is inferred after the fault is detected.

Glass et al. (1995) use a qualitative model-based approach to detect faults in an air-handling unit. The method uses outdoor, return, and supply air temperatures and control signals for the cooling coil, heating coil, and the damper system. Although Glass et al. (1995) mention that the diagnosis is inferred from the fault conditions, no clear explanation or examples are provided. Detection starts by analyzing the measured variables to verify whether steady-state conditions exist. Then, the controller values are converted to qualitative signal data and, using a model for expected values and measured temperature data, qualitative signals are estimated. Faults are detected based on discrepancies between measured qualitative controller outputs and corresponding model predictions based on the temperature measurements. Examples of qualitative states for the damper signal include "maximum position," "minimum position," "closed," and "in between." When the quantitative value of the damper signal approaches the maximum value, the corresponding qualitative value of "maximum" is assigned to the measured controller output. The results of testing the method on a laboratory AHU were mixed because the method requires steady-state conditions to be achieved before fault detection is undertaken. Fault detection sensitivity and ability to deal with false alarms are not discussed.

Yoshida et al. (1996) use ARX and the extended Kalman filter approach to detect abrupt faults with simulated test data for an AHU. Although the fault diagnosis approach is clearly described, the authors note that diagnosis is not feasible with the ARX method but that the Kalman filter approach could be used for diagnosis. Fault detection sensitivity and ability to deal with false alarms are not discussed.

Haves et al. (1996) use a combination of two models to detect coil fouling and valve leakage in the cooling coil of an AHU. The methodology was tested with data produced by the HVACSIM+ simulation tool (Clark 1985). A radial bias function (RBF) models the local behavior of the AHU and is updated using a recursive gradient-based estimator. The data generated by exercising the RBF over the operating range of the system are used in the estimation of the parameters for the physical model (UA and percent leakage) using a direct search method. Detection is accomplished by comparing estimated parameters to fault-free parameters.

Lee et al. (1996a) used two methods to detect eight different faults (mostly abrupt faults) in a laboratory test AHU. The first method uses discrepancies between measured and expected variables (residuals) to detect the presence of a fault. The expected values are estimated at nominal operating conditions. The second method compares parameters estimated using autoregressive moving average with exogenous input (ARMX) and ARX models with the normal (or expected) parameters to detect faults. The faults evaluated included complete failure of the supply and return fans, complete failure of the chilled-water circulation pump, stuck cooling-coil valve, complete failure of temperature sensors, complete failure of the static pressure sensor, and failure of the supply and return air fan flow stations. Because each of the eight faults has a unique signature, no separate diagnosis is necessary.

Lee et al. (1996b) used an ANN to detect the same faults described previously (Lee et al. 1996a). The ANN was trained using the normal data and data that represented each of the eight faults. Inputs to the ANN were values for seven normalized residuals, and the outputs were nine values that constitute patterns that represent the normal mode and the eight fault modes. Instead of generating the training data with faults, idealized training patterns were specified by considering the dominant symptoms of each fault. For example, supply fan failure implies that the supply fan speed is zero, the supply air pressure is zero, the supply fan control signal is maximum, and the difference between the flow rates in the supply and return ducts is zero. Using similar reasoning, a pattern of dominant training residuals was generated for each fault (see Table 4). A dominant symptom residual is assigned a value of +1 if the residual is positive and –1 if the residual is negative; all other residuals are assigned a value of 0. The ANN was trained using the pattern shown in Table 4. Normalized residuals were calculated for faults that were artificially generated in the laboratory AHU. The normalized residuals vector at each time step was then used with the trained ANN to identify the fault. Although the ANN was successful in detecting the faults from laboratory data, it is not clear how successful this method would be in general because the faults generated in the laboratory setting were severe and without noise.

Lee et al. (1997) extended the previous work described in Lee et al. (1996b). In the 1997 analysis, Lee et al. (1997) used two ANN models to detect and diagnose faults. The AHU is decomposed into various subsystems such as the pressure control subsystem, the flow-control subsystem, the cooling-coil subsystem, and the mixing-damper subsystem. The first ANN model is trained to identify the subsystem in which a fault occurs, while the second ANN model is trained to diagnose the specific cause of a fault at the subsystem level. An approach similar to the one used in Lee et al. 1996b is used to train both ANN models. Lee et al. (1997) note that this two-stage approach simplifies generalization by replacing a single ANN that encompasses all considered faults with a number of less complex ANNs, each one dealing with a subset of the residuals and symptoms. Although 11 faults are identified for detection and diagnosis, fault detection and diagnosis are presented for only one fault in the paper.

Peitsman and Soethout (1997) used several different ARX models to predict the performance of an AHU and compared the predictions to measured values to detect faults. The training data for the ARX models were generated using HVACSIM+. The AHU is modeled at two levels. The first level is the system level, where the complete AHU is modeled with one ARX model. The second level is the component level, where the AHU is subdivided into several subsystems such as the return fan, the mixing box, and the cooling coil. Each component is modeled with a separate ARX model. The first level ARX model is used to detect a problem and the second level models are used to diagnose the problem. Most abrupt faults were correctly identified and diagnosed, while slowly evolving faults were not detected. There is a potential for a conflict between the two levels with this approach; for example, the top-level ARX model could detect a fault with the AHU, while the second-level ARX models do not indicate any faults. Furthermore, there is a potential for multiple diagnoses at the second level. Peitsman and Soethout (1997)

Table 4. Normalized Patterns for AHU Fault Diagnosis Used in ANN Training (Lee et al. 1996b)

Fault Diagnosis	Network Inputs – Residuals: Supply Pressure	Difference in Supply and Return Airflow	Supply Air Temperature	Control Signal to Cooling Coil	Supply Fan Speed	Return Fan Speed	Cooling Coil Valve Position	Network Outputs								
Normal (no fault)	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
Supply Fan	–1	–1	0	1	–1	0	0	0	1	0	0	0	0	0	0	0
Return Fan	0	1	0	0	0	–1	0	0	0	1	0	0	0	0	0	0
Pump	0	0	0	1	0	0	0	0	0	0	1	0	0	0	0	0
Cooling Coil Valve	0	0	0	0	0	0	1	0	0	0	0	1	0	0	0	0
Temperature Sensor	0	0	–1	–1	0	0	0	0	0	0	0	0	1	0	0	0
Pressure Transducer	–1	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
Supply Fan Flow Station	0	–1	0	0	0	0	0	0	0	0	0	0	0	0	1	0
Return Fan Flow Station	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1

indicated that some of this multiple diagnosis could be discriminated by ranking of diagnoses according to their improbability; however, no details were provided on how to implement such a scheme.

House et al. (1999) compared several classification techniques for fault detection and diagnosis of seven different faults in an AHU. The data for the comparison were generated using an HVACSIM+ simulation model. Using the residuals, as defined in Lee et al. (1996a, 1996b), five different classification methods are evaluated and compared for their ability to detect and diagnose faults. The five classification methods include: ANN classifier, nearest neighbor classifier, nearest prototype classifier, a rule-based classifier, and a Bayes classifier.

Based on the performance of classification methods, the Bayes classifier appears to be a good choice for fault detection. For diagnosis, the rule-based method proves to be a better choice for the classification problems considered, where the various classes of faulty operations were well separated and could be distinguished by a single dominant symptom or feature.

Ngo and Dexter (1999) developed a semi-qualitative analysis of measured data using generic fuzzy reference models to diagnose faults with the cooling coil of an AHU. The method uses sets of training data with and without faults to develop generic fuzzy reference models for diagnosing faults in a cooling coil. The faults include leaky valve, waterside fouling, valve stuck closed, valve stuck midway, and valve stuck open. The fuzzy reference models describe in qualitative terms the steady-state behavior of a particular class of equipment with no faults present and when each of the faults has occurred. Measured data are used to identify a partial fuzzy model that describes the steady-state behavior of the equipment at a particular operating point. The partial fuzzy model is then compared to each of the reference models using a fuzzy matching scheme to determine the degree of similarity between the partial model and the reference models. Ngo and Dexter (1999) provide a detailed description of fault detection sensitivity and false alarm rates.

Yoshida and Kumar (1999) evaluated two model-based methods to identify abrupt (sudden) faults in an AHU. They report that both ARX and adaptive forgetting through multiple models (AFMM) seem promising for use in on-line fault detection of AHUs. They report that ARX models require only a minimal knowledge of the system, and the potential limitation of the technique is that it requires long periods to stabilize its parameters. On the other hand, Yoshida and Kumar (1999) report that the AFMM method requires long moving averages to suppress false alarms. When this is done, faults of lesser magnitude cannot be easily detected. Implementation details are not provided, and only one example of fault detection is provided.

Morisot and Marchio (1999) use an ANN-based approach to detect degradation of performance of a cooling coil in an AHU. The ANN network includes an input layer (six inputs), a hidden layer (four nodes), and an output layer (two outputs). The inputs include entering air temperature and humidity, entering and leaving water temperatures, fan-control signal, and cooling-coil-valve-control signal. The outputs are the leaving air temperature and humidity. The authors highlight the difficulties of using ANNs with real measured data, which include a need for an exhaustive training data set and the inability of the ANNs to extrapolate values outside the range of the training data. The proposed alternative is to use a simulation model to generate the training data for the ANN. Using this alternative approach, the authors test the ability of the ANN to detect two faults (air-side fouling and a sensor fault).

Dexter and Ngo (2001) outline a multi-step fuzzy model-based FDD approach to detecting and diagnosing faults with AHUs. This approach involves classifying measured data with fuzzy rules and comparing them to a set of fuzzy reference models for normal and faulty operations. The fuzzy reference models for a specific system are developed from data that are generated from simulations. Each rule is assigned a rule-confidence in the range from zero to one, where zero indicates no confidence and one indicates complete confidence in the rule correctly describing the behavior. Rule-confidence values are estimated from the data. The authors state that this method prevents false alarms because it accounts for major sources of uncertainty. The multi-step approach is shown to be capable of detecting and isolating faults in a cooling coil (leaking valves and fouling).

Kumar et al. (2001) propose a method based on an auto regressive exogenous model and a recursive parameter estimation algorithm to detect faults with AHUs. They conclude that changes in parameter estimates from real data cannot be directly used to detect faults; instead a statistical analysis of the frequency response of the model parameters is needed to detect faults.

Salsbury and Diamond (2001) develop a simplified physical model-based approach to both control and detect faults in AHUs. Results from a field test on a single AHU demonstrate the fault detection capabilities but also highlight some of the practical implementation difficulties including selection of model parameters, reliability of sensor signals, and difficulty in establishing a baseline of “correct” operation of the AHU.

Carling (2002) assesses the performance of three fault detection methods for AHUs: (1) qualitative model-based approach outlined in Glass et al. (1995), (2) rule-based approach outlined in House et al. (2001), and (3) simplified steady-state model-based. The normal and "faulty" data used for the assessment were collected from real systems for an offline analysis. The "faulty data" were collected by introducing artificial faults in the AHU. The qualitative model was easy to set up, generated few false alarms, but also detected fewer faults. The rule-based method detected more faults but required some analysis and customization during setup. The third method detected more faults but also generated more false alarms and took considerable time to set up and customize. It also required installation of additional sensors.

Norford et al. (2002) present results from controlled field tests for detecting and diagnosing faults in AHUs. These tests were part of an ASHRAE research project (RP-1020), which was to demonstrate FDD methods for AHUs. The first FDD method used a first-principles model-based approach, and the second one was based on semi-empirical polynomial correlations of submetered electrical power with flow rates or process control signals generated from historical data. Although data representing faulty operation were based on blind tests, the faults were selected from a predefined set for an agreed set of conditions and magnitudes. The criteria used in the evaluation of the two FDD methods were sensitivity, robustness, the number of sensors required, and ease of implementation.

Both methods were successful in detecting faults but had difficulty in diagnosing the actual cause of the fault. The first principles-based method requires more sensors and more training data and misdiagnosed more often than the semi-empirical method.

CURRENT STATE FOR DIAGNOSTICS IN BUILDINGS

During the 1990s, significant growth occurred in research on the development of fault detection and diagnostic methods for HVAC&R systems. Still, very few commercial FDD products exist today, and the ones that do are very specialized or not fully automated. There are several reasons for lack of widespread availability and deployment of FDD systems: lack of demand by the building operations and maintenance (O&M) community, possibly as a result of insufficient information on the improvements possible from automated FDD, lack of adequate sensors installed on building systems, reliable sensors being too costly, high perceived cost-to-benefit ratio of deploying FDD systems with current sensor technologies, lack of acceptable benchmarks to quantify the potential benefits from deploying FDD systems, lack of easy access to real-time data unless FDD is built directly into building automation systems, and lack of infrastructure to gather data from existing building automation systems (BASs) for add-on applications.

Most papers reviewed for this study did not cover the evaluation and decision stages of a generic O&M support system using FDD; yet to be useful in the field FDD must be embedded in complete building management and decision support systems. Katipamula et al. (1999), Rossi and Braun (1996), and Breuker and Braun (1998b) have addressed the evaluation aspect of the O&M support system, and Katipamula et al. (2002) and Brambley and Katipamula (2003) proposed a decision step for AHUs. Furthermore, many of the FDD methods have only been tested in laboratory or special test environments (Castro et al. 2003). Some FDD tools have been tested in the field (Katipamula et al. 2003; Castro et al. 2003; Braun et al. 2003). The detection sensitivity of the methods and occurrence rates for false alarms have not been thoroughly investigated in real buildings yet. Although the R&D reviewed is focused on methods for automating FDD, most papers do not address the automation itself in sufficient detail. Efficiently and cost-effectively creating the code that implements these methods represents an important aspect of creating usable tools based on these methods.

A significant number of papers address FDD methods based on process history. In most cases, models based on process history are specific to the system from which the training data are collected. In order to make these methods broadly applicable, the models need to be developed in factory settings for equipment model lines or automatically online in an as-installed setting. Automation of the model development process is critical to controlling the costs of FDD systems. Preliminary work on online modeling has been done by Reddy et al. (2001), but more work is needed in this general area.

Another major limitation of most FDD methods developed to date is that they work well when a single dominant fault is present in a system, but if multiple faults occur simultaneously or are present when FDD is done initially, many of the methods fail to properly detect or diagnose the causes of the faults. Braun et al. (2003) extended the previous work by Rossi and Braun (1996) and Breuker and Braun (1998b) to diagnose multiple simultaneous faults. More work is needed in development of methods that can reliably handle multiple faults.

FUTURE FOR AUTOMATED DIAGNOSTICS IN BUILDINGS

The application of automated FDD to building HVAC&R is still in its infancy. Key technical problems still requiring solutions include:

- eliminating the need to handcraft FDD systems
- automating generation of FDD systems
- selecting the best FDD method for each type of HVAC&R application and the constraints applicable to it
- developing the balance of system for operation and maintenance support tools—evaluation and decision support
- development of prognostics to transform HVAC&R maintenance from corrective and preventive to predictive condition-based maintenance
- lowering the cost of obtaining data for FDD and O&M support

To the extent that FDD requires handcrafting for each installation, costs will likely be prohibitive. Three generically different solutions for this problem exist: (1) deploy FDD in service tools with databases sufficient to cover many equipment model lines, (2) deploy FDD as part of on-board equipment control packages, and (3) develop methods for automatically generating FDD tools. The first approach has already been introduced to the market in a hand tool for air-conditioning service providers (Honeywell 2003). More tools of this type, embedding automated FDD, are likely to evolve. The second approach of embedding monitoring and safety controls capabilities in on-board equipment control is already underway to some extent by manufacturers of equipment and equipment control packages (such as chillers for safety reasons but not for system performance). Capabilities deployed to date appear limited and details of methods are difficult to obtain because of their proprietary nature, but FDD deployment is beginning to emerge via this route. The third approach involving rapid generation, possibly in an automated manner, requires further research not only into the methods for FDD but also for automated code generation (in the fields of software development, adaptive systems, genetic systems, etc.).

Additional R&D is needed in the field of FDD itself to further develop fundamental methods for FDD, selection and specialization of methods to the constraints of the built environment (e.g., pressure to keep costs low and a data-poor environment in buildings), application and testing of FDD to the various systems, equipment, and components used in buildings, and development and application of FDD for building systems of the future, which are likely to include integration with on-site electricity generation, management of electric loads, real-time purchasing of electricity, and other interactions with the electric power grid of the future, and transition to new fuels (e.g., energy carriers such as hydrogen). All provide rich areas for research and development that will improve the performance and efficiency of commercial and residential buildings.

Prognostics are critical to transitioning building equipment maintenance as practiced today to condition based so that it accounts for the expected remaining life of equipment and its performance degradation over time. Only with this information can decisions be made regarding the optimal scheduling of maintenance. The field of prognostics presents a rich area of investigation and development for the HVAC&R research community. Little has been published to date on prognostics for HVAC&R.

Beyond research into FDD methodologies and their application to building systems, the HVAC&R field is faced with the opportunity to develop an entirely new class of tools and to add them to building automation systems. FDD methods may provide a core capability for enhanced operation and maintenance support systems of the future, but the balance of those systems must be developed. Packaging is critical to success in the market. Tools must be developed that meet the needs and fit into the environment of building operators and maintenance service providers and provide them value.

Probably the most constraining of all problems facing the application of FDD&P to HVAC&R is the dearth of data. Relatively small numbers of sensors are generally installed in building systems and the quality (accuracy, precision, and reliability) of the sensors that are installed is inadequate for many uses. Sensors frequently fail or drift out of calibration and remain that way for long periods of time until fortuitously discovered. Performance, cost, and durability need to be addressed to promote better sensing in buildings.

With the development of low-cost reliable sensor technology (Kintner-Meyer and Brambley 2002; Kintner-Meyer et al. 2002), a major hurdle to commercial deployment of FDD systems would be overcome. This would potentially speed the deployment of third party FDD tools and integration of FDD into individual equipment controllers and building automation systems to provide continuous monitoring, real-time fault detection and diagnostic information, and recommendations for maintenance service and would lead to much improved maintenance of HVAC&R systems. Ultimately, as networking infrastructure matures, the use of automated FDD systems should enable a small support staff to operate, monitor, and maintain a large number of different systems from a remote, centralized location. Local FDD systems could communicate across a network to provide reports on the health of the equipment that they monitor. Failures that lead to loss of comfort could be identified quickly before significant impacts on comfort or equipment damage occurs. In many cases, degradation faults could be identified well before they lead to loss of comfort or uneconomical operation, allowing more efficient scheduling of (and lower costs for) maintenance service.

At present, no fully automated FDD systems have been integrated into individual controllers for commercial HVAC&R equipment. In general, larger equipment applications (e.g., chillers) can absorb more add-on costs than smaller ones (e.g., rooftop units) and, therefore, automated FDD will probably appear first in larger equipment.

Open communication standards for building automation systems are catching on, and use of Internet and intranet technologies is pervasive. These developments enable FDD systems to be deployed more readily. In addition, the structure of the industry that provides services for the operations and maintenance of buildings is changing; companies are consolidating and offering whole-building operations and maintenance packages. Furthermore, as utilities are deregulated, they will begin to offer new services, including complete facility management. With complete and distributed facility management, the cost-to-benefit of deploying FDD systems will improve because the cost can be spread over a large number of buildings (Katipamula et al. 1999). To benefit from these changes, facility managers, owners, operators, and energy service providers are challenged to acquire or develop new capabilities and resources to better manage this information and, in the end, their buildings and facilities.

Although the incentives for application of FDD systems for HVAC&R and other building systems have never been greater, there still are several obstacles to their development and deployment. Beyond research and development, there is a need to quantify the benefits, to establish benchmarks for acceptable costs, and to provide market information. Assessing and demonstrating value for these technologies is an opportunity for public/private partnerships. Public agencies can help reduce risk to facility owners and operators while promoting and accelerating transition to a more efficient buildings sector by demonstrating the value of these technologies and transforming the market to accelerate adoption where public benefits warrant. FDD&P promises to help transform the buildings sector to a new level of energy and operational performance and efficiency.

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TAC: Electrical

Total Mods for **Electrical** in **Pending Review : 16**

Total Mods for report: 16

Sub Code: Energy Conservation

E10077

8

Date Submitted	02/03/2022	**Section**	401.2	**Proponent**	Bryan Holland
Chapter	4	**Affects HVHZ**	No	**Attachments**	No
TAC Recommendation	Pending Review				
Commission Action	Pending Review				

Comments

General Comments Yes **Alternate Language No**

Related Modifications

Summary of Modification

This proposed modification reinstates sections 8.4.2 and 8.4.3 of the ASHRAE 90.1 standard to the optional compliance path in C401.2 and the electrical power applicability in C405.5.1.

Rationale

The exclusion of section 8.4.2 and 8.4.3 of the ASHRAE 90.1 Standard, when that compliance path is selected for compliance in C401.2 and when complying with C405.5.1 (DS 2016-033), is in direct violation of F.S. 553.886 that states; "the Florida Building Code must facilitate and promote the use of cost-effective energy conservation, energy-demand management, and renewable energy technologies in buildings" and reduces the energy efficiency of buildings established by the United States Department of Energy under Section 304(a) of the Energy Conservation and Production Act (ECPA). Automatic receptacle control and electrical energy monitoring are now both mandatory requirements of the 2021 IECC and ASHRAE 90.1-2019.

Fiscal Impact Statement

Impact to local entity relative to enforcement of code

This proposed modification will require the local entity to confirm the design and installation of ARC and Energy Monitoring systems at time of plan review and inspection.

Impact to building and property owners relative to cost of compliance with code

This proposed modification will increase the cost of compliance with the code but will result in improved energy conservation and the effective use of energy over time. Both ARC and Energy Monitoring systems do require specialized training for design, installation, and use/operation.

Impact to industry relative to the cost of compliance with code

This proposed modification will increase the cost of compliance with the code for industry. ARC and Energy Monitoring systems have an initial design and installation cost not currently required in the code.

Impact to small business relative to the cost of compliance with code

Requirements

Has a reasonable and substantial connection with the health, safety, and welfare of the general public

This proposed modification will improve the health and welfare of the general public by improving the energy saving and energy conservation of commercial buildings through application of these specialized systems.

Strengthens or improves the code, and provides equivalent or better products, methods, or systems of construction

This proposed modification improves the code and meets the mandate outlined in F.S. 553.886 that states; "the Florida Building Code must facilitate and promote the use of cost-effective energy conservation, energy-demand management, and renewable energy technologies in buildings.

Does not discriminate against materials, products, methods, or systems of construction of demonstrated capabilities

This proposed modification does not discriminate against any materials, methods, or systems of constructions.

Does not degrade the effectiveness of the code

This proposed modification improves the effectiveness of the code.

1st Comment Period History

E10077-G1

Proponent	Muthusamy Swami	Submitted	4/17/2022 12:46:37 PM	Attachments	No

Comment:

Response: FSEC agrees that we should not exclude the “Automatic receptacle control and electrical energy monitoring” requirements. Current technologies that support the code requirements are cost-effective. Electrical energy monitoring is part and parcel of advanced maintenance plans and failure diagnostics. FSEC has done economic analysis of Section 8.4.3 of the 2019 ASHRAE 90.1 and determined to be cost-effective with SIR value range of 3.44 - 14.01. Note that building floor size less than 25,000 square foot are exempted from Section 8.4.3 requirement.

C401.2 Application.

Commercial buildings shall comply with one of the following:

1. The requirements of ANSI/ASHRAE/IESNA 90.1, excluding section 9.4.1.1(g)~~, section 8.4.2 and section 8.4.~~3 of the standard.

C405.5.1 Applicability.

This section applies to all building power distribution systems. The provisions for electrical distribution for all sections of this code are subject to the design conditions in ASHRAE Standard 90.1

~~**Exception:** Compliance with ASHRAE 90.1 Sections 8.4.2, 8.4.3 and 9.4.1.1(g) are not required.~~

TAC: Electrical

Total Mods for **Electrical** in **Pending Review : 16**

Total Mods for report: 16

Sub Code: Energy Conservation

9

E10079

Date Submitted	02/03/2022	**Section**	405.5.3	**Proponent**	Bryan Holland
Chapter	4	**Affects HVHZ**	No	**Attachments**	No
TAC Recommendation	Pending Review				
Commission Action	Pending Review				

Comments

General Comments No **Alternate Language No**

Related Modifications

Summary of Modification

This proposed modification adds "customer-owned service conductors" to the voltage drop requirement with an exception for service conductors installed by or under the exclusive control of the electric utility.

Rationale

Voltage drop occurs on all conductors of a premises wiring system. However, only branch circuit and feeder conductors are currently addressed in the code. This proposal adds customer-owned service conductors but only if they are installed by and under the exclusive control of the owner. Where the electric utility installs and controls the service conductors, they are exempt from this rule. Voltage drop is a total waste of energy that can easily be mitigated by limiting these losses to 5% from the service point to the furthest outlet.

Fiscal Impact Statement

Impact to local entity relative to enforcement of code

This proposed modification will require the local entity to confirm the voltage drop calculations have been applied to customer-owned service conductors at time of plan review and inspection.

Impact to building and property owners relative to cost of compliance with code

This proposed modification will increase the cost of compliance with the code where service conductor runs are excessively long, however, the energy savings will result in ROI over time.

Impact to industry relative to the cost of compliance with code

This proposed modification will increase the cost of compliance with the code for industry where larger service conductor sizes are required to recue voltage drop below 5%.

Impact to small business relative to the cost of compliance with code

Requirements

Has a reasonable and substantial connection with the health, safety, and welfare of the general public

This proposed modification will improve the health and welfare of the general public by improving system efficiency and ensure energy loses are limited to 5% across the entire wiring system.

Strengthens or improves the code, and provides equivalent or better products, methods, or systems of construction

This proposed modification improves the code and meets the mandate outlined in F.S. 553.886 that states; "the Florida Building Code must facilitate and promote the use of cost-effective energy conservation, energy-demand management, and renewable energy technologies in buildings.

Does not discriminate against materials, products, methods, or systems of construction of demonstrated capabilities

This proposed modification does not discriminate against any materials, methods, or systems of construction.

Does not degrade the effectiveness of the code

This proposed modification improves the effectiveness of the code.

C405.5.3 Voltage drop.

~~The conductors for feeders and branch circuits combined shall be sized for a maximum of 5 percent voltage drop total.~~ The total voltage drop across the combination of customer-owned service conductors, feeder conductors and branch circuit conductors shall not exceed 5 percent.

Exception: Customer-owned service conductors installed by or under the exclusive control of the electric utility.

TAC: Electrical

Total Mods for **Electrical** in **Pending Review : 16**

Total Mods for report: 16

Sub Code: Energy Conservation

10

E10085

Date Submitted	02/04/2022	**Section**	405.9	**Proponent**	Bryan Holland
Chapter	4	**Affects HVHZ**	No	**Attachments**	Yes
TAC Recommendation	Pending Review				
Commission Action	Pending Review				

Comments

General Comments Yes **Alternate Language No**

Related Modifications

Summary of Modification

This proposed modification adds requirements for automatic receptacle control to the code.

Rationale

Plug loads can represent up to 30% of the electrical energy used in a commercial building. And much like lighting that is automatically controlled to turn off when no human occupancy is present, this proposal provides prescriptive criteria for ensuring nonessential receptacle loads are turned off when no human occupancy is present. A CASE initiative study found that in smaller 10,000 sqft office buildings, the annual electrical savings was 4,900 kwh/yr and a demand savings of 1.97 kw. Based on installed costs and utilization of lighting control system elements already installed to support the plug load control, simple payback was 4.2 years. In larger 175,000 sqft office building, annual electrical savings was 107,000 kwh/yr and demand savings of 23.6 kw with a simple payback calculated at 2.4 years. This proposal meets the mandate outlined in F.S. 553.886 that states; "the Florida Building Code must facilitate and promote the use of cost-effective energy conservation, energy-demand management, and renewable energy technologies in buildings.

Fiscal Impact Statement

Impact to local entity relative to enforcement of code

This proposed modification will require the local entity to confirm the design and installation of ARC at time of plan review and inspection.

Impact to building and property owners relative to cost of compliance with code

This proposed modification will increase the cost of compliance with the code where dedicated or advanced techniques are used for ARC. Energy savings are immediate and ROI is less than 5 years.

Impact to industry relative to the cost of compliance with code

This proposed modification will increase the cost of compliance with the code for industry. ARC technology has been in the marketplace for over ten years. The installation and use of ARC does require specialized training.

Impact to small business relative to the cost of compliance with code

Requirements

Has a reasonable and substantial connection with the health, safety, and welfare of the general public

This proposed modification will improve the health and welfare of the general public by improving energy savings and energy conservation by the control of plug loads.

Strengthens or improves the code, and provides equivalent or better products, methods, or systems of construction

This proposed modification improves the code and meets the mandate outlined in F.S. 553.886 that states; "the Florida Building Code must facilitate and promote the use of cost-effective energy conservation, energy-demand management, and renewable energy technologies in buildings.

Does not discriminate against materials, products, methods, or systems of construction of demonstrated capabilities

This proposed modification does not discriminate against any materials, methods, or systems of constructions.

Does not degrade the effectiveness of the code

This proposed modification improves the effectiveness of the code.

1st Comment Period History

E10085-G1

Proponent Muthusamy Swami Submitted 4/17/2022 12:56:11 PM Attachments No

Comment:

This proposed code change is the same as Section 8.4.2 of the 2019 ASHRAE 90.1. ASHARE adopted this code at least since 2013 but FBCEC (2017, and 2020) has excluded it. See proposed code change EN10077 (item #1 in this document) FSEC has not done any cost-effectiveness analysis but PNNL and others claim it is cost-effective. FSEC encourages adoption of this proposed code change because it is current technology.

C405.11 Automatic receptacle control. The following shall have automatic receptacle control complying with Section C405.11.1.

1. At least 50 percent of all 125V, 15- and 20-amp receptacles installed in enclosed offices, conference rooms, rooms used primarily for copy or print functions, breakrooms, classrooms and individual workstations, including those installed in modular partitions and module office workstation systems.

2. At least 25 percent of branch circuit feeders installed for modular furniture not shown on the construction documents.

C405.11.1 Automatic receptacle control function. Automatic receptacle controls shall comply with the following:

1. Either split controlled receptacles shall be provided with the top receptacle controlled, or a controlled receptacle shall be located within 12 inches (304.8 mm) of each uncontrolled receptacle.

2. One of the following methods shall be used to provide control:

2.1. A scheduled basis using a time-of-day operated control device that turns receptacle power off at specific programmed times and can be programmed separately for each day of the week. The control device shall be configured to provide an independent schedule for each portion of the building of not more than 5,000 square feet (464.5 m2) and not more than one floor. The occupant shall be able to manually override an area for not more than 2 hours. Any individual override switch shall control the receptacles of not more than 5,000 feet (1524 m).

2.2. An occupant sensor control that shall turn off receptacles within 20 minutes of all occupants leaving a space.

2.3. An automated signal from another control or alarm system that shall turn off receptacles within 20 minutes after determining that the area is unoccupied.

3. All controlled receptacles shall be permanently marked in accordance with NFPA 70 and be uniformly distributed throughout the space.

4. Plug-in devices shall not comply.

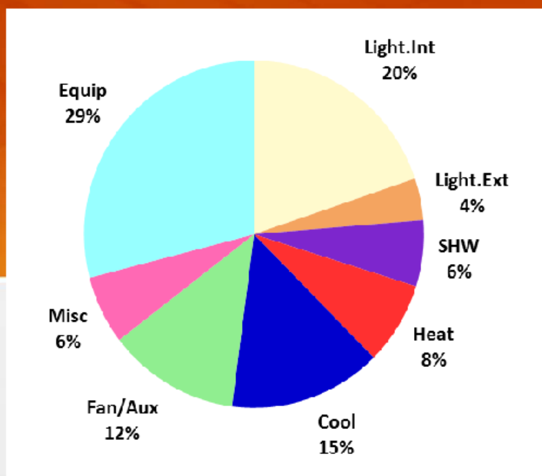
Exceptions: Automatic receptacle controls are not required for the following:

1. Receptacles specifically designated for equipment requiring continuous operation (24 hours per day, 365 days per year).

2. Spaces where an automatic control would endanger the safety or security of the room or building occupants.

3. Within a single modular office workstation, noncontrolled receptacles are permitted to be located more than 12 inches (304.8 mm), but not more than 72 inches (1828 mm) from the controlled receptacles serving that workstation.

PNNL-24043



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End-Use Opportunity Analysis from Progress Indicator Results for ASHRAE Standard 90.1-2013

December 2014

R Hart
Y Xie

U.S. DEPARTMENT OF ENERGY

Prepared for the U.S. Department of Energy
under Contract DE-AC05-76RL01830

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Pacific Northwest National Laboratory
Richland, Washington 99352

E10085Text Modification

Summary

This report and an accompanying spreadsheet posted online[1] compile the end use building simulation results for prototype buildings throughout the United States. The results represent the energy use of each edition of ANSI/ASHRAE/IES[2] Standard 90.1, *Energy Standard for Buildings Except Low-Rise Residential Buildings*. Pacific Northwest National Laboratory examined the simulation results to determine how the remaining energy was used.

Figure S.1 shows end-use cost data by building type weighted by national construction by climate zone. Prototype results are grouped by similar type, including Office, Warehouse (Wh), Retail, Hotel, Apartment (Apt), School, Medical, and Food Service (Food Svc). The widths of the building type (vertical) bars are scaled to represent each building type's share of impact on national building energy cost. The end uses include heating, ventilation, and air conditioning (HVAC) fans and pumps (Fan Aux), Cooling (Cool), Heating (Heat), service hot water (SHW), interior lighting (Light Int), exterior lighting (Light Ext), miscellaneous loads including refrigeration, elevators and transformers (Misc), and plug loads, cooking, and information technology (IT) equipment (Equip). The area of each block represents the proportion of national energy cost for each end use. The entire width of the plot matches national building energy use based on Standard 90.1-2013.

[1] PNNL. 2014. *2013EndUseTables.xlsx*. Pacific Northwest National Laboratory, Richland, WA. Available at http://www.energycodes.gov/sites/default/files/documents/2013EndUseTables.zip.

[2] ANSI – American National Standards Institute; ASHRAE – American Society of Heating, Refrigerating, and Air-Conditioning Engineers; IES – Illuminating Engineering Society

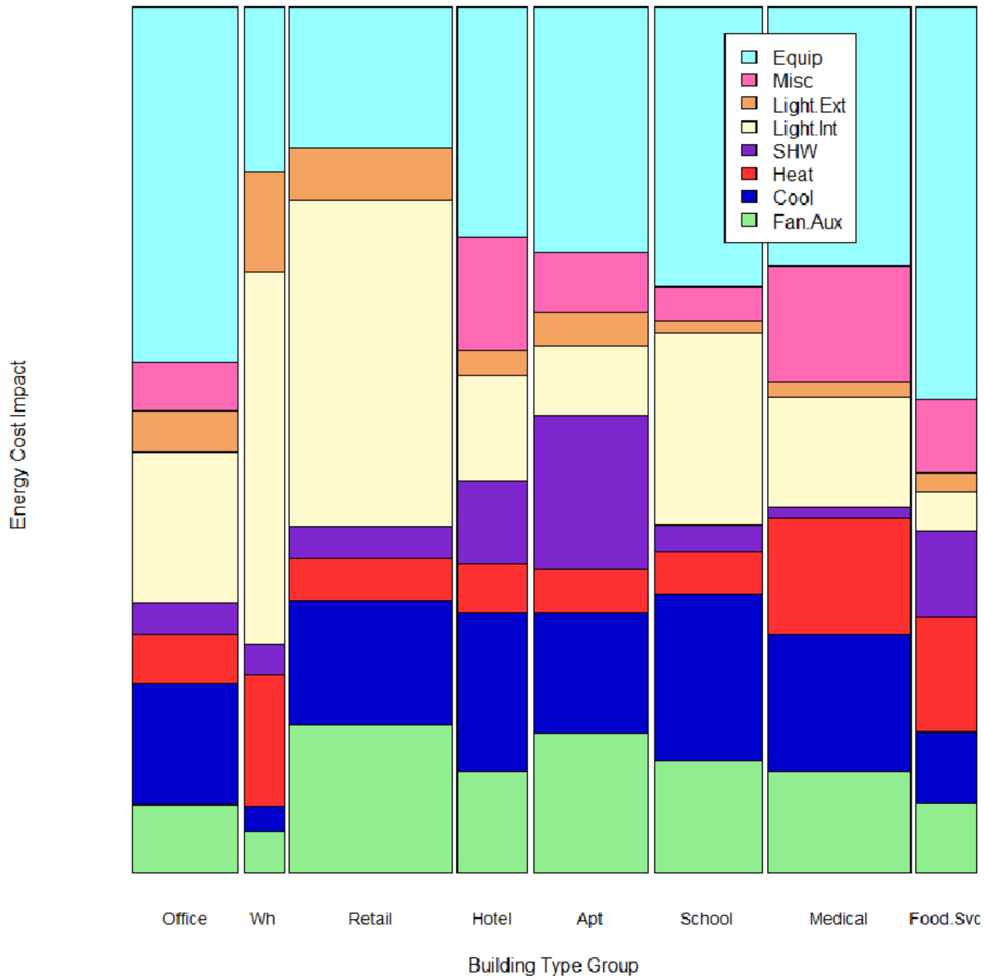


Figure S.1. Commercial energy cost impact by end use U.S. weighted, after 90.1-2013

Acknowledgments

The data that was used as the basis for this end use analysis was developed by the Pacific Northwest National Laboratory codes team for the 2013 progress indicator that measured improvements in the ANSI/ASHRAE/IES Standard 90.1-2013 vs. earlier editions of Standard 90.1. Their long-term work on development and enhancement of the building prototypes used in that analysis made this report possible. Team members include Michael Rosenberg, Mark Halverson, Raul Athalye, YuLong Xie, Weimin Wang, Jian Zhang, Supriya Goel, and Vrushali Mendon, with team leadership by Bing Liu and Jamie Holladay. Editing was provided by Mike Parker and Matt Wilburn. Members of the ASHRAE Standing Standards Project Committee 90.1 provided valuable feedback to development of the prototypes and typical buildings, and funding was provided by the U.S. Department of Energy.

Acronyms and Abbreviations

ANSI	American National Standards Institute
ASHRAE	American Society of Heating, Refrigerating, and Air-Conditioning Engineers
BECP	Building Energy Codes Program
CZ	climate zone
ECI	energy cost index
EUI	energy use index
HVAC	heating, ventilation, and air conditioning
IES	Illuminating Engineering Society
IT	information technology
MHC	McGraw-Hill Construction
PNNL	Pacific Northwest National Laboratory
SSPC	Standing Standard Project Committee
WBCI	weighted building cost index

E10085Text Modification

Contents

Figures

Tables

Background and Method

End Uses Analyzed

Pacific Northwest National Laboratory (PNNL) conducts analysis to project the energy use of each edition of ANSI/ASHRAE/IES[1] Standard 90.1, *Energy Standard for Buildings Except Low-Rise Residential Buildings* (ASHRAE 2004, 2007, 2010, 2013). The comparison of the savings of each edition to the prior edition is called the "progress indicator." Based on analysis of the Standard 90.1-2013 (ASHRAE 2013) progress indicator, PNNL examined the detailed results to determine how the remaining energy was used. Where helpful, miscellaneous (e.g., elevator) and equipment (cooking and information technology [IT] equipment) results were extracted to increase the precision of end-use categories. This report provides analysis results using the simple and detailed breakdowns as shown in Table 1.

Table 1. Simple and detailed end-use category descriptions

Simple Breakdown Abbreviation	Color Code	Detailed Breakdown Abbreviation	End-Use Description
Light.int		Light.int	Interior lighting
Light.ext		Light.ext	Exterior lighting
SHW		SHW	Service hot water
Heat		Heat	Space heating
		Humidify	Humidification (dehumidification in heat and cool)
Cool		Cool	Mechanical cooling (including unitary heat rejection)
		Ht.Rej	Heat rejection, cooling towers (unitary is in cool)
Fan.Aux		Fans	Heating, ventilation, and air conditioning (HVAC) supply, return and exhaust fans
		Ht.Rcvy	Heat recovery fan and wheel energy
		Pumps	Hydronic pumping, including SHW recirculation
Misc		Refrig	Refrigeration equipment and kitchen refrigerators and freezers
		Elevator	Elevators
		Txfmr	In-building transformers
Equip		Cook	Cooking equipment
		IT	Computer room IT and telephone equipment
		Equip	Other plug loads and equipment including non-kitchen refrigerators

The graphs in this report are based on energy cost index (ECI) and most use the simple breakdown.

Prototype Buildings for the Progress Indicator

To determine the savings impact from various editions of ANSI/ASHRAE/IES Standard 90.1, PNNL developed prototype commercial building models. They have been described in detail previously in *Achieving the 30% Goal: Energy and Cost Savings Analysis of ASHRAE Standard 90.1-2010* (Thornton et al. 2011). As noted in that report, PNNL developed a suite of 16 prototype buildings covering the majority of the commercial building stock and mid-rise to high-rise buildings. The prototypes used in the

[1] American National Standards Institute/American Society of Heating, Refrigerating, and Air-Conditioning Engineers/Illuminating Engineering Society of North America.

simulations are intended to represent a cross section of common commercial building types and cover the building types that comprise 80% of new commercial construction floor area. The 16 prototype building models were reviewed extensively by building industry experts on the ASHRAE Standing Standard Project Committee (SSPC) 90.1 during development and assessment of multiple editions of Standard 90.1. These prototype models, their detailed characteristics, and their development are described in detail on the Building Energy Codes Program (BECP) web site.[2] A detailed description of the prototypes may also be found in the completed savings analysis of Standard 90.1-2010: *Energy and Cost Savings Analysis of ASHRAE Standard 90.1-2010*, which can be found on the BECP web site.[3] The prototype models described in that report have since been modified as described in the document *Enhancements to ASHRAE Standard 90.1 Prototype Building Models* (PNNL 2014b), also available at the same web site.

The energy analysis of the 16 prototype buildings shown in Table 2 was completed with the EnergyPlus building simulation program (DOE 2013). The results from that analysis are further analyzed to produce this end-use analysis. Each prototype building model is defined as characteristic of a certain class of buildings, mostly corresponding to a classification scheme established in the 2003 DOE/Energy Information Administration Commercial Building Energy Consumption Survey (EIA 2003). Building configurations of the prototype models are shown in Figure 1.

Table 2. ASHRAE commercial prototype building models

Building Type	Prototype building	Prototype Abbreviation	Prototype Floor Area (ft^2)
Office	Small Office	OfcS	5,502
	Medium Office	OfcM	53,628
	Large Office	OfcL	498,588
Retail	Stand-Alone Retail	RtlB	24,692
	Strip Mall	RtlS	22,500
School	Primary School	SchP	73,959
	Secondary School	SchS	210,887
Medical	Outpatient Health Care	MedC	40,946
	Hospital	MedH	241,501
Hotel	Small Hotel	HotS	43,202
	Large Hotel	HotL	122,120
Warehouse	Non-Refrigerated Warehouse	Whse, Wh	52,045
Food Service	Fast Food Restaurant	Fast	2,501
	Sit-Down Restaurant	Rest	5,502
Apartment	Mid-Rise Apartment	AptM	33,741
	High-Rise Apartment	AptH	84,360

[2] Prototype detail on BECP web site at www.energycodes.gov/development/commercial/90.1_models.
[3] BECP web site at www.energycodes.gov/achieving-30-goal-energy-and-cost-savings-analysis-ashrae-ASHRAE Standard-901-2010.

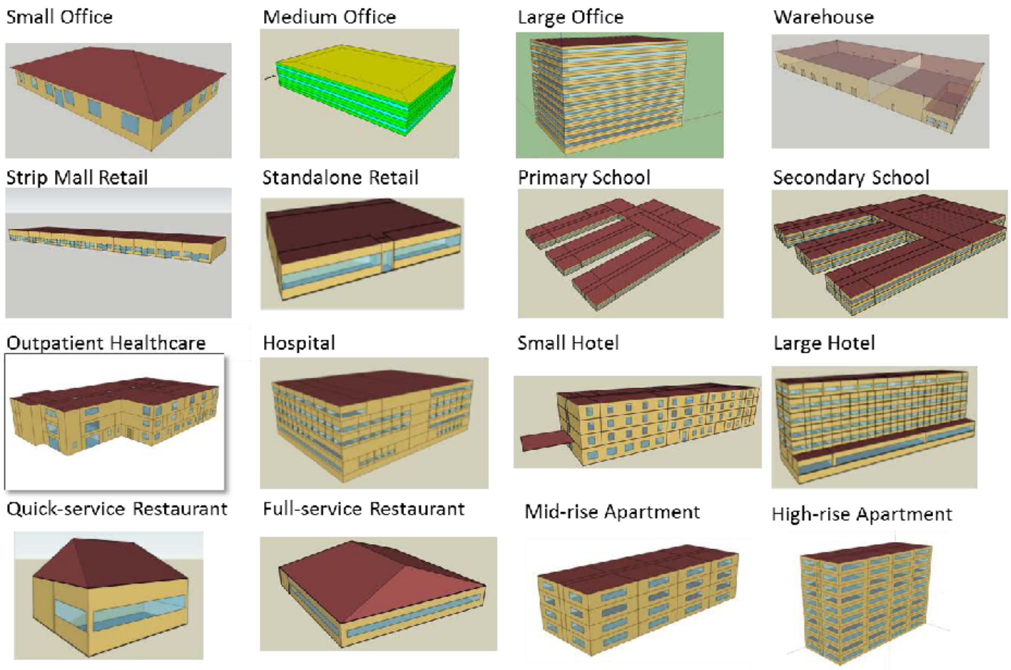


Figure 1. Prototypes analyzed for the end-use dataset

Detailed Tables and Lists

In addition to the graphs included here, an Excel workbook with detailed results for each prototype at the detailed end-use level is available online (PNNL 2014a).[4] That workbook contains a worksheet for each prototype and a matrix of tables with summary national results and detailed results for each climate zone. In addition to ECI, site energy use index (EUI) results, source EUI results, and gas and electric end-use results are included. The workbook also contains the following tables:

- U.S. average summary results, based on construction weighting,
- climate zone detail for Standard 90.1 in 2004, 2007, 2010, and 2013, and
- percentage savings from Standard 90.1-2004 to 90.1-2013.

The workbook also includes a worksheet (i.e., the "DetPri" tab) that provides all detailed ECIs by end use and prototype, sorted by remaining use after Standard 90.1-2013 and sorted by savings from Standard 90.1-2013 when compared to 90.1-2004.

[4] Available at http://www.energycodes.gov/sites/default/files/documents/2013EndUseTables.zip.

Cost Breakdown Results

The resulting data from the analysis is presented in one of several ways:

- Weighted by U.S. 2003–2007 new construction to give an idea of the impact on total U.S. commercial energy cost (Jarnagin and Bandyopadhyay 2010). Such weightings are usually for the nation as a whole, but may focus on energy cost for a particular climate zone. The weightings are based on factors shown in Table 8. Where results are noted as weighted by building type, this data is used. While the data is from early in the first decade of this millennium, it avoids the economic and construction downturn that would be inherent in more recent data.
- Partial weighting is applied to subset building prototypes to arrive at the use and cost breakdown for a building type. For instance, to find the end-use costs for the Office type, the end-use costs for the large, medium, and small offices are weighted proportionally by the individual prototype construction weightings.
- Unweighted results represent the end-use cost experienced by a particular building type and provide a good idea of the ECI on a floor area basis.

Throughout, the cost is based on the energy rates from the Scalar Method for Standard 90.1-2013 proposal analysis: 0.1032/kWh for electricity and $0.99/therm for fossil fuels.[5]

[5] The ASHRAE Scalar Method identifies a fossil fuel rate that is primarily applied to heating energy use. For this reason, the fossil fuel rate is a blended heating rate and includes proportional (relative to national heating fuel use) costs for natural gas, propane, heating oil, and electric heat. Heating energy use in the prototypes for fossil fuel equipment is calculated in therms based on natural gas equipment, but in practice, natural gas equipment may be operated on propane, or boilers that are modeled as natural gas may use oil in some regions.

U.S. End-Use Cost Breakdown, 90.1-2013

Figure 2 provides a breakdown of building energy costs after implementation of Standard 90.1-2013 across U.S. climate zones, weighted by U.S. new construction.

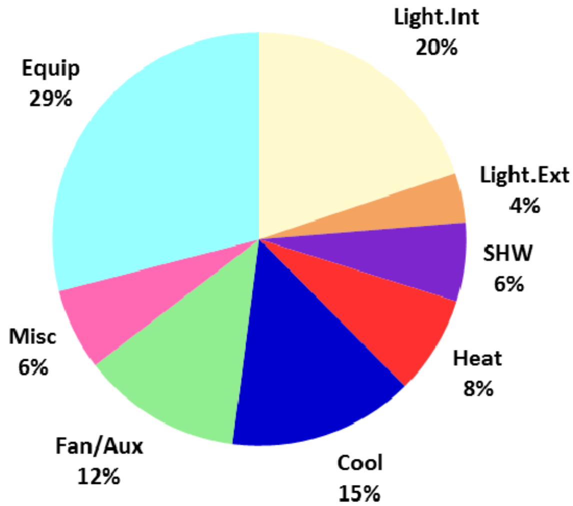


Figure 2. End-use cost for buildings in all U.S. climate zones

Figure 3 shows the same weighted national energy cost with a finer breakdown of end uses and an increase in significant digits for the percentages.

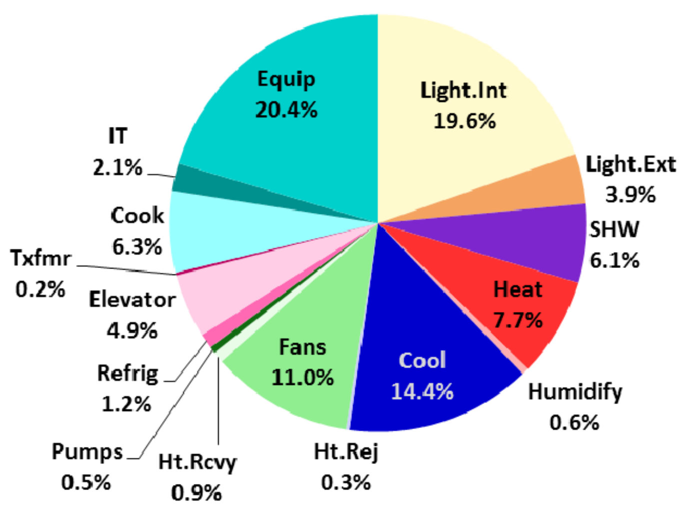


Figure 3. Detailed end-use cost for buildings in all U.S. climate zones

U.S. Weighted Cost by End Use, 2004 vs. 2013

Total U.S. weighted end-use building energy costs can be directly compared for Standards 90.1-2004 and 90.1-2013 (see Figure 4). Most categories show significant reduction; however, the cost reductions for equipment, miscellaneous, and service hot water were not significant.

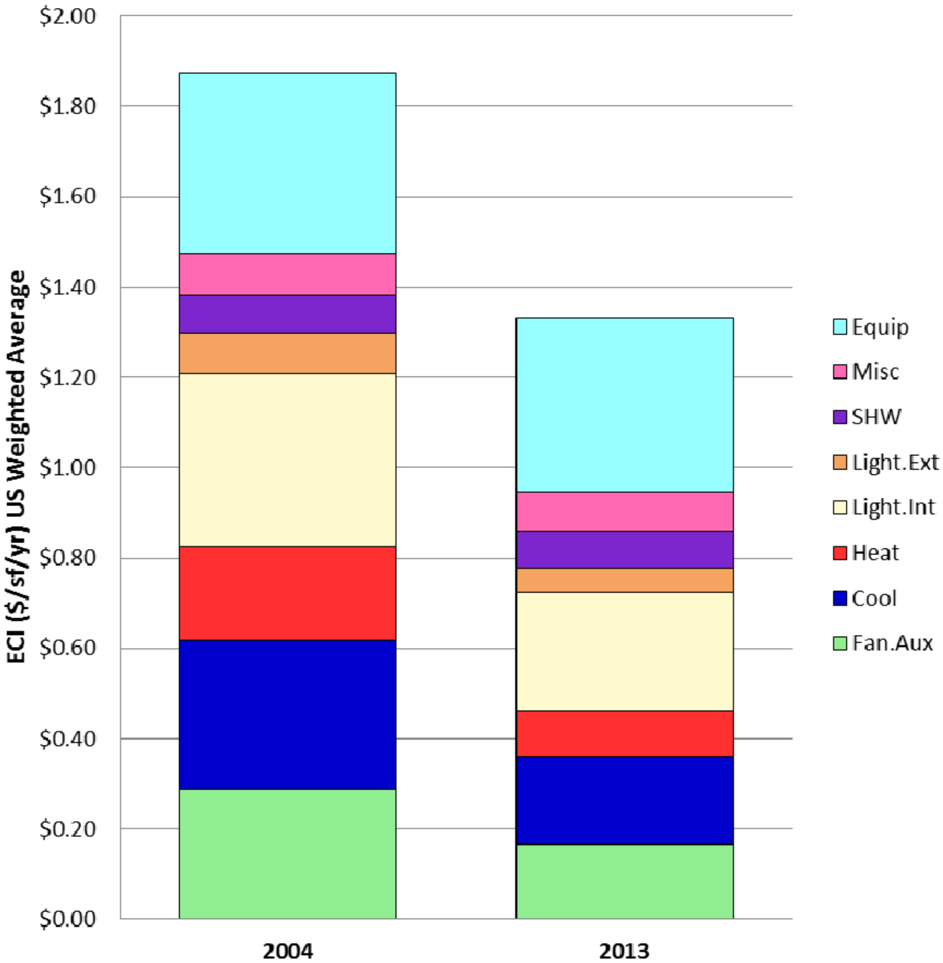


Figure 4. Standard 90.1 end-use cost improvement

U.S. Weighted Cost Impact by Building Type and End Use, 2013 Base

An examination of end-use cost data by building type is presented in this section. Figure 5 illustrates building type and energy cost impact weighted by national construction by climate zone. Prototypes are grouped by similar type. The widths of the building type (vertical) bars are scaled to represent each building type's share of impact on national building energy cost. The entire width of the plot matches national building energy use based on Standard 90.1-2013. Using the same 8.2 billion square feet of new building floor area from 2003−2007 construction data reports (Jarnagin and Bandyopadhyay 2010), the area of the plot represents a commercial new construction building energy cost of $11 billion per year.

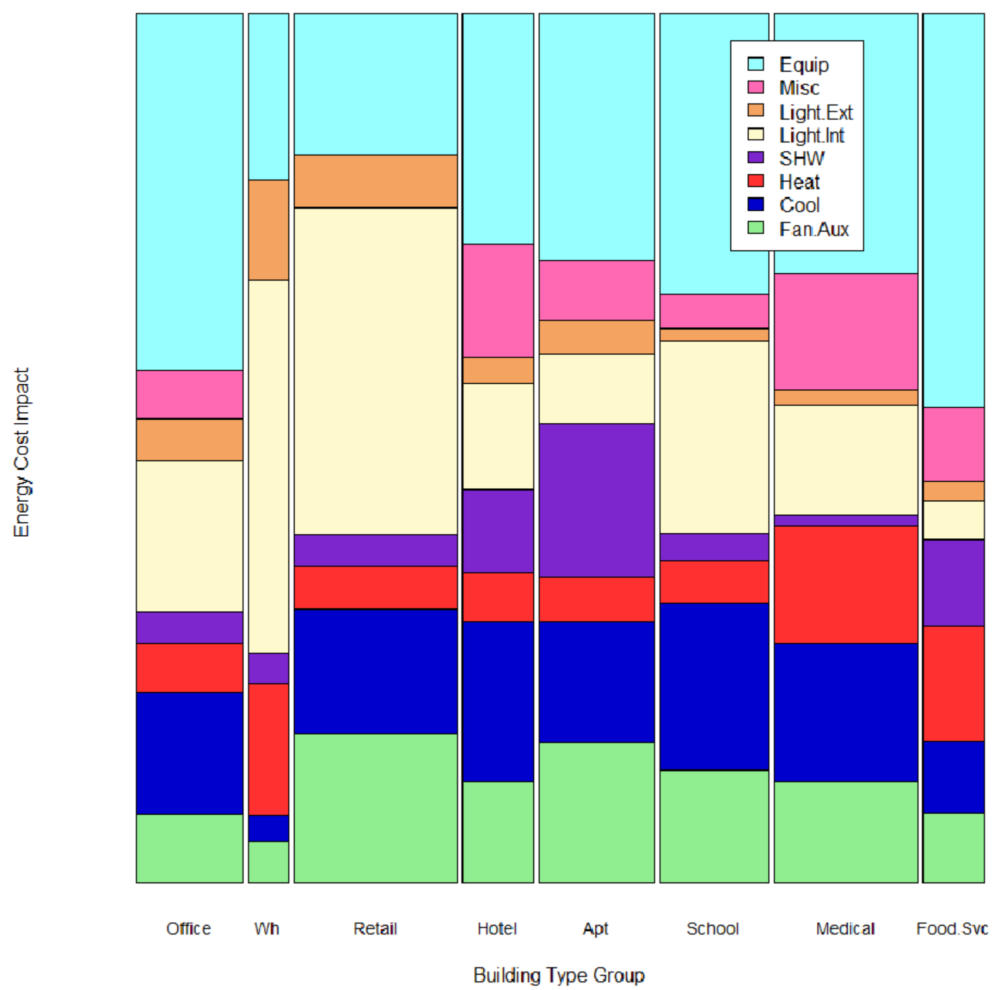


Figure 5. Commercial energy cost impact by end use U.S. weighted, after 90.1-2013

U.S. Weighted Cost Impact by Building Type and End Use, 2004 Base

Figure 6 shows the same nationally weighted results after Standard 90.1-2013 against a base of Standard 90.1-2004. Again, the widths of the building type (vertical) bars are scaled to represent each building type's share of impact on national building energy cost. The entire area of the plot matches national building energy cost based on Standard 90.1-2004, or $15.5 billion. The white savings blocks show the difference for 90.1-2013 compared to 90.1-2004, which amounts to $4.5 billion per year. So, we can see both the savings from the stable 2004 baseline and the remaining energy cost after 90.1-2013.

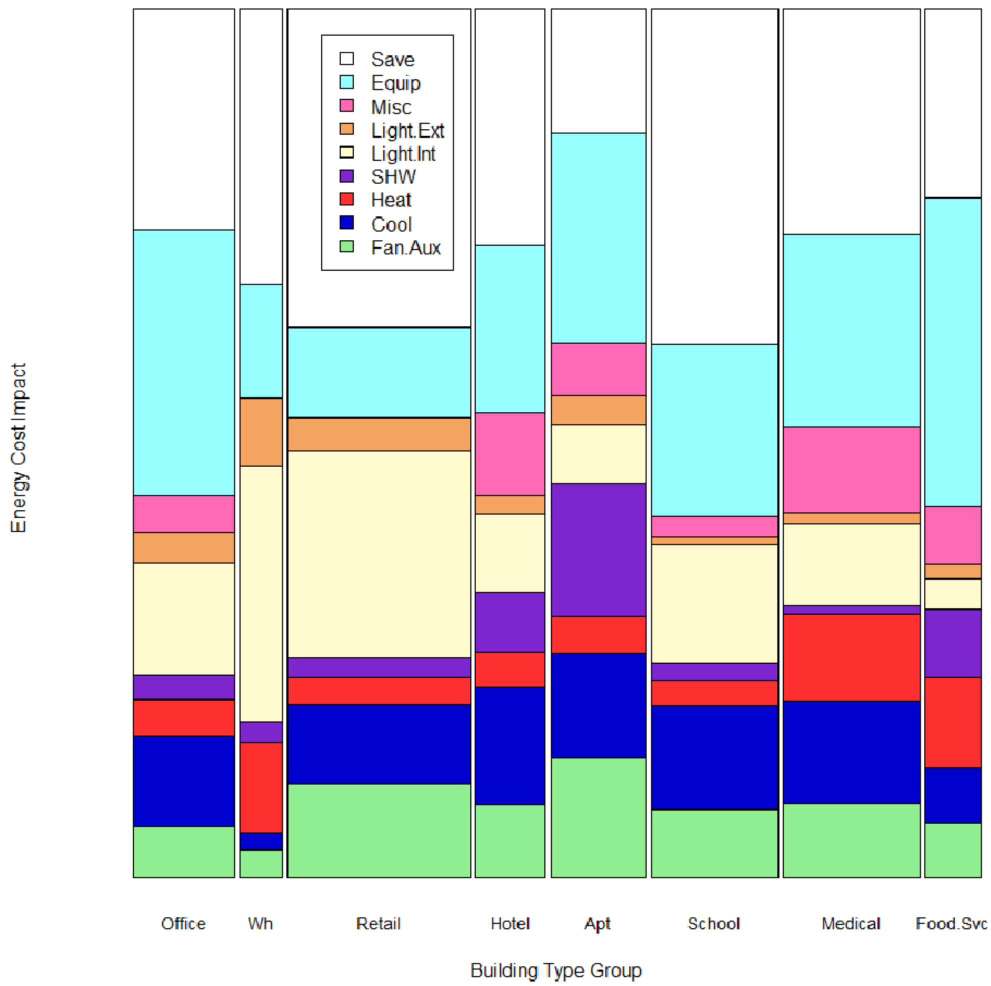


Figure 6. Commercial energy cost impact by end use U.S. weighted (90.1-2004).
White area represents savings from 90.1-2004 to 2013

U.S. Weighted End-Use Prioritization

Figure 7 shows overall progress by detailed end use, measured as cost savings from Standard 90.1-2004 to Standard 90.1-2013. The information is prioritized for end uses by national weighted building energy impact or percentage of U.S. total building use after Standard 90.1-2013.

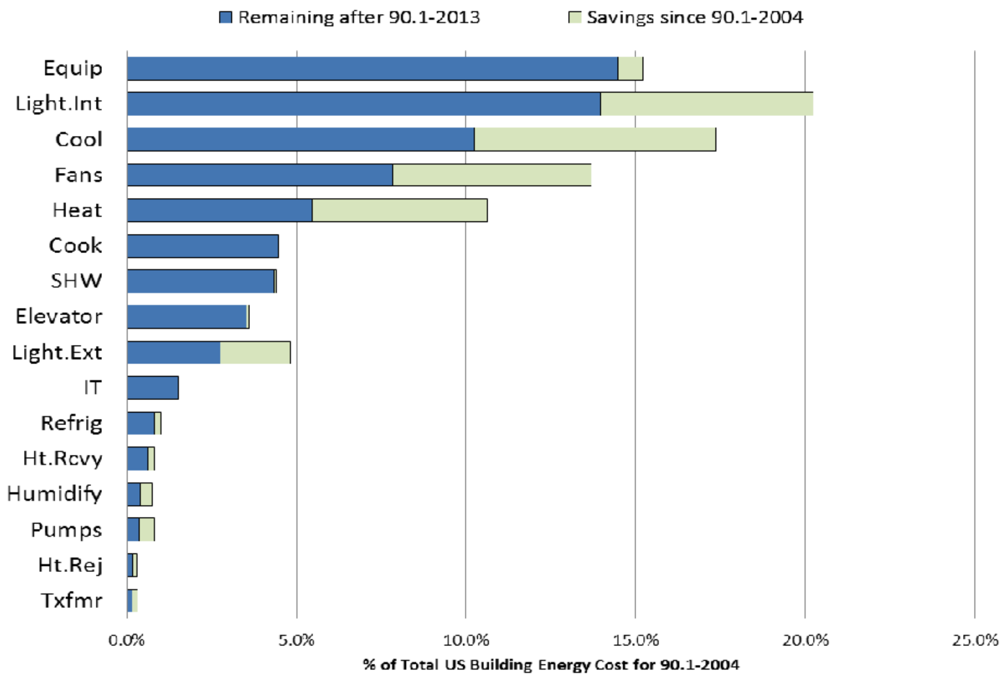


Figure 7. U.S. building energy cost by end use prioritized by post-2013 cost

Table 3 shows the breakdown by building type, with remaining energy cost after Standard 90.1-2013. Red indicates highest remaining cost impact, and white represents lowest remaining cost impact. Appendix A includes more detailed heat maps of costs and cost savings from Standard 90.1-2004 to Standard 90.1-2013.

Table 3. Impact percent of U.S. building energy cost remaining after 90.1-2013

	Light.Int	Light.Ext	SHW	Heat	Cool	Fan.Aux	Misc	Equip	Total
Office	2.3%	0.6%	0.5%	0.7%	1.8%	1.0%	0.7%	5.4%	13.1%
Warehouse	2.1%	0.6%	0.2%	0.8%	0.1%	0.2%	0.0%	0.9%	5.0%
Retail	7.6%	1.2%	0.7%	1.0%	2.9%	3.5%	0.0%	3.3%	20.2%
Hotel	1.1%	0.3%	0.8%	0.5%	1.6%	1.0%	1.1%	2.3%	8.8%
Apt	1.1%	0.6%	2.5%	0.7%	2.0%	2.3%	1.0%	4.0%	14.3%
School	3.0%	0.2%	0.4%	0.6%	2.6%	1.7%	0.5%	4.3%	13.5%
Medical	2.2%	0.3%	0.2%	2.4%	2.8%	2.1%	2.3%	5.3%	17.6%
Food.Svc	0.3%	0.2%	0.8%	1.0%	0.6%	0.6%	0.6%	3.4%	7.6%
U.S. Weighted	19.8%	3.9%	6.2%	7.7%	14.5%	12.5%	6.4%	29.0%	**100%**

Segment Graphs

Segment Graphs, ECI Weighted for Climate

The segment graphs for each building type (see Figure 8) show the relative end uses based on individual building ECI. Because they are weighted by climate zone construction, they represent national averages. The radius of each segment is proportional to the end-use ECI ($/ft^2/yr) for the building type shown, relative to the largest building end-use ECI in the data set. On this graph, most building graphs are quite small, but we can see the very high equipment, heating, and service water heating intensity in the food service sector. Following graphs show the other buildings and uses at a more readable scale.

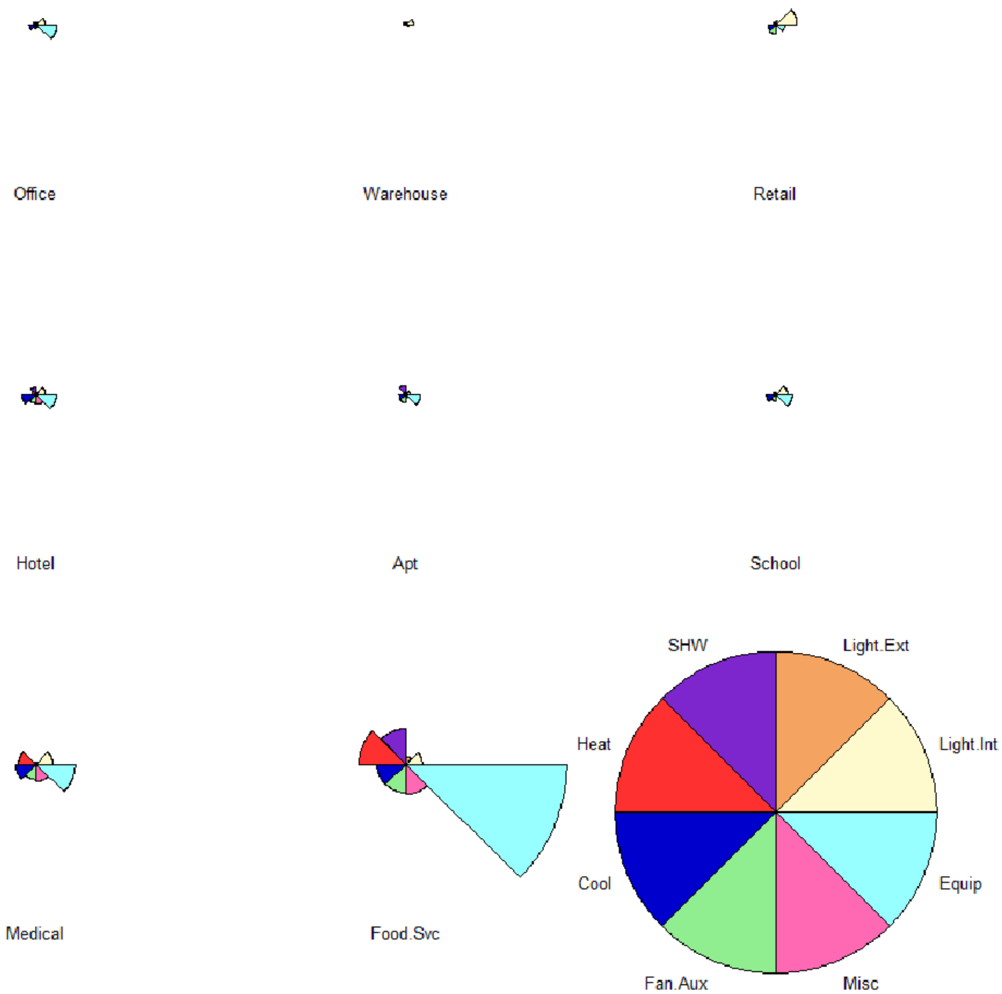


Figure 8. U.S. ECI of building end uses, after 90.1-2013

Segment Graphs, ECI by Climate with Scaled Food Equipment

Figure 9 is based on the same data as Figure 8 and shows the food service equipment (primarily cooking) at one-fourth the scale of the other segments. The radius of each segment is proportional to the end-use ECI for the building type shown, relative to the largest full-scale building end-use ECI in the data set (Food.Svc heat).

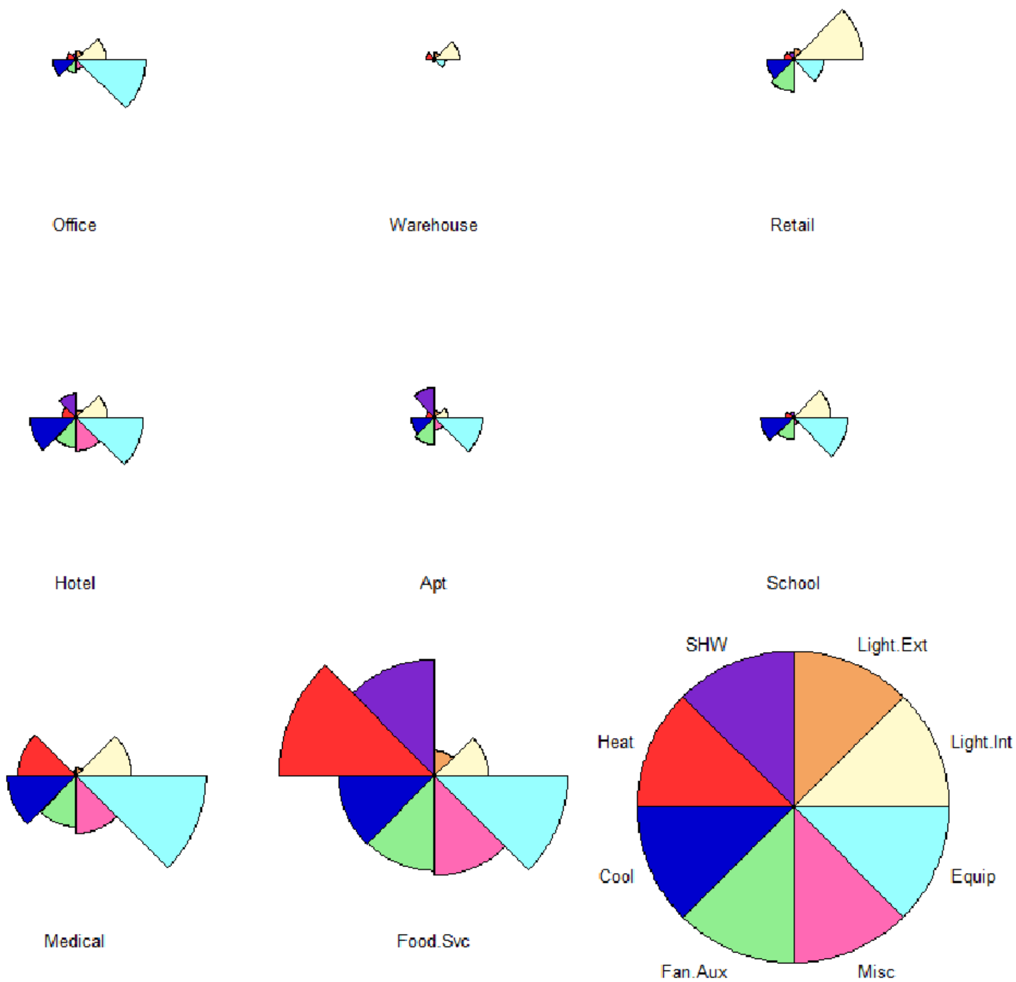


Figure 9. U.S. ECI of building end uses, after 90.1-2013 (Cooking NTS). (Food service equipment is shown at 25% of actual scale.)

Segment Graphs, ECI Weighted for U.S. Construction

When individual building ECI results are weighted by each building's share of new construction floor area (see Figure 10), the impact on total U.S. commercial building cost by type and end use becomes apparent. This result can be referred to as the weighted building cost index (WBCI). Retail interior lighting has the largest contributing end use. Equipment dominates in most other areas; however, service water heating captures a large segment of contributing end use for apartments.

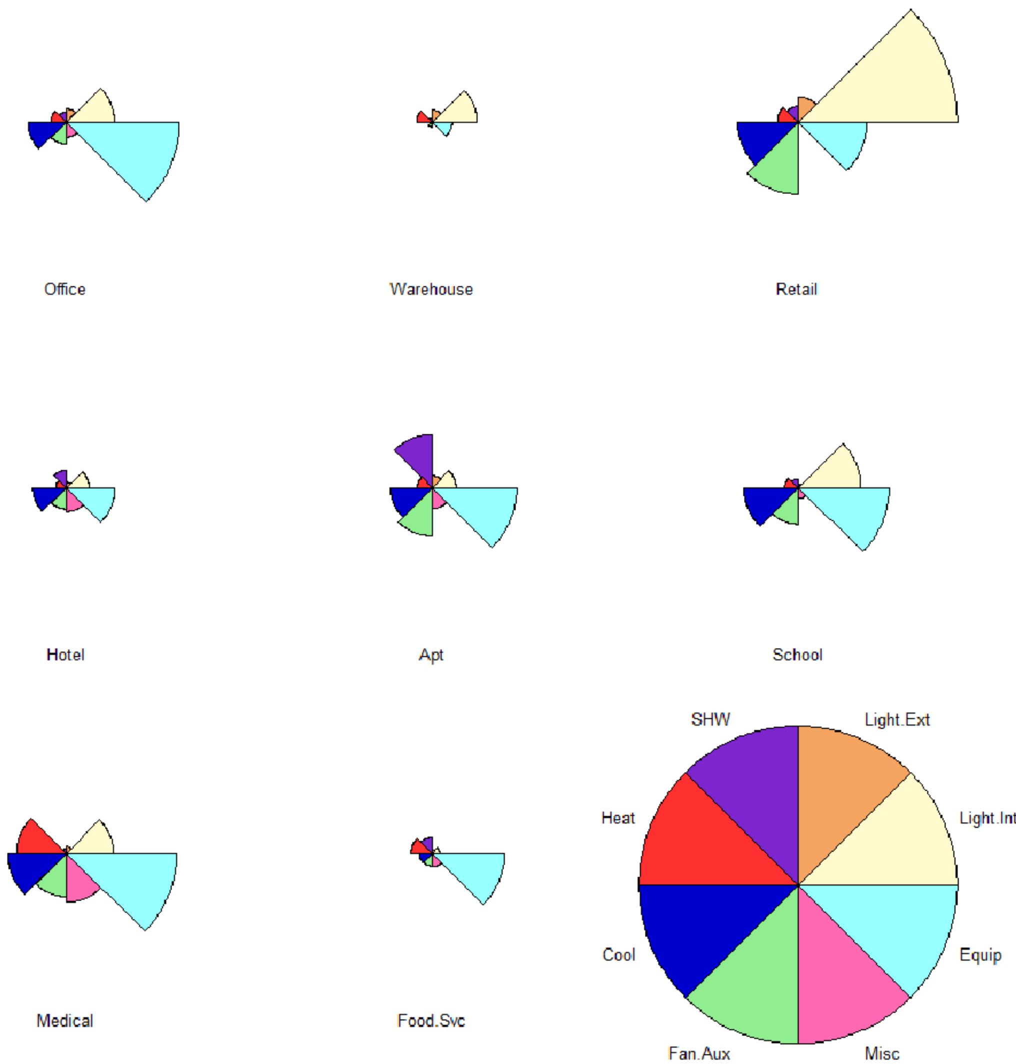


Figure 10. U.S. WBCI of building end uses, after 90.1-2013.
(WBCI = weighted building cost impact or contribution to total energy cost)

U.S. Weighted Sorted End Use ECI, with Building Splits

Figure 11 breaks down end uses based on overall weighted U.S. impact (from largest to smallest impact) and shows the breakdown in each bar by building. Separating equipment and miscellaneous (e.g., transformers, refrigeration, and elevators) helps identify which unregulated loads are impacted.

Though units are in dollars per square foot contribution to an average U.S. building (i.e., a weighted combination of all building types), it may be easier to think of this graph as showing a relative impact factor, since the results are partial. That is, the sum of all end uses shown would equal the weighted average U.S. building ECI based on total construction, or about $1.33 per square foot.

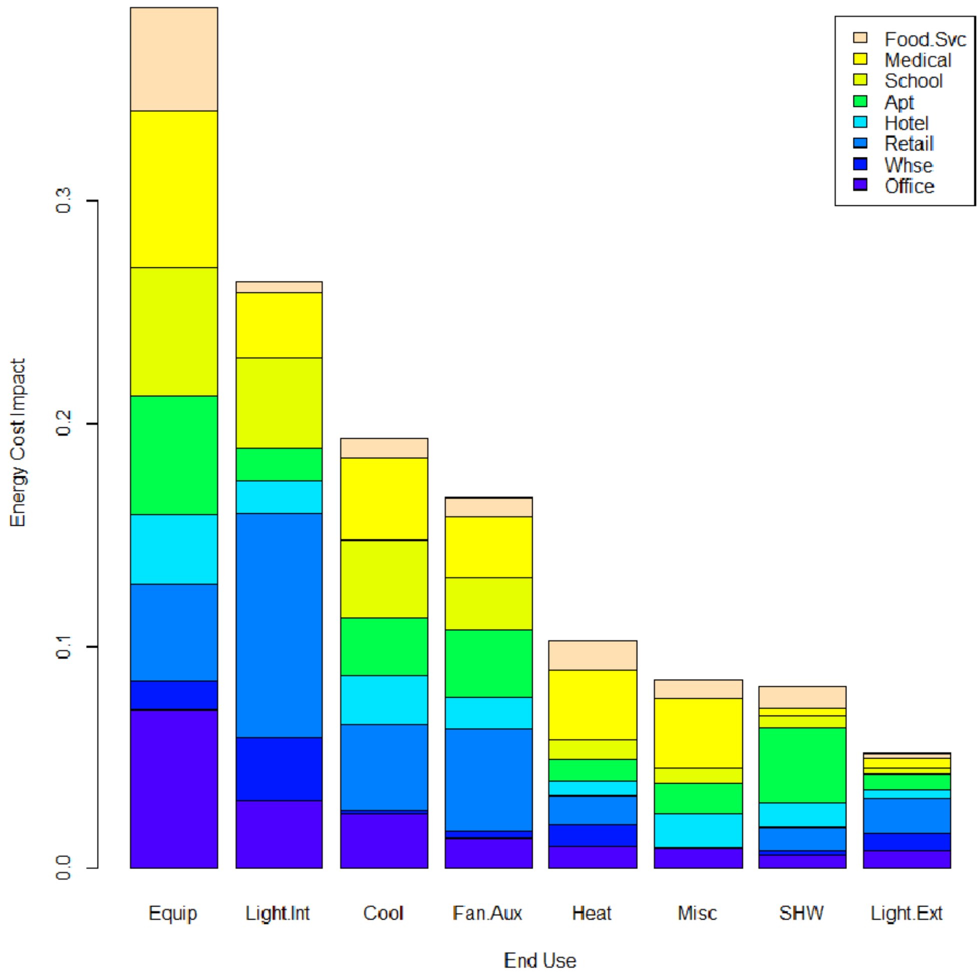


Figure 11. U.S. commercial energy cost impact by end use (weighted by new construction floor area)

Total U.S. Energy Cost by Building Type

Figure 12 shows energy costs following the implementation of Standard 90.1-2013 by building type group weighted for all climate zones. Energy cost savings from Standard 90.1-2004 vs. 90.1-2013 are also shown. Figure 12 indicates that energy cost intensity for food service is highest, based primarily on the high energy density of fast food restaurants. Medical is next, followed by hotel, retail, and office. Appendix B provides separate graphs for each end use to better illustrate the distribution of individual end-use costs by building type.

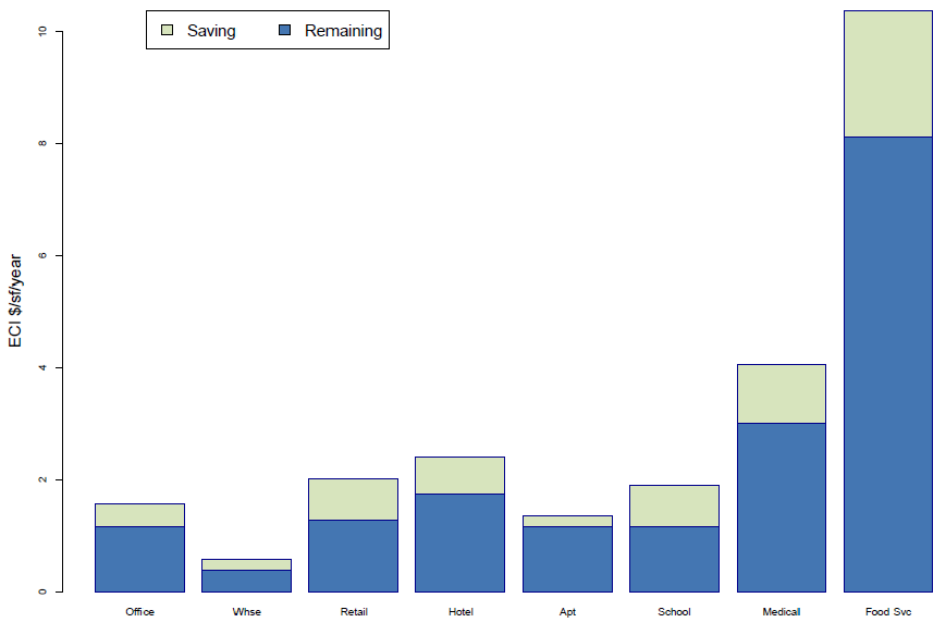


Figure 12. Total Standard 90.1-2013 vs 90.1-2004; U.S. energy cost

Focus Potential Score

The focus potential scoring method was developed, using a somewhat arbitrary numerical approach, to help focus on end uses where there may be future savings potential. While scores are simply numerical and do not include judgment about what is possible or an analysis of maximum technical potential, they provide a second look at end uses we might have dismissed. For example, the equipment end-use scores high, even though it has been considered an "unregulated" load. The focus potential scoring method combines the three factors shown in Table 4.

Table 4. Focus potential scoring method factors

Weight	Focus	Low score	High score
6	Savings from 90.1-2004 to 90.1-2013	Low (2) if high previous savings	High (6) if little previous savings
3	Individual building end-use cost (ECI)	Low (0) if building ECI low	High (3) if building ECI high
3	National end-use cost (ECI)	Low (0) if national ECI low	High (3) if national ECI high

Although the focus potential scoring approach is not perfect, it draws attention to the end uses that have not had large savings historically and that have high building-level ECI and high national weighted impact. In the heat map of focus potential scoring results (see Table 5), green indicates areas that may have high savings potential, and white indicates areas that have lower savings potential. Focus Potential Scores are rolled up at the simple end-use level and for building groups rather than the detailed level as many of the detailed uses are so small, they would score zero. Because restaurant and equipment end uses are outliers, their partial scores are capped at the maximum. The Focus Potential Scores are shown in Table 5 and charted in Figure 13 at the end-use level overall for all building types.

Table 5. Total end-use "Focus Potential Scores"

Potential	Light.Int	Light.Ext	SHW	Heat	Cool	Fan.Aux	Misc	Equip
Office	5.9	3.5	6.4	4.1	5.3	5.4	6.1	10.8
Warehouse	5.7	4.4	6.0	4.4	3.2	3.1		6.7
Retail	10.5	4.0	6.3	2.8	5.2	5.6		8.6
Hotel	5.5	4.9	7.3	3.3	6.4	4.9	7.5	9.5
Apt	6.6	4.5	8.3	4.1	6.0	6.8	6.5	9.6
School	6.1	3.2	6.3	3.0	5.3	4.4	5.3	9.5
Medical	8.2	3.5	6.3	6.0	8.0	6.9	9.2	11.0
Food.Svc	4.7	4.5	9.3	8.4	7.1	5.8	7.9	10.4
U.S. Weighted	7.1	4.0	6.7	3.8	5.3	5.2	4.1	9.2

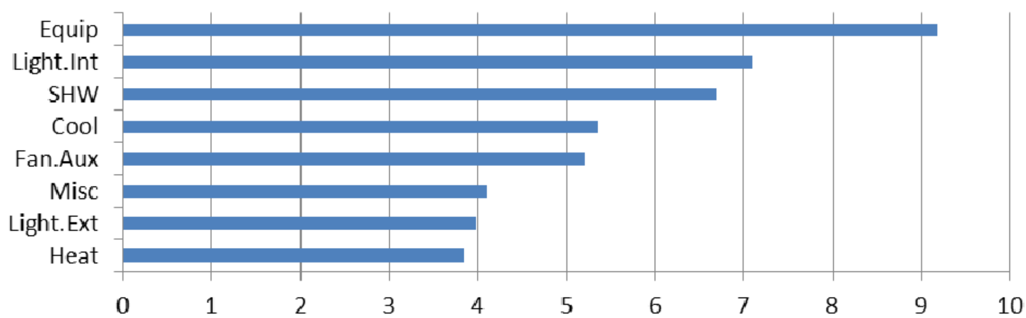


Figure 13. Total end-use "Focus Potential Scores," prioritized

HVAC by Climate Zone

The heating and cooling ECIs by climate zone (weighted by building type construction within each climate zone) are shown in Figure 14. Climate zones are grouped by moisture regime, and climate zones 1B and 5C are excluded because they have no U.S. construction. Heat rejection is included with cooling, but humidification is not included.

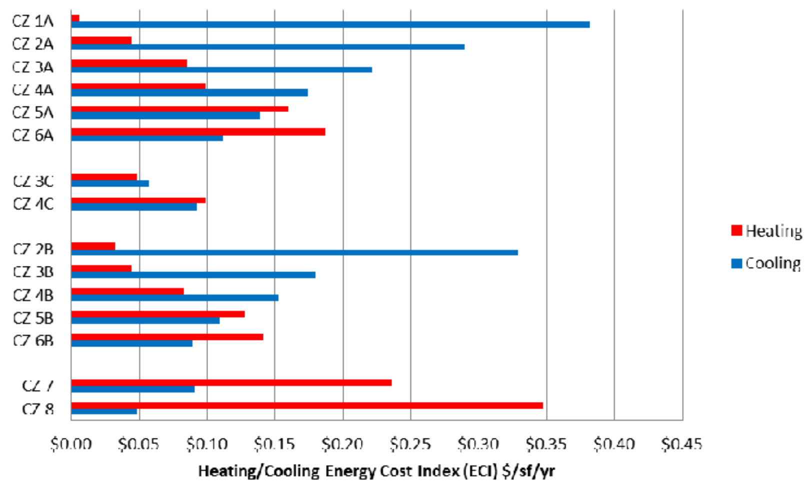


Figure 14. Building ECI heating and cooling by climate zone (CZ)

While Figure 14 shows individual climate zone ECIs, Figure 15 shows the relative contribution of each climate zone's heating and cooling to the total U.S. energy cost. This graph indicates that reducing heating in climate zone 5A is more important than reducing heating in climate zones 6, 7, or 8.

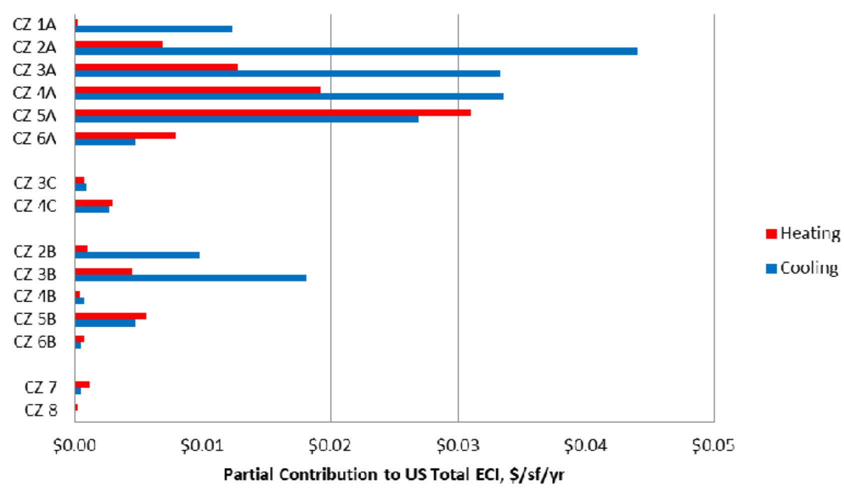
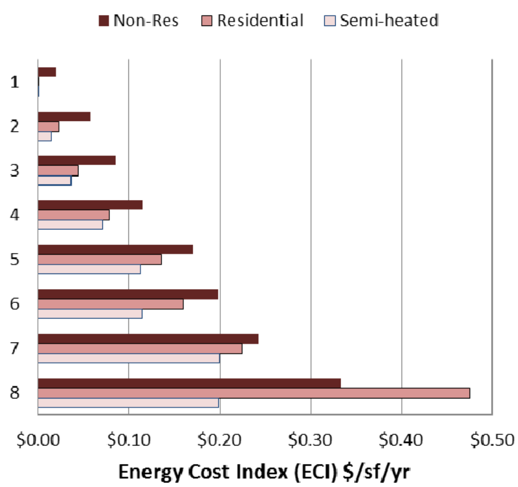


Figure 15. Weighted impact of climate zone heating and cooling on U.S. heating and cooling costs

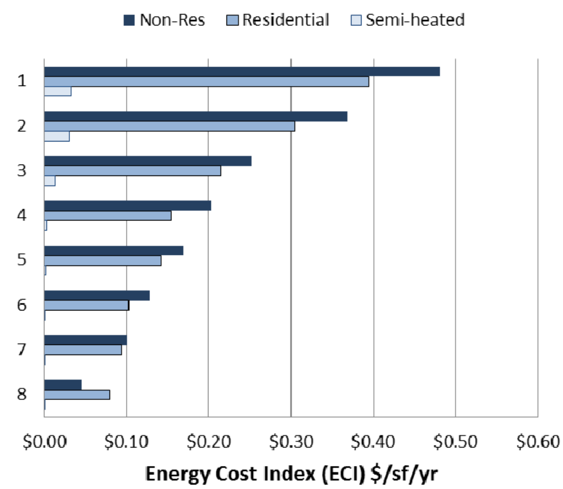
16

HVAC Building ECI by Numerical Climate Zone and Space Conditioning Category

To more closely evaluate the prescriptive insulation categories in Standard 90.1, the heating and cooling data was split by building category and numerical climate zone (without moisture regimes). Climate zones 1B and 5C are not included because there are no U.S. locations. Heating and cooling energy cost indices, by climate zone, are shown in Figure 16. Apartments and hotels are grouped in the residential category, warehouses in the semi-heated category, and all other buildings in the non-residential category. Note that although some residential areas exist in hospitals, some non-residential areas can be found in large hotels, and only about half of the warehouse prototypes are semi-heated; this grouping used in Figure 16 is based on the predominant category in each individual building type. In addition, different building types have different HVAC systems and ventilation or other HVAC differences, but are not excluded from this analysis. Further, heat rejection is included with cooling, but humidification is not included.



(a) heating

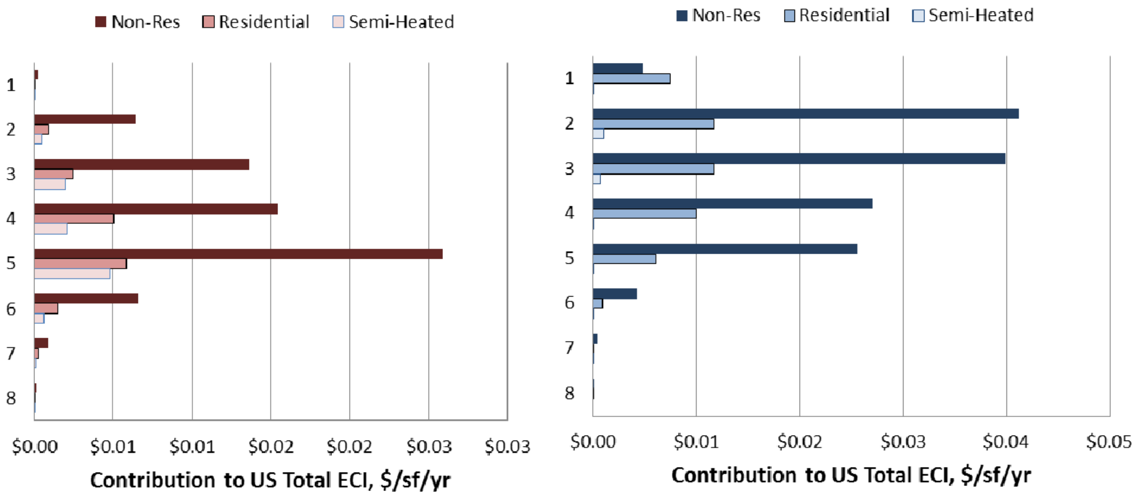


(b) cooling

Figure 16. Total (a) heating and (b) cooling ECI by climate zone

HVAC Weighted Cost Impact by Numerical Climate Zone and Space Conditioning Category

While Figure 16 shows individual climate zone building ECIs (weighted for building type construction in each numerical climate zone), Figure 17 shows the relative contribution of each climate zone’s heating and cooling to the total U.S. energy cost. Groupings for building type and climate zone are the same as in Figure 16. Figure 17 indicates the importance of reducing heating in climate zone 5 and the cooling in zones 2 and 3.



(a) heating (b) cooling

Figure 17. Weighted impacts on total U.S. (a) heating and (b) cooling costs

Heating ECI Detail by Climate Zone

A heat map (see Table 6) is used to display detailed heating ECI by climate zone. Darker red indicates a higher heating cost for the building type and climate zone. Because these values are not weighted, all climate zones are included. Heat map shading is provided separately for the medical and restaurant groups because their heating costs are much higher than the other building prototypes. Again, humidification energy is not included with heating.

Table 6. Heating ECI detail by climate zone

	Moist Climates						Marine Climates			Dry Climates						Cold	
Building	CZ 1A	CZ 2A	CZ 3A	CZ 4A	CZ 5A	CZ 6A	CZ 3C	CZ 4C	CZ 5C	CZ 1B	CZ 2B	CZ 3B	CZ 4B	CZ 5B	CZ 6B	CZ 7	CZ 8
AptH	$0.000	$0.021	$0.080	$0.089	$0.175	$0.202	$0.018	$0.059	$0.095	$0.001	$0.002	$0.016	$0.022	$0.069	$0.112	$0.270	$0.373
AptM	$0.000	$0.011	$0.043	$0.057	$0.108	$0.126	$0.010	$0.040	$0.061	$0.001	$0.002	$0.011	$0.020	$0.048	$0.079	$0.171	$0.250
HotL	$0.016	$0.059	$0.101	$0.096	$0.143	$0.167	$0.078	$0.096	$0.115	$0.031	$0.029	$0.044	$0.059	$0.101	$0.141	$0.200	$0.398
HotS	$0.001	$0.023	$0.072	$0.119	$0.211	$0.249	$0.016	$0.079	$0.106	$0.004	$0.009	$0.026	$0.057	$0.109	$0.181	$0.339	$0.547
OfcL	$0.000	$0.012	$0.042	$0.057	$0.101	$0.121	$0.004	$0.023	$0.033	$0.005	$0.004	$0.008	$0.016	$0.035	$0.089	$0.159	$0.248
OfcM	$0.004	$0.043	$0.105	$0.087	$0.160	$0.188	$0.029	$0.079	$0.108	$0.011	$0.019	$0.032	$0.039	$0.092	$0.146	$0.184	$0.342
OfcS	$0.000	$0.009	$0.030	$0.031	$0.055	$0.071	$0.007	$0.019	$0.027	$0.001	$0.003	$0.013	$0.018	$0.031	$0.056	$0.102	$0.173
RtlB	$0.002	$0.011	$0.028	$0.039	$0.069	$0.082	$0.031	$0.081	$0.114	$0.014	$0.014	$0.027	$0.050	$0.106	$0.052	$0.123	$0.255
RtlS	$0.003	$0.036	$0.095	$0.134	$0.228	$0.278	$0.039	$0.111	$0.164	$0.008	$0.015	$0.030	$0.047	$0.129	$0.206	$0.362	$0.577
SchP	$0.017	$0.058	$0.095	$0.117	$0.145	$0.172	$0.064	$0.120	$0.093	$0.018	$0.025	$0.053	$0.082	$0.130	$0.130	$0.212	$0.388
SchS	$0.001	$0.010	$0.027	$0.021	$0.039	$0.050	$0.048	$0.107	$0.049	$0.011	$0.016	$0.044	$0.076	$0.130	$0.038	$0.075	$0.228
Whse	$0.000	$0.016	$0.044	$0.073	$0.120	$0.118	$0.045	$0.062	$0.073	$0.004	$0.011	$0.026	$0.048	$0.070	$0.084	$0.199	$0.199
MedC	$0.233	$0.317	$0.394	$0.316	$0.384	$0.415	$0.225	$0.279	$0.292	$0.236	$0.220	$0.224	$0.250	$0.315	$0.381	$0.459	$0.711
MedH	$0.159	$0.222	$0.279	$0.323	$0.375	$0.412	$0.234	$0.285	$0.318	$0.189	$0.191	$0.213	$0.200	$0.321	$0.360	$0.461	$0.653
Rest	$0.052	$0.308	$0.616	$0.916	$1.333	$1.584	$0.566	$0.911	$1.093	$0.101	$0.185	$0.349	$0.586	$0.971	$1.353	$2.047	$3.119
Fast	$0.181	$0.645	$1.144	$1.530	$2.143	$2.501	$1.057	$1.478	$1.753	$0.284	$0.443	$0.773	$1.104	$1.641	$2.223	$3.193	$4.718

Cooling ECI Detail by Climate Zone

A heat map (Table 7) is also used to show detailed cooling ECI by climate zone. Darker blue indicates a higher cooling cost for the building type and climate zone. Because these values are not weighted, all climate zones are included. Heat map shading is provided separately for the medical and restaurant groups because their cooling costs are much higher than the other building prototypes.

Table 7. Cooling ECI detail by climate zone

	Moist Climates						Marine Climates			Dry Climates						Cold	
Building	CZ 1A	CZ 2A	CZ 3A	CZ 4A	CZ 5A	CZ 6A	CZ 3C	CZ 4C	CZ 5C	CZ 1B	CZ 2B	CZ 3B	CZ 4B	CZ 5B	CZ 6B	CZ 7	CZ 8
AptH	$0.381	$0.245	$0.182	$0.146	$0.113	$0.070	$0.007	$0.076	$0.040	$0.344	$0.294	$0.168	$0.157	$0.112	$0.077	$0.059	$0.055
AptM	$0.275	$0.185	$0.141	$0.108	$0.086	$0.058	$0.021	$0.060	$0.036	$0.280	$0.235	$0.132	$0.115	$0.083	$0.059	$0.045	$0.038
HotL	$0.862	$0.611	$0.464	$0.318	$0.260	$0.183	$0.116	$0.163	$0.105	$0.775	$0.603	$0.371	$0.272	$0.201	$0.142	$0.145	$0.098
HotS	$0.405	$0.299	$0.229	$0.170	$0.139	$0.106	$0.116	$0.116	$0.087	$0.364	$0.323	$0.213	$0.164	$0.124	$0.096	$0.086	$0.062
OfcL	$0.473	$0.365	$0.309	$0.268	$0.173	$0.133	$0.083	$0.118	$0.073	$0.449	$0.352	$0.250	$0.187	$0.144	$0.109	$0.103	$0.070
OfcM	$0.362	$0.270	$0.202	$0.151	$0.131	$0.088	$0.052	$0.084	$0.046	$0.359	$0.309	$0.178	$0.139	$0.098	$0.068	$0.065	$0.035
OfcS	$0.190	$0.142	$0.107	$0.083	$0.070	$0.051	$0.038	$0.051	$0.037	$0.193	$0.170	$0.105	$0.087	$0.060	$0.046	$0.040	$0.029
RtlB	$0.442	$0.279	$0.214	$0.156	$0.124	$0.079	$0.036	$0.074	$0.027	$0.515	$0.365	$0.205	$0.148	$0.104	$0.070	$0.053	$0.031
RtlS	$0.435	$0.328	$0.220	$0.147	$0.113	$0.073	$0.028	$0.073	$0.029	$0.472	$0.391	$0.185	$0.134	$0.100	$0.064	$0.048	$0.022
SchP	$0.435	$0.319	$0.242	$0.189	$0.158	$0.111	$0.070	$0.095	$0.073	$0.396	$0.350	$0.202	$0.139	$0.106	$0.086	$0.084	$0.049
SchS	$0.487	$0.356	$0.276	$0.205	$0.167	$0.113	$0.075	$0.104	$0.064	$0.452	$0.384	$0.233	$0.162	$0.128	$0.085	$0.085	$0.042
Whse	$0.033	$0.021	$0.014	$0.004	$0.002	$0.000	$0.000	$0.000	$0.000	$0.130	$0.073	$0.014	$0.004	$0.002	$0.000	$0.000	$0.000
MedC	$1.159	$0.909	$0.721	$0.546	$0.456	$0.361	$0.357	$0.341	$0.262	$0.937	$0.850	$0.577	$0.440	$0.337	$0.260	$0.303	$0.209
MedH	$0.785	$0.584	$0.449	$0.339	$0.299	$0.228	$0.158	$0.187	$0.150	$0.456	$0.425	$0.312	$0.218	$0.192	$0.145	$0.177	$0.116
Rest	$1.532	$1.077	$0.766	$0.422	$0.314	$0.173	$0.037	$0.161	$0.029	$1.528	$1.284	$0.659	$0.332	$0.239	$0.132	$0.096	$0.035
Fast	$1.932	$1.380	$0.977	$0.537	$0.396	$0.210	$0.046	$0.194	$0.032	$1.908	$1.606	$0.775	$0.425	$0.305	$0.164	$0.114	$0.038

Construction Weightings by Building Type and Climate Zone

To estimate the energy savings impact on a national scale, PNNL acquired disaggregated construction volume data from McGraw-Hill Construction (MHC) Project Starts Database. The MHC database contains the floor area of new construction in the United States for the years 2003 to 2007. PNNL analyzed this MHC database to develop detailed construction weights by climate zones, subzones, and states (Jarnagin and Bandyopadhyay 2010). These weights were used in developing a weighted national energy savings estimate for the impact of ASHRAE standards. Table 8 summarizes the percentage weights by building type and climate zone. The 16 prototypes cover 80% of new construction floor area and percentages; however, percentages in Table 8 have been normalized to result in 100% coverage. Weightings have been applied in the following three ways:

- For national results, weightings in Table 8 were applied to individual results for each building type and climate zone.
- For average building type results, normalized climate zone weightings, totaling 100% for each building type or group, were applied.
- For heating and cooling results within each climate zone, normalized building type results were applied.

Table 8. U.S. new construction weighting (basis 2003 to 2007 MHC database)

Building	Moist Climates						Marine Climates			Dry Climates						General		U.S.
Type	CZ 1A	CZ 2A	CZ 3A	CZ 4A	CZ 5A	CZ 6A	CZ 3C	CZ 4C	CZ 5C	CZ 1B	CZ 2B	CZ 3B	CZ 4B	CZ 5B	CZ 6B	CZ 7	CZ 8	All CZ
AptH	1.5%	1.5%	0.7%	2.5%	1.2%	0.1%	0.2%	0.4%	0.0%	0.0%	0.1%	0.7%	0.0%	0.1%	0.0%	0.0%	0.0%	9.0%
AptM	0.3%	1.1%	0.8%	1.7%	1.1%	0.3%	0.3%	0.4%	0.0%	0.0%	0.1%	0.9%	0.0%	0.3%	0.1%	0.0%	0.0%	7.3%
HotL	0.1%	0.6%	0.6%	1.0%	0.9%	0.2%	0.1%	0.1%	0.0%	0.0%	0.1%	0.8%	0.0%	0.2%	0.1%	0.0%	0.0%	5.0%
HotS	0.0%	0.3%	0.3%	0.3%	0.4%	0.1%	0.0%	0.0%	0.0%	0.0%	0.0%	0.1%	0.0%	0.1%	0.0%	0.0%	0.0%	1.7%
OfcL	0.1%	0.3%	0.4%	1.1%	0.4%	0.1%	0.1%	0.2%	0.0%	0.0%	0.1%	0.3%	0.0%	0.1%	0.0%	0.0%	0.0%	3.3%
OfcM	0.1%	0.8%	0.8%	1.2%	1.1%	0.3%	0.1%	0.2%	0.0%	0.0%	0.3%	0.7%	0.0%	0.3%	0.0%	0.0%	0.0%	6.0%
OfcS	0.1%	1.1%	1.0%	0.9%	0.9%	0.2%	0.1%	0.1%	0.0%	0.0%	0.3%	0.5%	0.0%	0.3%	0.0%	0.0%	0.0%	5.6%
RtlB	0.2%	2.2%	2.4%	2.5%	3.4%	0.9%	0.2%	0.4%	0.0%	0.0%	0.5%	1.3%	0.1%	0.8%	0.1%	0.1%	0.0%	15.3%
RtlS	0.1%	1.0%	1.0%	1.0%	1.0%	0.2%	0.1%	0.1%	0.0%	0.0%	0.3%	0.6%	0.0%	0.2%	0.0%	0.0%	0.0%	5.7%
SchP	0.1%	0.9%	0.9%	0.9%	0.9%	0.2%	0.0%	0.1%	0.0%	0.0%	0.2%	0.4%	0.0%	0.2%	0.0%	0.0%	0.0%	5.0%
SchS	0.2%	1.5%	1.9%	2.0%	2.3%	0.4%	0.1%	0.2%	0.0%	0.0%	0.2%	0.8%	0.1%	0.4%	0.1%	0.1%	0.0%	10.4%
Whse	0.3%	2.6%	3.0%	2.4%	3.6%	0.5%	0.2%	0.4%	0.0%	0.0%	0.6%	2.3%	0.1%	0.7%	0.0%	0.0%	0.0%	16.7%
MedC	0.0%	0.6%	0.6%	0.8%	1.1%	0.3%	0.1%	0.2%	0.0%	0.0%	0.1%	0.3%	0.0%	0.2%	0.0%	0.0%	0.0%	4.4%
MedH	0.0%	0.5%	0.5%	0.6%	0.8%	0.2%	0.0%	0.1%	0.0%	0.0%	0.1%	0.3%	0.0%	0.2%	0.0%	0.0%	0.0%	3.4%
Rest	0.0%	0.1%	0.1%	0.1%	0.1%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.7%
Fast	0.0%	0.1%	0.1%	0.1%	0.1%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.1%	0.0%	0.0%	0.0%	0.0%	0.0%	0.6%
All Bldg	3.2%	15.2%	15.0%	19.3%	19.4%	4.2%	1.6%	3.0%	0.0%	0.0%	3.0%	10.1%	0.5%	4.3%	0.6%	0.5%	0.1%	100%

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Appendix A

Heat Maps

E10085Text Modification

Mod_10085_Text_PNNL - End-Use Opportunity Analysis from Progress Indicator Results for ASHRAE Standard 90.1-2013.pdf

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Appendix A

Heat Maps

The heat maps presented in this appendix provide multiple views of prototypes by end use. The term “heat map” does not relate to the heating end use, but to a representation of relative intensity of a factor by color. Two types of heat maps (i.e., cost and savings) are used here:

- Cost heat maps: In the cost heat maps, red indicates the highest remaining cost impact and white indicates lowest remaining cost impact. Darker reds indicate higher remaining cost and, thus, a higher potential for future savings.
- Savings heat maps: In the savings heat maps, green indicates the higher cost savings from Standard 90.1-2004 to Standard 90.1-2013 and red indicates lower cost savings. Darker reds indicate a lower savings to date and, thus, a possible higher potential for future savings.

Some of the heat maps are weighted by construction and some represent individual building constructions. The weighting conditions are noted with each map. Likewise, building types and end uses presented as detailed or in groups, as noted.

Energy Cost Index by Building Type and End Use

Table A.1 shows ECI results grouped by building and end use after Standard 90.1-2013; Table A.2 shows the detailed results. Results in this section relate to the prototype independently except the last row (U.S. Weighted), which is weighted for both climate and prototype. The results are national, weighted by relative construction of each prototype in each climate zone.

Table A.1. ECI ($/ft²/yr) remaining after 90.1-2013, by building group and end use

	Light.Int	Light.Ext	SHW	Heat	Cool	Fan.Aux	Misc	Equip	Total
Office	$0.203	$0.055	$0.043	$0.066	$0.164	$0.093	$0.065	$0.479	$1.167
Warehouse	$0.170	$0.045	$0.014	$0.060	$0.012	$0.019		$0.075	$0.395
Retail	$0.482	$0.076	$0.047	$0.063	$0.184	$0.219		$0.209	$1.281
Hotel	$0.215	$0.052	$0.166	$0.099	$0.322	$0.205	$0.229	$0.463	$1.750
Apt	$0.092	$0.046	$0.207	$0.058	$0.163	$0.189	$0.081	$0.329	$1.165
School	$0.259	$0.016	$0.037	$0.056	$0.225	$0.151	$0.046	$0.376	$1.166
Medical	$0.381	$0.054	$0.037	$0.404	$0.476	$0.352	$0.398	$0.897	$3.000
Food.Svc	$0.371	$0.175	$0.806	$1.078	$0.668	$0.656	$0.690	$3.679	$8.124
U.S. Weighted	$0.263	$0.052	$0.082	$0.103	$0.193	$0.166	$0.085	$0.386	**$1.330**

Table A.2. ECI ($/ft²/yr) remaining after 90.1-2013, by building type and detailed end use

	Light.Int	Light.Ext	SHW	Heat	Humidfy	Cool	Ht.Rej	Fans	Ht.Rcvy	Pumps	Refrig	Elevator	Txfmr	Equip	Cook	IT	Total
Sm Office	0.238	0.064	0.094	0.029		0.100		0.104						0.252			0.880
Md Office	0.175	0.056	0.013	0.089		0.174		0.045	0.000	0.000		0.088	0.009	0.313			0.962
Lg Office	0.196	0.039	0.010	0.048	0.037	0.230	0.023	0.126	0.006	0.031		0.109	0.005	0.307		0.858	2.023
Warehouse	0.170	0.045	0.014	0.060		0.012		0.019						0.075			0.395
Retail Store	0.432	0.071	0.035	0.046		0.178		0.215	0.018					0.226			1.221
Strip Mall	0.618	0.090	0.080	0.109		0.200		0.183						0.163			1.443
Sm Hotel	0.214	0.044	0.127	0.116		0.190		0.185		0.000		0.166		0.296			1.336
Lg Hotel	0.215	0.055	0.179	0.093		0.367		0.151	0.044	0.017	0.020	0.223	0.007	0.205	0.316		1.893
Pri School	0.274	0.018	0.025	0.099		0.216		0.123	0.032	0.000	0.047		0.009	0.362	0.104		1.311
Sec School	0.252	0.016	0.042	0.035		0.229		0.111	0.032	0.007	0.026	0.009	0.006	0.259	0.073		1.096
Mid Apartment	0.094	0.034	0.322	0.049		0.121		0.171				0.106		0.328			1.226
Hi Apartment	0.091	0.055	0.113	0.065		0.187	0.009	0.186		0.017		0.054	0.007	0.330			1.115
Clinic	0.353	0.078	0.028	0.340	0.076	0.570		0.261	0.013	0.011		0.448		0.876			3.055
Hospital	0.417	0.024	0.049	0.306	0.082	0.299	0.058	0.345	0.028	0.064	0.025	0.298	0.012	0.632	0.291		2.930
Fast Food	0.371	0.177	0.673	1.373		0.751		0.762			0.977				4.469		9.553
Restaurant	0.372	0.173	0.925	0.816		0.594		0.560		0.002	0.435				2.977		6.854
U.S. Weighted	0.263	0.052	0.082	0.095	0.007	0.189	0.004	0.148	0.012	0.007	0.016	0.066	0.003	0.273	0.084	0.029	1.330

National Energy Cost Impact, by Building Type and End Use, U.S. New Construction

Table A.3 shows grouped national new construction energy cost impact results after Standard 90.1-2013; Table A.4 shows the detailed results. Results in this section are weighted by prototype and climate zone based on 8.2 billion square feet of new construction. The numerical results represent the contribution to national new construction energy cost and red shading indicates the greatest national impacts.

Table A.3. Million $/y-U.S. spend on new commercial building energy; after 90.1-2013

	Light.Int	Light.Ext	SHW	Heat	Cool	Fan.Aux	Misc	Equip	Total
Office	$252M	$69M	$53M	$81M	$202M	$115M	$80M	$593M	$1,446M
Warehouse	$235M	$63M	$19M	$83M	$16M	$26M		$104M	$546M
Retail	$834M	$132M	$82M	$109M	$318M	$380M		$361M	$2,216M
Hotel	$118M	$29M	$91M	$55M	$177M	$113M	$126M	$255M	$965M
Apt	$124M	$62M	$279M	$78M	$219M	$254M	$109M	$443M	$1,568M
School	$329M	$21M	$46M	$71M	$286M	$192M	$58M	$477M	$1,480M
Medical	$246M	$35M	$24M	$261M	$308M	$228M	$257M	$580M	$1,939M
Food.Svc	$38M	$18M	$83M	$111M	$69M	$68M	$71M	$379M	$837M
U.S. Weighted	$2,177M	$428M	$678M	$848M	$1,596M	$1,375M	$702M	$3,192M	**$10,997M**

Table A.4. Detailed million $/y-U.S. spend on new commercial building energy; after 90.1-2013

	Light.Int	Light.Ext	SHW	Heat	Humidify	Refrig	Elevator	Txfmr	Equip	Cook	IT	Cool	Ht.Rej	Fans	Ht.Rcvy	Pumps	Total
Sm Office	$110M	$30M	$43M	$13M					$117M			$46M		$48M			$408M
Md Office	$88M	$28M	$6M	$45M			$44M	$5M	$156M			$87M		$22M	$0M	$0M	$481M
Lg Office	$54M	$11M	$3M	$13M	$10M		$30M	$1M	$84M		$236M	$63M	$6M	$35M	$2M	$8M	$556M
Warehouse	$235M	$63M	$19M	$83M					$104M			$16M		$26M			$546M
Retail Store	$545M	$90M	$45M	$58M					$284M			$225M		$271M	$23M		$1,540M
Strip Mall	$290M	$42M	$37M	$51M					$77M			$94M		$86M			$676M
Sm Hotel	$30M	$6M	$18M	$16M			$24M		$42M			$27M		$26M		$0M	$190M
Lg Hotel	$88M	$23M	$73M	$38M		$8M	$91M	$3M	$84M	$129M		$150M		$62M	$18M	$7M	$775M
Pri School	$113M	$7M	$10M	$41M		$20M		$4M	$150M	$43M		$89M		$51M	$13M	$0M	$541M
Sec School	$216M	$13M	$36M	$30M		$22M	$8M	$5M	$222M	$63M		$196M		$95M	$27M	$6M	$939M
Mid Apt	$57M	$21M	$195M	$30M			$64M		$199M			$73M		$104M			$742M
Hi Apt	$67M	$41M	$84M	$48M			$40M	$5M	$245M			$139M	$7M	$138M		$12M	$827M
Clinic	$128M	$28M	$10M	$123M	$28M		$162M		$317M			$206M		$94M	$5M	$4M	$1,104M
Hospital	$119M	$7M	$14M	$87M	$23M	$7M	$85M	$3M	$180M	$83M		$85M	$17M	$98M	$8M	$18M	$835M
Fast Food	$18M	$9M	$33M	$67M		$47M				$217M		$36M		$37M			$463M
Restaurant	$20M	$9M	$50M	$45M		$24M				$162M		$32M		$31M		$0M	$374M
All Buildings	$2,177M	$428M	$678M	$787M	$61M	$128M	$547M	$26M	$2,260M	$697M	$236M	$1,566M	$30M	$1,224M	$95M	$56M	**$10,997M**

Energy Cost Savings, by Building Type and End Use

Table A.5 shows grouped results and Table A.6 shows the detailed results. These results are for savings from Standard 90.1-2004 to 2013 and are weighted by climate zone based on new construction. The percentages represent independent savings for each individual end use.

Table A.5. Percentage cost savings by end use and building type, 90.1-2004 to 90.1-2013 (% savings per individual end use)

	Light.Int	Light.Ext	SHW	Heat	Cool	Fan.Aux	Misc	Equip	Total
Office	37.1%	50.4%	0.3%	42.2%	39.5%	25.7%	10.0%	5.5%	25.4%
Warehouse	36.0%	33.1%	3.2%	36.4%	46.3%	50.6%		2.0%	31.8%
Retail	24.0%	48.0%	5.1%	64.2%	50.1%	49.9%		0.4%	36.7%
Hotel	36.6%	25.0%	0.3%	56.5%	35.7%	45.2%	5.8%	4.4%	27.2%
Apt	6.7%	32.4%	0.1%	41.3%	29.2%	21.0%	6.3%	0.3%	14.2%
School	43.0%	47.1%	0.9%	58.1%	50.0%	52.5%	19.2%	9.7%	38.5%
Medical	16.8%	47.0%	0.8%	54.8%	33.1%	33.4%	3.3%	1.5%	26.0%
Food.Svc	59.5%	43.3%	0.7%	15.9%	34.5%	55.7%	21.6%	0.0%	21.7%
U.S. Weighted	30.9%	43.2%	1.0%	50.4%	41.4%	42.5%	8.6%	3.4%	**29.0%**

Table A.6. Detailed percentage cost savings by end use and building type, 90.1-2004 to 90.1-2013 (% savings per individual end use)

	Light.Int	Light.Ext	SHW	Heat	Humidify	Cool	Ht.Rej	Fans	Ht.Rcvy	Pumps	Refrig	Elevator	Txfmr	Equip	Cook	IT	Total
Sm Office	35.6%	52.1%	0.2%	43.3%		50.2%		24.2%						8.5%			30.2%
Md Office	40.6%	53.6%	1.5%	52.0%		36.1%		30.9%		0.0%		5.5%	49.5%	8.8%			31.6%
Lg Office	33.6%	30.9%	0.2%	42.2%	-685%	31.6%	54.8%	12.9%		56.7%		2.8%	44.5%	9.1%		0.0%	14.6%
Warehouse	36.0%	33.1%	3.2%	36.4%		46.3%		50.6%						2.0%			31.8%
Retail Store	24.4%	46.7%	2.1%	73.7%		50.4%		54.4%						0.4%			38.1%
Strip Mall	23.3%	50.6%	8.3%	39.3%		49.3%		47.7%						0.4%			33.3%
Sm Hotel	35.4%	30.9%	0.1%	45.5%		30.8%		6.7%		0.0%		3.6%		7.3%			21.3%
Lg Hotel	37.0%	23.2%	0.3%	60.0%		36.5%		44.0%	59.8%	70.1%	17.5%	2.8%	45.6%	9.1%	0.0%		28.5%
Pri School	41.6%	46.0%	3.5%	42.0%		45.6%		37.1%	37.7%	2.7%	10.0%		49.6%	14.7%	0.0%		32.6%
Sec School	43.7%	47.7%	0.1%	69.6%		51.7%		55.4%	57.4%	77.9%	9.1%	13.1%	48.5%	10.2%	0.0%		41.5%
Mid Apartment	8.5%	45.0%	0.1%	38.5%		36.8%		20.2%				3.6%		0.5%			13.2%
Hi Apartment	5.1%	23.7%	0.1%	42.9%		24.7%	22.0%	20.2%		33.7%		2.8%	42.5%	0.2%			15.1%
Clinic	17.5%	51.0%	1.2%	58.6%	50.1%	31.0%		36.9%		17.7%		2.0%		0.9%			27.0%
Hospital	16.0%	21.3%	0.6%	47.0%	61.1%	38.8%	25.2%	34.6%		50.7%	21.9%	1.3%	40.6%	3.2%	0.0%		24.6%
Fast Food	56.9%	43.6%	-0.1%	8.1%		32.1%		48.4%			21.3%				0.0%		17.9%
Restaurant	61.6%	43.0%	1.2%	25.4%		37.1%		62.3%		0.0%	22.0%				0.0%		26.0%

Appendix B

End-Use Energy Cost by Building Type

Appendix B

End-Use Energy Cost by Building Type

The following figures show the energy cost (ECI, $/ft²/yr) for each end use on a separate graph with a bar for each building type group. These figures show use after Standard 90.1-2013 and are weighted for the building type across all U.S. climate zones. Energy cost savings from 90.1-2004 to 90.1-2013 are also shown to indicate which building types have the highest energy cost intensity for a particular end use. These figures also show the distribution of individual end-use costs by building type.

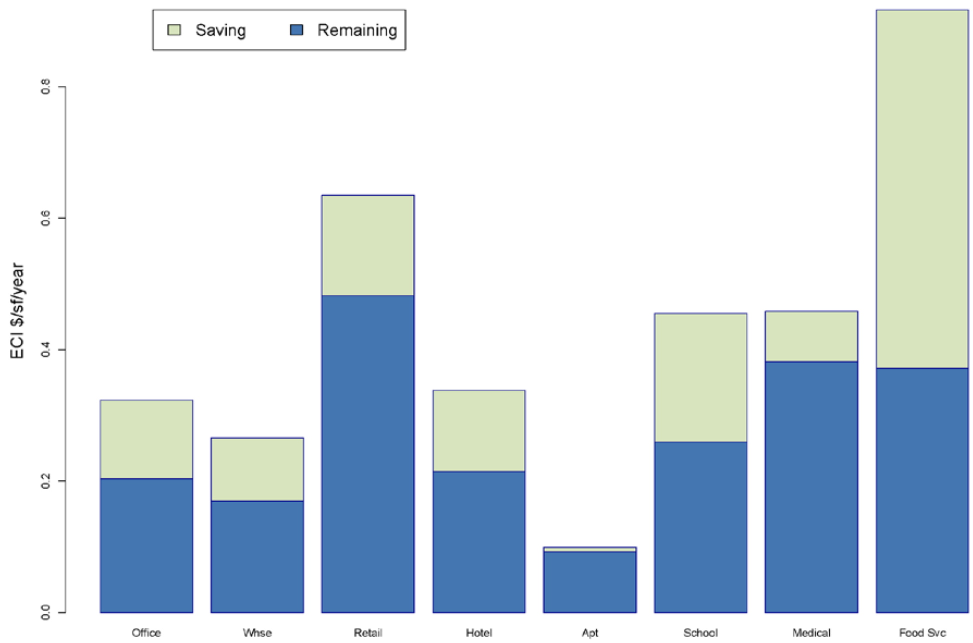

Figure B.1. Interior lighting: 90.1-2013 vs. 90.1-2004; U.S. energy cost

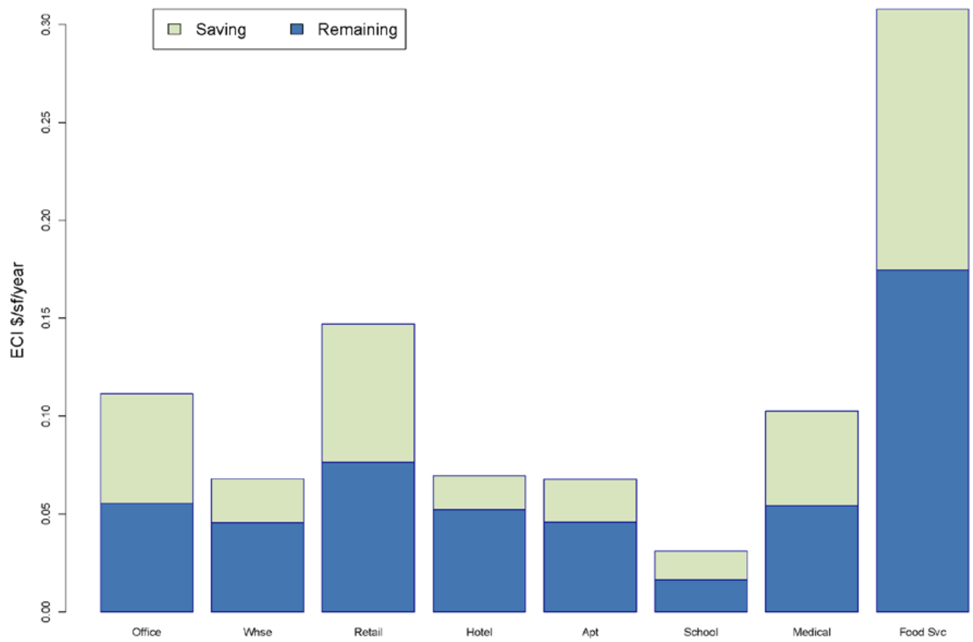

Figure B.2. Exterior lighting: 90.1-2013 vs 90.1-2004; U.S. energy cost

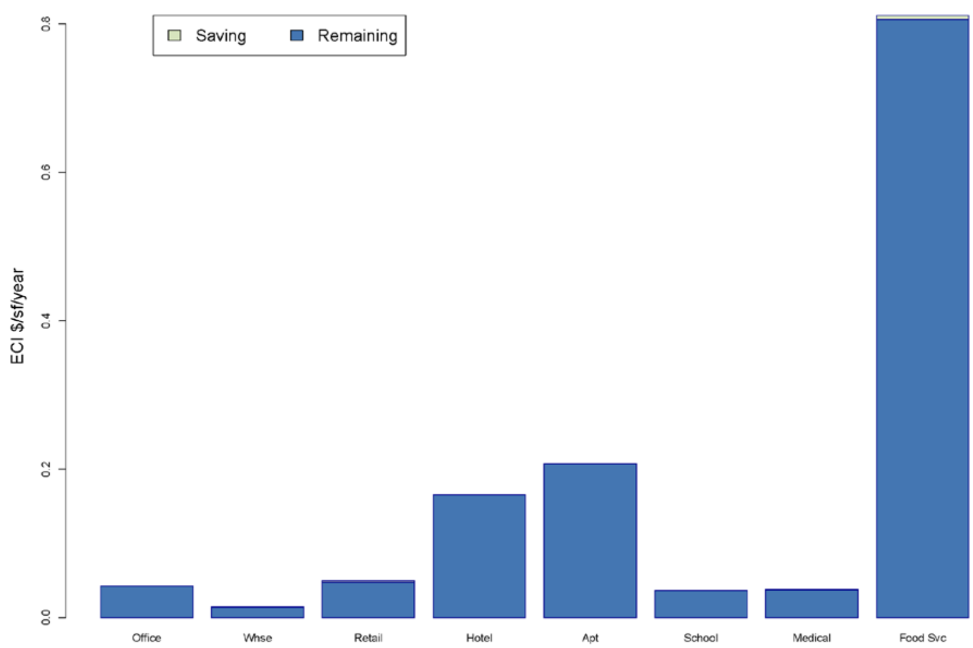

Figure B.3. Service hot water: 90.1-2013 vs. 90.1-2004; U.S. energy cost

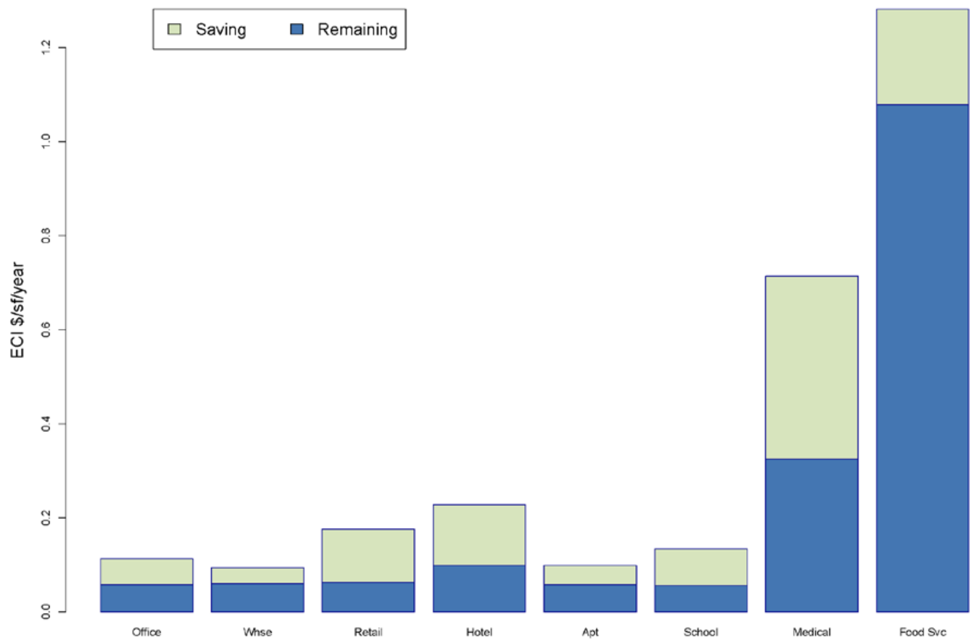

Figure B.4. Heating: 90.1-2013 vs 90.1-2004; U.S. energy cost

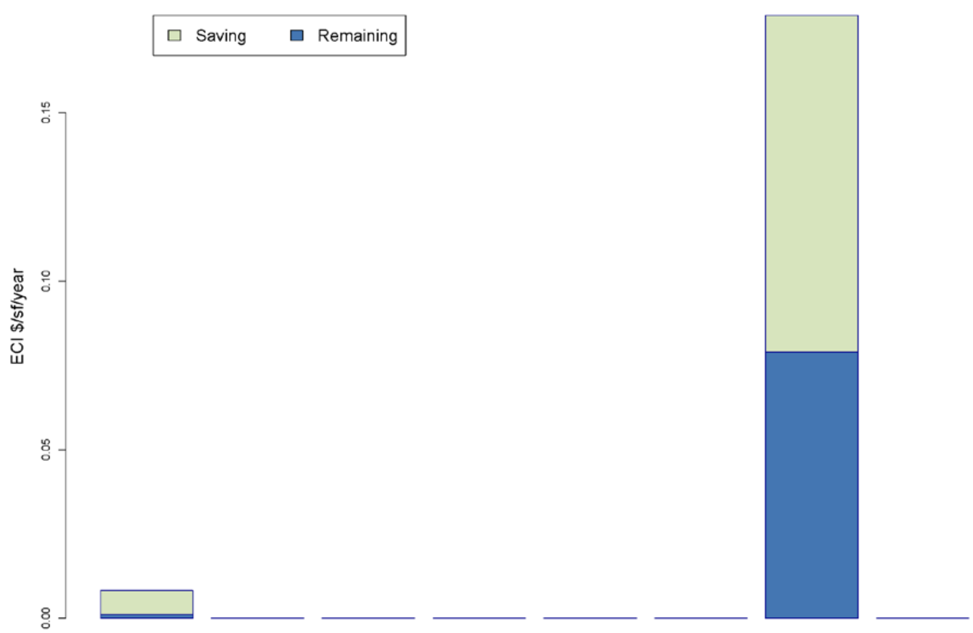

Figure B.5. Humidify: 90.1-2013 vs 90.1-2004; U.S. energy cost

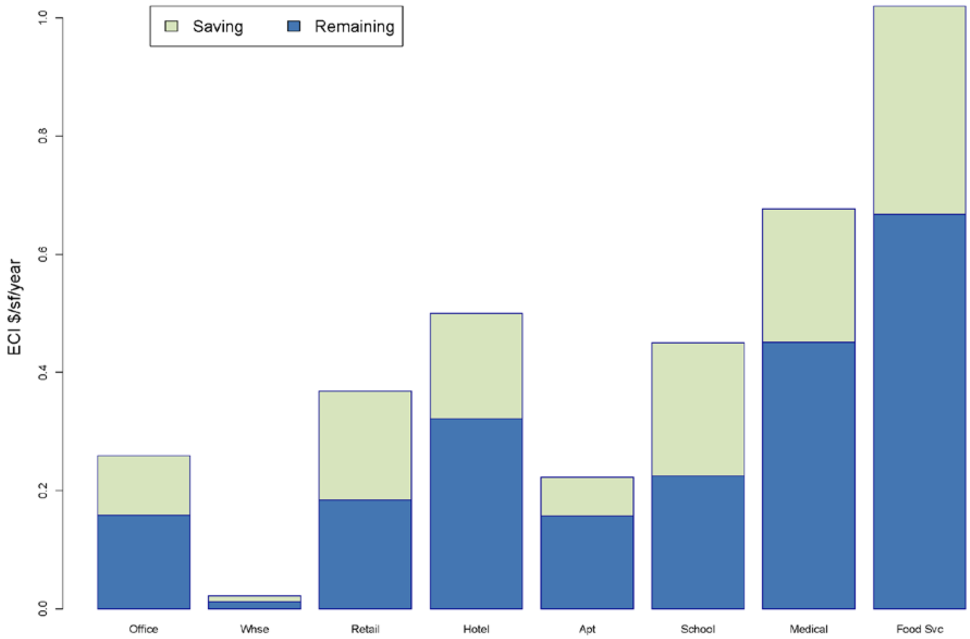

Figure B.6. Cooling: 90.1-2013 vs 90.1-2004; U.S. energy cost

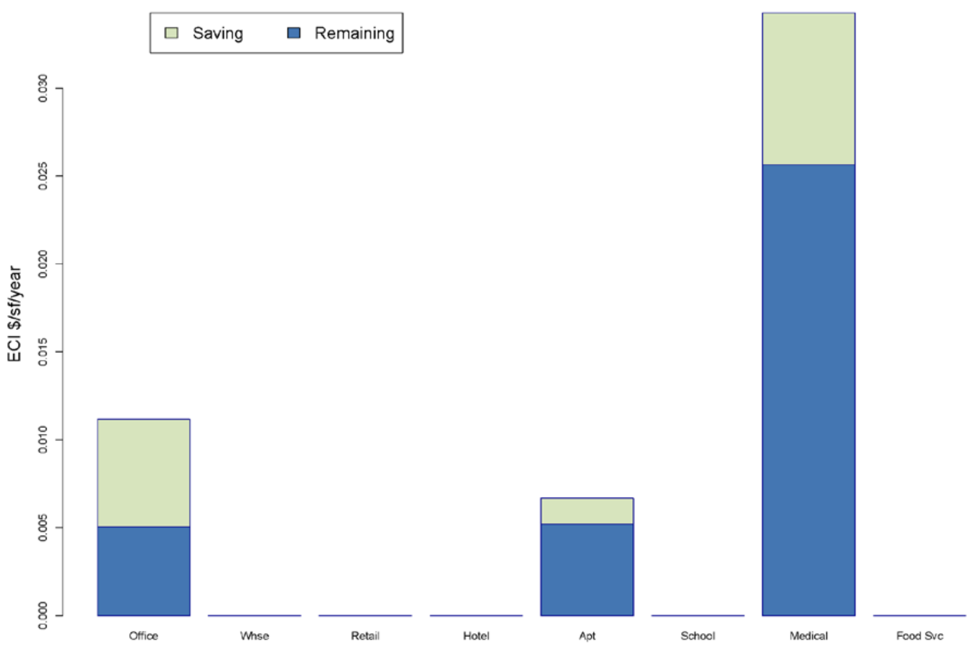

Figure B.7. Heat rejection: 90.1-2013 vs 90.1-2004; U.S. energy cost

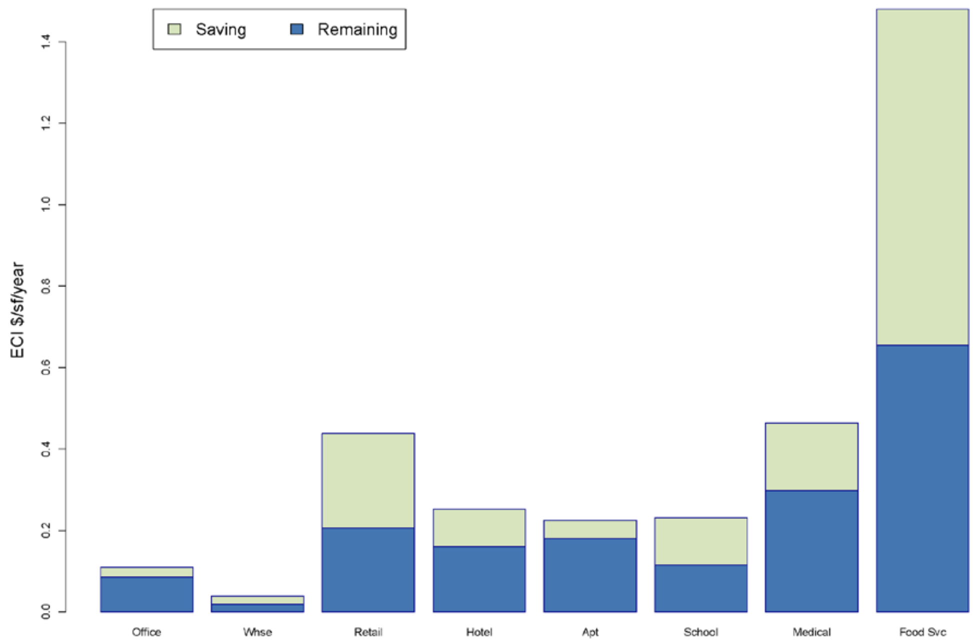

Figure B.8. Fans: 90.1-2013 vs 90.1-2004; U.S. energy cost

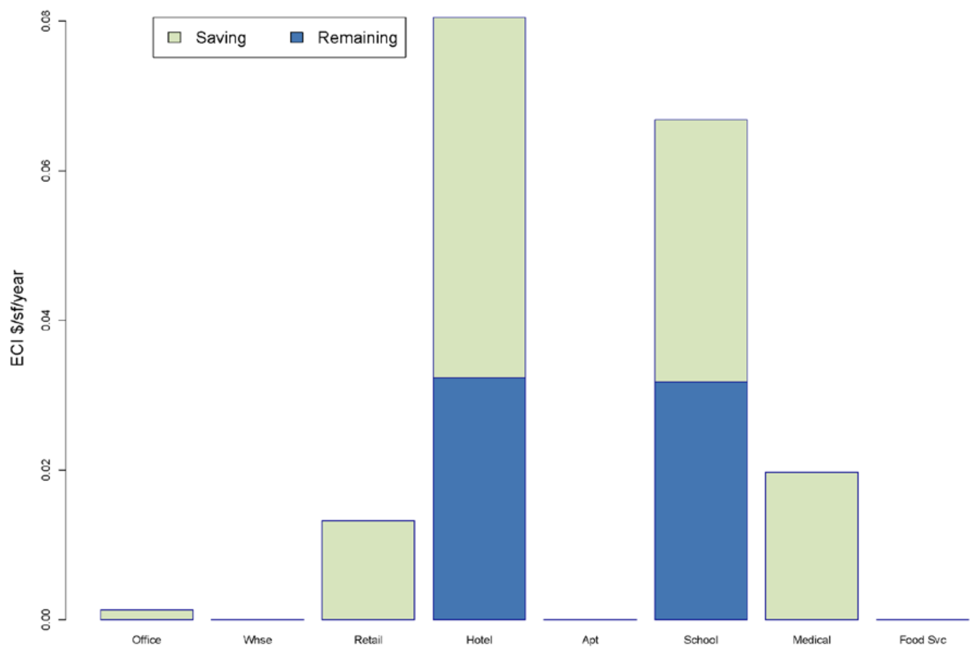

Figure B.9. Heat recovery: 90.1-2013 vs 90.1-2004; U.S. energy cost

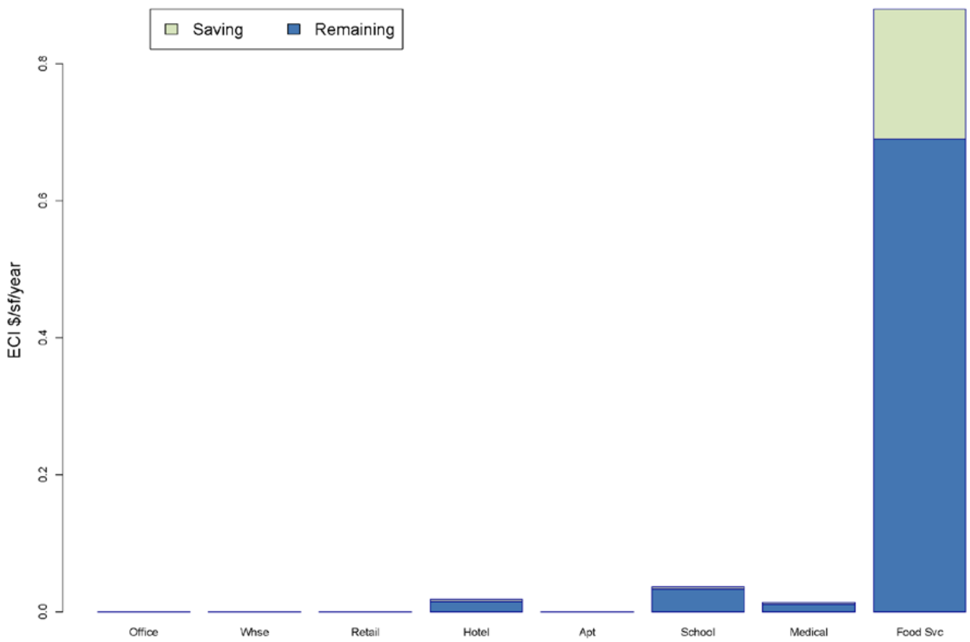

Figure B.10. Refrigeration: 90.1-2013 vs 90.1-2004; U.S. energy cost

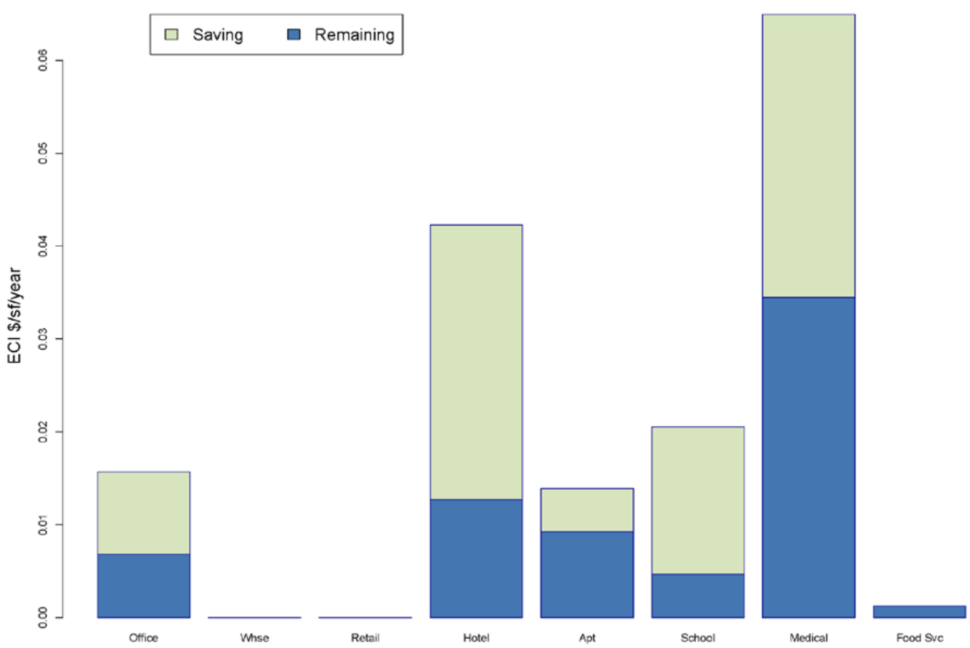

Figure B.11. Pumps: 90.1-2013 vs 90.1-2004; U.S. energy cost

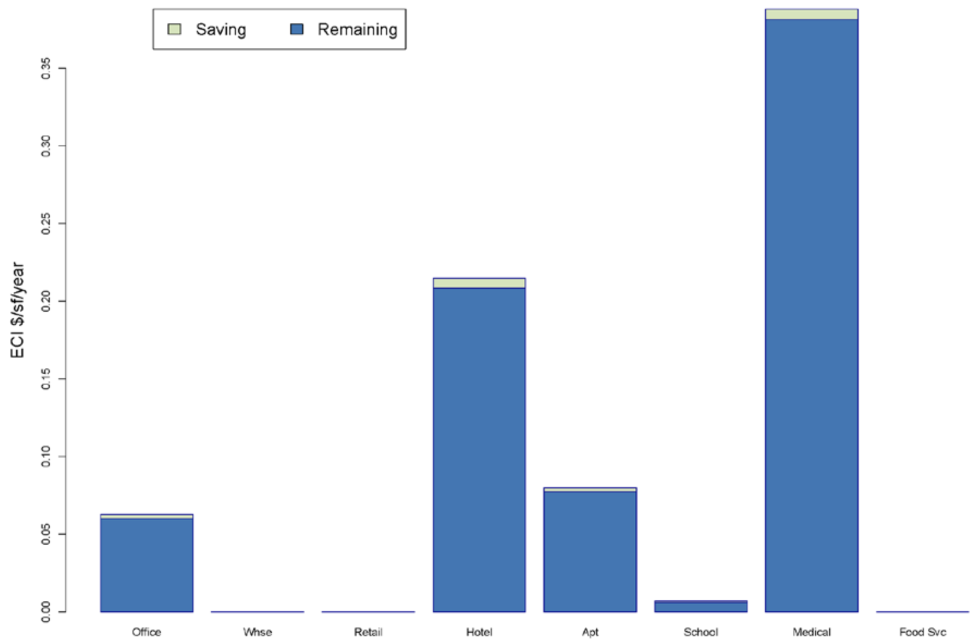

Figure B.12. Elevator: 90.1-2013 vs 90.1-2004; U.S. energy cost

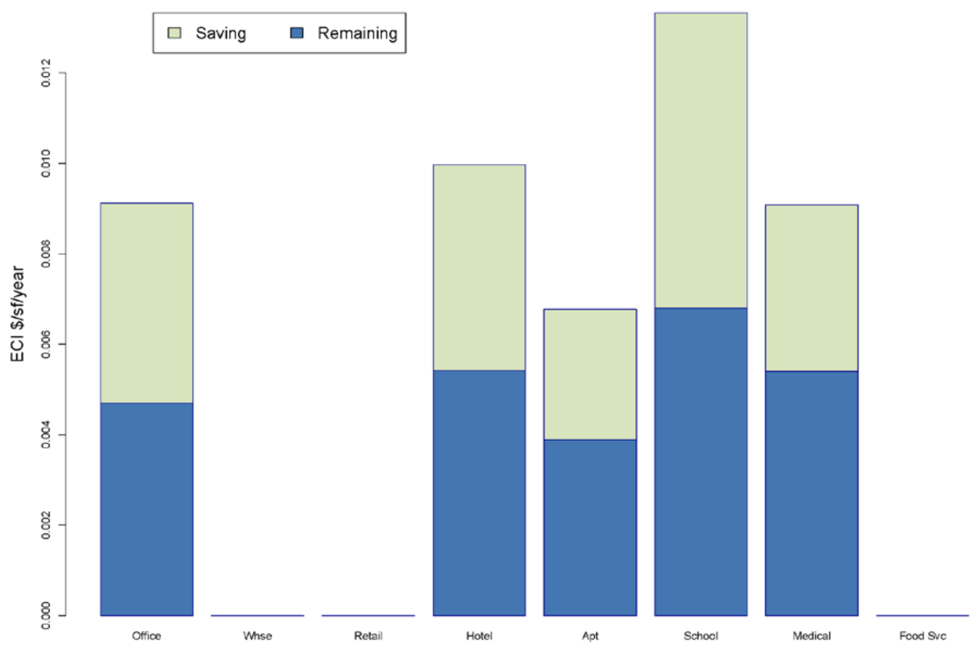

Figure B.13. Transformer loss: 90.1-2013 vs 90.1-2004; U.S. energy cost

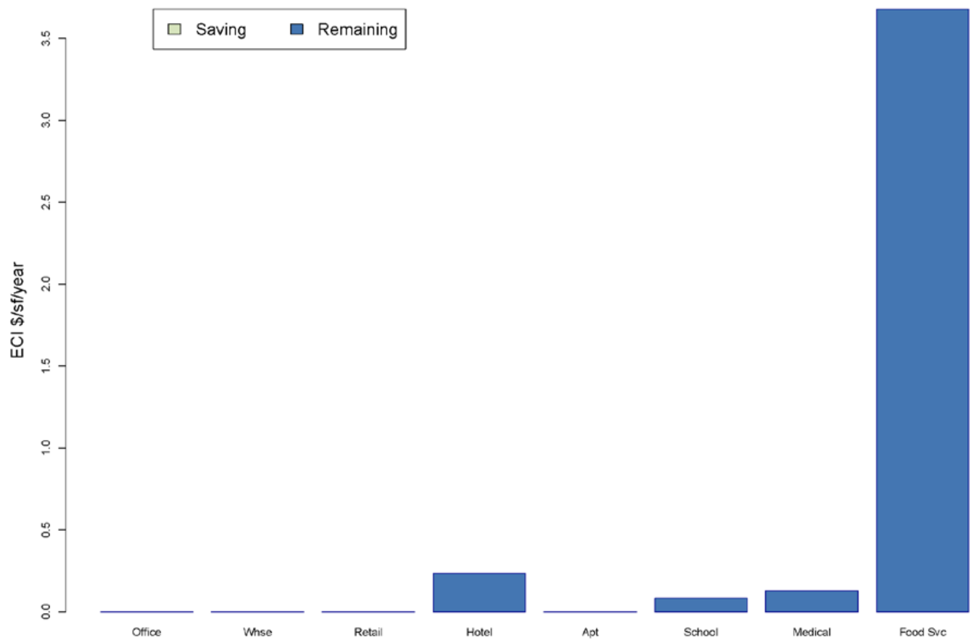

Figure B.14. Cooking: 90.1-2013 vs 90.1-2004; U.S. energy cost

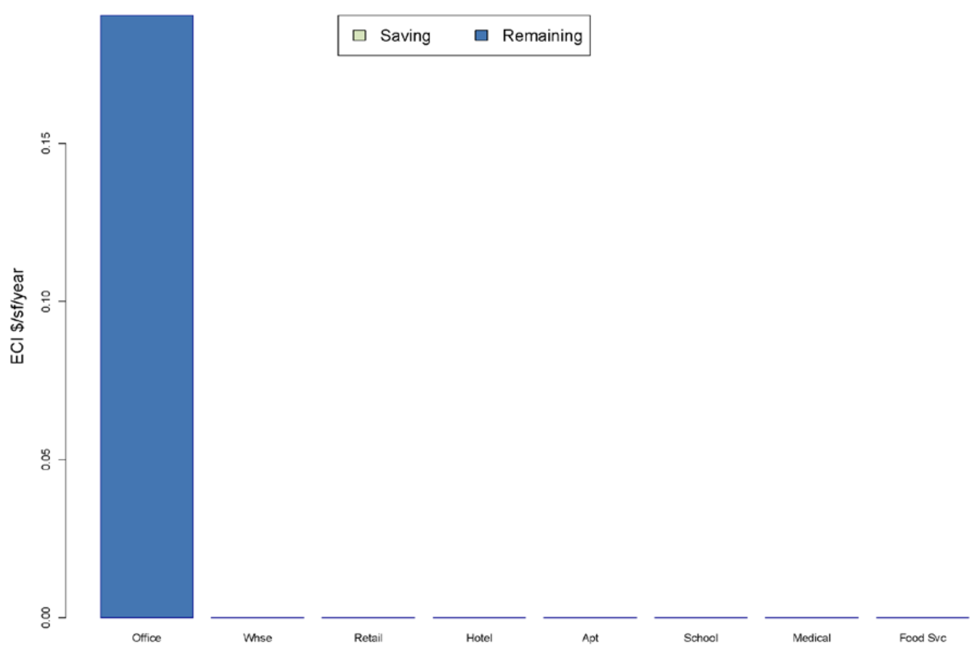

Figure B.15. IT: 90.1-2013 vs 90.1-2004; U.S. energy cost

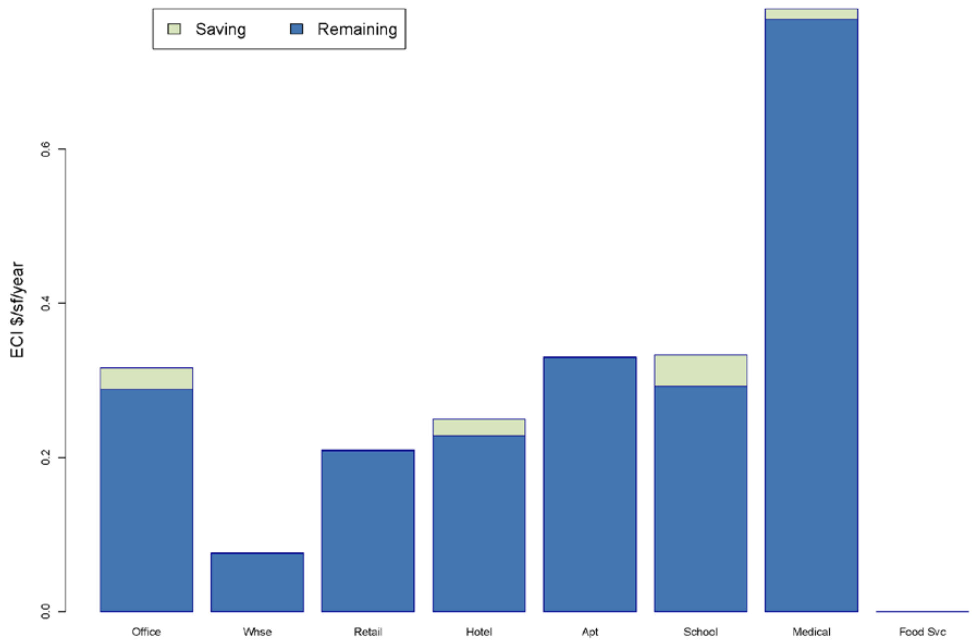

Figure B.16. Equipment: 90.1-2013 vs. 90.1-2004; U.S. energy cost

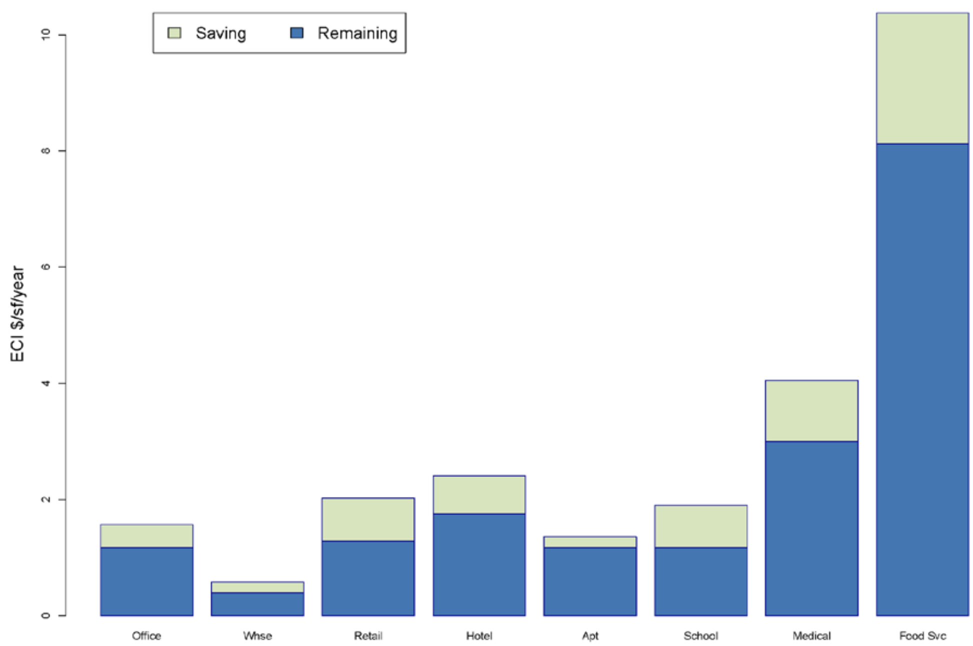

Figure B.17. Total: 90.1-2013 vs. 90.1-2004; U.S. energy cost

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Reducing Office Plug Loads through Simple and Inexpensive Advanced Power Strips

Preprint

I. Metzger, M. Sheppy, and D. Cutler

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Reducing Office Plug Loads through Simple and Inexpensive Advanced Power Strips

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Michael Sheppy
Member ASHRAE

Dylan Cutler

ABSTRACT

As efficiency gains are made in building lighting and HVAC systems, plug loads become a greater percentage of building energy use and must be addressed to meet energy goals. HVAC and lighting systems are targeted because they are typically the highest energy end uses, but plug load reduction and control should be considered as part of a comprehensive approach to energy reduction. In a minimally code compliant office building, plug loads typically account for 25% of the total electrical load. In an ultra-efficient office building, plug loads are typically one of the last end uses to be considered for energy conservation and, as a result, can account for more than 50% of the total electrical load (Lobato et. al, 2011). Plug load efficiency strategies are different than other building efficiency strategies because they involve relatively small loads distributed throughout a building. These loads typically move around in the building when office configuration changes are made, so these loads may shift between circuits over time. Commercially available advanced power strips (APS) can be used to mitigate wasted energy from most plug loads and, in many cases, can have a return-on-investment of approximately two years or less. In recent technology demonstrations, data from occupancy sensors tracking plug load reductions with occupancy have shown energy-saving potential for both business and nonbusiness hours. Also, dense panel-level sub-metering has been used to quantify whole-building receptacle circuit energy consumption, energy savings, and return on investment for the whole building. Receptacle-level metering has been used to show the plug load energy consumption of individual devices and workstations. This paper documents the process (and results) of applying advanced power strips with various control approaches.

INTRODUCTION

Advanced power strips (APS) have been tested in numerous demonstration projects and wide-scale deployments. Basic mechanical schedule timers have been commercially available for a long time, while newer electronic, logic-based controls have started becoming commercially available over the past three to five years. There are an abundance of APSs that offer a variety of complexity, control strategies, data collection abilities, and costs. Some APSs come with a web-based dashboard that allows users to implement and change control strategies, as well as look at the real-time energy consumption of plug loads in their buildings. This centralized, web-based approach to plug load management is novel because conventional plug strips typically have to be configured and controlled locally.

Plug load energy savings are achieved when the device is either transitioned to a low-power state, or it is de-energized to eliminate the power draw. Both can be executed either manually or automatically. A low-power state is between a de-energized state and a ready-to-use state, such as standby, sleep, hibernate, and "off" state with parasitic power draw. A de-energized state is when electricity is not being provided to the device, such as physically disconnecting or unplugging the power cord from an electrical outlet.

Ian Metzger, Michael Sheppy, and Dylan Cutler are engineers at the U.S. Department of Energy National Renewable Energy Laboratory, Golden, Colorado.

Commercially available APSs offer a variety of control approaches, including manual control, automatic low-power state, schedule timers, load-sensing, occupancy, and vacancy. This paper describes each control approach in more detail and presents multiple case studies demonstrating plug load controls.

Manual Control

Built-in power buttons, shutdown procedures, or switched power strips are among the most common manual controls for plug loads. Switches, whether built into a device or on a power strip, provide a quick and easy manual method of powering down electronics. Other devices, such as computers, may have a shutdown procedure that users must perform to shut down the device. For some devices, manual control is the best or only method. The energy savings potential for this type of control depends entirely on user behavior.

Automatic Low-Power State Control

Built-in automatic low-power state functionality, such as standby or sleep, can often be a very effective energy saving approach. Idle time can be monitored by internal processes, causing the device to power down to a low-power state when it has been idle for a given period of time. Automatic low-power states provide limited control but are often the most accessible (and inexpensive) and effective when configured correctly. The prime example of this type of control is a computer entering a "sleep" mode. One hurdle with low-power state control is ensuring that the information services departments are enabling the appropriate settings and utilizing newly available updating techniques (such as wake-on LAN) to enable both low-power states and effective business operations.

Schedule Timer Control

Certain devices are used during the same times each day or at regular intervals, causing them to have predictable load profiles. Predictable plug loads can be effectively managed with schedule timers, which apply user-programmed schedules to de-energize and energize the device to match its pattern of usage. A schedule timer control can take multiple forms, such as electrical outlet timers, power strips, or centralized circuit controls. Schedule timer controls are generally straightforward, consistent, and reliable, but target only the energy that is wasted during nonbusiness hours.

Load Sensing Control

A device, such as a computer, may operate in conjunction with other devices, such as a monitor or other peripherals. Load-sensing control automatically energizes and de-energizes secondary devices (e.g., monitor or other peripherals) based on the "sensed" power load of the primary device (e.g., computer). If the primary device goes into a power state below a given threshold, the load-sensing control can power down the secondary devices. Load-sensing control may save more energy than scheduling control because it can reduce energy use during business and nonbusiness hours. However, it is a more complex control approach and relies on the built-in automatic low-power state functionality in the primary device.

Occupancy Control

Plug load energy savings are accomplished when devices are de-energized or transitioned into a low-power state when not in use, which for many instances, can be determined by whether or not the occupant is in the vicinity of the device. Occupancy control energizes plug loads only when users are present and de-energizes them when the space is vacant. This approach pinpoints the main source of wasted energy at workstations and has a high energy savings potential because it reduces energy use during business and nonbusiness hours. However, it is a more complex control, and depends on proper sensor placement and sensitivity.

Vacancy Control

Currently, vacancy control is not commercially available for plug loads but is commonly implemented in lighting controls because it effectively reduces energy. Vacancy control is a slight modification to occupancy control; it energizes a plug load when it receives manual input from a user and de-energizes the plug load automatically based on lack of occupancy. Plug loads that are needed only when users are present (e.g., task lights, monitors, and computers) would be good applications of vacancy control. This approach also has the highest potential for energy savings at workstations because the plug load will stay in a de-energized state until a user manually energizes the device, thus eliminating the wasted energy associated with false positives.

OCCUPACY CONTROL CASE STUDY

A demonstration project of plug load occupancy control was conducted at the U.S. Environmental Protection Agency (EPA) Region 8 Headquarters located in Denver, Colorado, from February 2011 to June 2011. This research study was undertaken in an effort to identify effective ways to reduce plug load energy. A centralized occupancy control approach was implemented on a sample of 126 occupant workstations in the building, to de-energize circuits feeding groups of six or eight cubicles. An automated energy management system de-energized the circuits when all cubicles in a group were unoccupied for a given period of time. This demonstration project also examined the influences of behavioral change on plug load energy consumption, which is not discussed in this paper.

A four-week baseline was established to quantify normal operating conditions. Occupancy controls were enabled to de-energize plug load circuits after 15 minutes of no occupancy in a group of cubicles. Energy savings of the occupancy controls were quantified by comparison to the baseline.

Energy Savings Results

The study found that the occupancy control was an effective method for reducing plug load energy consumption. Figure 1 shows workstation occupancy rates were found to be significantly less than building occupancy rates, contributing to the high energy savings potential of occupancy controls during business hours.

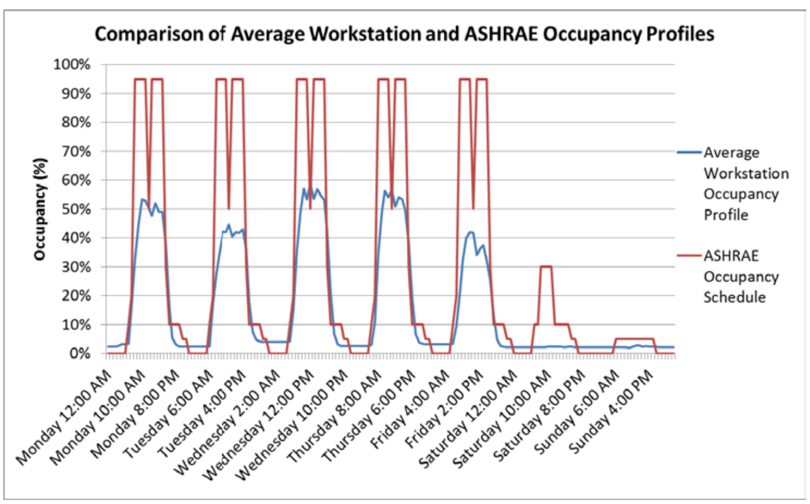

Figure 1 Comparison of the average workstation occupancy rates observed during the demonstration project compared to the ASHRAE occupancy profiles for buildings. (Credit: Ian Metzger, NREL)

The measured occupancy rates of approximately 50% during business hours confirm that control devices with the ability to track occupancy will have a higher energy saving potential at workstations. Other studies conducted by the U.S. General Services Administration (GSA) show that occupants are only at their workstations approximately 30% of the day during business hours. Energy savings for the occupant controls relative to the baseline for the 126-person test group are presented in **Table 1**.

Table 1. Occupancy Control Energy Savings Results

Plug Load Control Approach	Percent Energy Reduction from Baseline
Occupancy Control	21%

Energy savings were found to be significant during both business and nonbusiness hours. Occupancy control was found to have higher energy savings than the behavioral change methods examined in the demonstration project. It is important to note that only workstations were examined in this demonstration project. Shared equipment in common areas (e.g., kitchens, break rooms, print rooms, conference room, etc.) were not included in this study. Higher energy savings are conceivable if all office plug loads are controlled appropriately.

Lessons Learned

Collecting occupancy data can be a sensitive issue, which may require protocols to be followed that would ensure occupant anonymity could be maintained. Anonymity is typically required for field research and should be included in dashboard interfaces for displaying data.

Installation of the control and submetering system took longer and was more costly than expected. The wired installation of the control system and communications were very cumbersome and complex. Wireless communications and controls with "plug and play" installation are expected to have less complexity, are quoted at lower costs, and are currently commercially available. However, wireless communication reliability can be an issue and cyber-security at federal facilities will be a hurdle for all dashboard and data storage submetering systems. It is often more efficient to set up an independent wireless network for the submetering system.

Developing the appropriate plug load management process can have a significant influence on the success of energy reduction goals. This may include behavioral change mechanisms, control systems, or other policies. Establishing a program champion, developing a business case, benchmarking, identifying occupant needs, selecting equipment, controlling equipment schedules, institutionalizing reduction measures, and promoting occupant awareness can all be critical steps in the process.

SCHEDULE TIMER AND LOAD-SENSING CASE STUDY

A demonstration project of plug load schedule timer and load-sensing control with APS was conducted by GSA's Mid-Atlantic Region. According to several energy assessments of GSA's buildings conducted by the National Renewable Energy Laboratory (NREL), plug loads account for approximately 21% of the total electricity consumed within a standard GSA office building (Metzger et al., 2012). This project tested the effectiveness of two types of plug load control strategies: schedule timer control and load-sensing control. An APS that provided both control approaches and submetering was deployed in seven GSA field offices.

This study aimed to measure the holistic energy consumption of an office, including shared equipment and common areas, such as break rooms and print rooms. Overall, 295 devices were monitored during the study, which consisted of a baseline and two subsequent test periods, each 4 weeks long.

Energy Savings

The study found that the schedule timer control was an effective method for reducing plug load energy consumption in all space types, but most notably in the common areas, such as print rooms and break rooms. **Table 2** shows the energy savings from schedule timer controls for different space types in a typical office environment.

Table 2. Schedule Timer Control Energy Savings Results by Space Type

Space Type	Percent Energy Reduction from Baseline
Workstation	26%
Print Rooms	50%
Break Rooms	46%

Load-sensing control was only found to be moderately effective at reducing plug load energy consumption. The low energy saving results at workstations was attributed to the fact that GSA computers were being controlled by a centralized computer power management system. Computer power management is an example of automatic low-power state control. This centralized system was already putting computers and monitors into low-power states, therefore limiting the energy savings potential for this demonstration project. It should be noted that this can be a low/no-cost measure that, properly implemented, can effectively control computer power consumption. **Table 3** shows the energy savings from load-sensing control for different space types in a typical office environment.

Table 3. Load-Sensing Control Energy Savings Results by Space Type

Space Type	Percent Energy Reduction from Baseline
Workstation	4%
Print Rooms	32%
Break Rooms	N/A

Lessons Learned

Although schedule timers were found to have higher energy savings, they were only able to achieve energy savings during nonbusiness hours. In contrast, load-sensing control was able to achieve energy savings during both nonbusiness and business hours, but relied on good occupant behavior or the proper computer power settings to put the computer in sleep mode. In general, schedule timer and load-sensing controls are effective in saving energy for office equipment and can be economical if applied properly. The deployed APS had a manufacturer's suggested retail price (MSRP) of $120 per plug strip. However, there are advanced plug strips on the market that incorporate these technologies and have an MSRP of approximately $20 to $60, although these less expensive APSs typically do not provide submetering capability.

Submetering data are valuable in spotting wasted energy use, informing the future procurement of low-energy equipment, and identifying equipment that is behaving erratically (which is often a precursor to equipment failure). These data are also valuable to building energy modelers, allowing them to more accurately model plug loads in a building. However, the increased cost is typically not economical unless data are actively managed by onsite personnel. It was difficult to set the load threshold for some equipment, such as computers and monitors. The complexity of the load-sensing control resulted in instances where the equipment was being de-energized when the occupants needed them to be energized. Occupant feedback indicated a lack of training/instruction with the devices leading to limited understanding of their operation in some instances. Schedule timer controls are simple and easy to understand for users, which led to larger energy savings in this study. Load-sensing control is more complicated and difficult to understand, leading to complaints and disabling in some instances, which resulted in limited energy savings. More detailed training and maintenance could have made load-sensing control more effective.

INEXPENSIVE SCHEDULE TIMER CASE STUDY

A demonstration project of simple inexpensive schedule timer control with APS was conducted at an office building in Honolulu, Hawaii, from November 2012 through May 2013. The deployed APS could only be controlled locally, each device had to be programmed individually, and no built-in submetering capability existed. Therefore, the programmed schedule timer control was set to be more conservative to accommodate the schedules of different users. This project tested the effectiveness of schedule timer control deployed on a whole building rather than a small sample size as in other demonstration projects. APSs were deployed throughout the entire building, capturing all plug loads.

This study aimed to measure the whole building energy consumption of office plug loads using dense panel-level submetering and calculated energy savings associated with inexpensive schedule timer controls. A total of 689 plug load devices were monitored during the study, which consisted of baseline and test periods, each 4-6 weeks long.

Energy Savings

The study found that the schedule timer control is an effective method for reducing plug load energy consumption in all space types and for all occupant types. Plug loads at the demonstration building are estimated to account for approximately 22% of the whole building energy consumption. **Figure 2** shows the whole building plug load average daily usage profile, comparing the baseline to the schedule timer control. Energy savings are achieved only during nonbusiness hours. Some variation is observed during business hours, which is not attributed to the control devices but an indication that occupant behavior varied between the uncontrolled and controlled phases of the project. Occupancy and behavior are uncontrolled variables; however, occupancy data was collected and used to normalize the energy data in an attempt to remove the variability between the two phases.

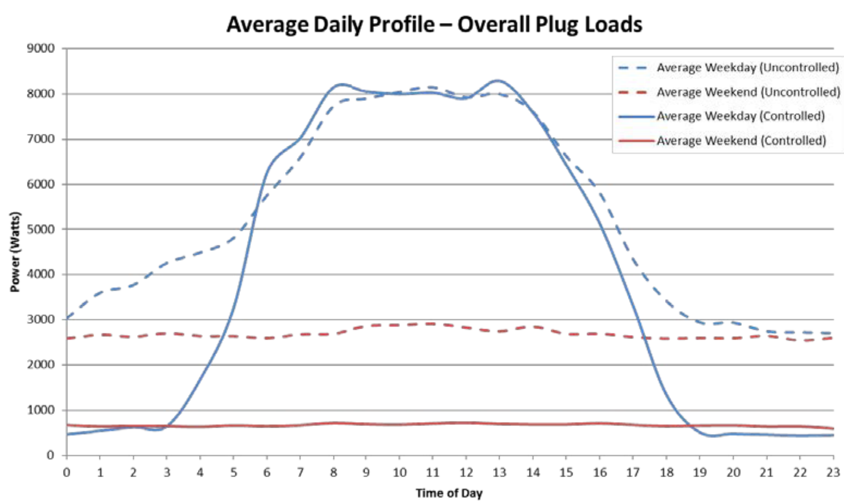

Figure 2 Baseline and APS schedule timer control plug load energy consumption profiles. (Credit: Michael Sheppy, NREL)

Energy savings were analyzed by space type to identify applications with the highest energy savings, for prioritized deployment. **Figure 3** shows the energy savings by space type. Print rooms, open offices, and hallways were found to have the highest energy savings.

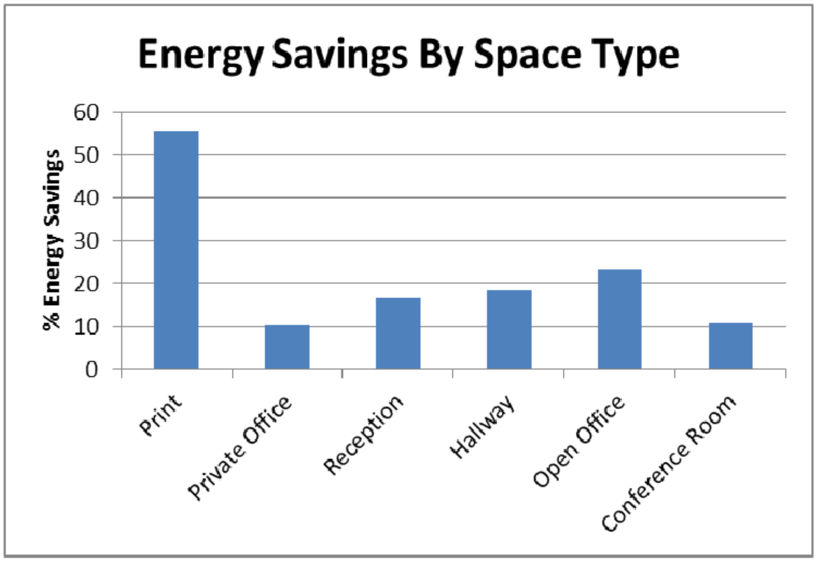

Figure 3 Energy savings by space type. (Credit: Michael Sheppy, NREL)

Measured data was extrapolated to predict annual energy savings using eQUEST energy simulation software developed by the U.S. Department of Energy. Reduction in plug load energy consumption is expected to reduce the energy required for the air conditioning system. **Table 4** shows the modeled energy savings from schedule timer controls for different energy systems.

Table 4. Schedule Timer Control Energy Savings Results by Space Type

Energy System Type	Percent Energy Reduction from Baseline
Plug Loads	28%
Air Conditioning	5%
Whole Building	***8%***

Lessons Learned

Simple and inexpensive schedule timer APSs can be effective in whole building deployments. However, schedule timers are unable to capture energy savings during business hours when occupants are not at their workstations. These devices are easy for the occupants to understand and operate, resulting in higher acceptability in wide-scale deployments. Schedule timer APSs are typically inexpensive, approximately $20 or less MSRP, and can result in payback periods of less than 2 years if applied properly.

CONCLUSION

Advanced power strips with various control approaches are commercially available and have been proven to save energy. However, selecting the appropriate control approach is critical to achieving maximum energy savings. Different equipment types require different control approaches. For example, control approaches that track occupancy, such as load-sensing, occupancy, and vacancy controls, should be applied to equipment found at workstations, such as computers, monitors, and task lights. Schedule timers should be applied to shared equipment, such as printers, coffee makers, and water coolers, but can also be effective at workstations as an alternative to automated computer power settings. However, it is also very important to understand the built-in capabilities of a device, such as automatic low-power states, and how the built-in capabilities may interact with the control approach (e.g., load-sensing). In all cases, it is important for the occupant to understand the purpose and operability of any APS. Therefore, education is paramount when considering the deployment of advanced power strips.

Potential barriers for APSs include: occupant acceptance, communications, lack of personnel time for analysis, and complex controls in some instances. These devices may require operation and maintenance to update controls, manage data, and troubleshoot incorrect operations and communication failures on a regular basis. All control strategies should provide manual override to accommodate atypical times when a plug load device would not normally be in use (e.g., using a device outside normal business hours). APSs may create a parasitic load, which must be included in the analysis of total costs savings potential.

There is the opportunity for significant energy savings through appropriate deployment of APSs. These savings can achieve very attractive returns on investment due to the low cost of certain APS devices. This has been proven with schedule based control in two case studies discussed here. There is significant opportunity for more precisely tuned control of the plug and process loads utilizing occupancy or vacancy control, but a commercially available system that accomplishes this effectively (both in effort and cost) has not been perfected.

Sub metering data are valuable in spotting wasted energy use and identifying equipment that is behaving erratically, but the increased cost is typically not economical unless data are actively managed by onsite personnel. A more effective feedback loop to the end users than the currently available web dashboard approach will be necessary to achieve higher levels of savings for submetering.

Research has been conducted on appropriate control approaches for different types of equipment and published resources are available, such as Assessing and Reducing Plug and Process Loads in Office Buildings (NREL, 2012) and Selecting a Control Strategy for Plug and Process Loads (Lobato et al, 2012). These documents provide a methodical approach to assessing and determining the appropriate control mechanism for different plug loads. Selecting the appropriate control approach and considering lessons learned from the presented case studies will help to make future deployments more effective and increase plug load energy reduction in office buildings.

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NREL
NATIONAL RENEWABLE ENERGY LABORATORY

Building Owners | Energy Managers

OFFICE BUILDINGS

Assessing and Reducing Plug and Process Loads in Office Buildings

Overview

Plug and process loads (PPLs) account for 33% of U.S. commercial building electricity consumption (McKenney et al. 2010). (See Figure 1.) Minimizing these loads is a significant challenge in the design and operation of an energy-efficient building. Lobato et al. (2011) and Lobato et al. (2012) define PPLs as energy loads that are not related to general lighting, heating, ventilation, cooling, and water heating, and that typically do not provide comfort to the occupants. The percentage of total building energy use from PPLs is increasing. According to the U.S. Department of Energy (DOE), by 2030, commercial building energy consumption is expected to increase by 24%; PPL energy consumption is anticipated to increase by 49% in the same time frame (DOE 2010). These trends illustrate the importance of PPL energy reduction to achieve an overall goal of reducing whole-building energy consumption.

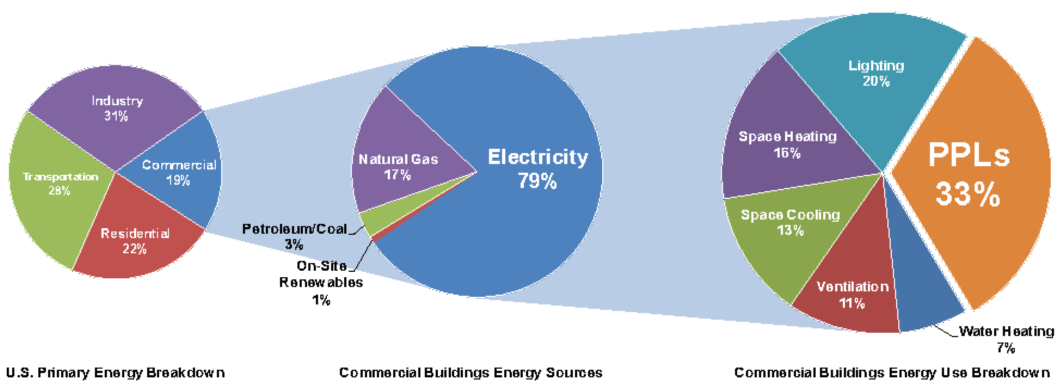

Figure 1. PPLs account for 33% of the total energy consumed by commercial buildings. *Graph by Chad Lobato, NREL; Data source: DOE (2010)*

Using the process and strategies outlined in this brochure, the U.S. Department of Energy's National Renewable Energy Laboratory (NREL) was able to drastically reduce its PPL energy use in the Research Support Facility (RSF). NREL's previous office space PPLs used nearly 2,257,000 kWh/year; after implementing these PPL strategies, the RSF used 1,290,000 kWh/year (see Figure 2). At NREL's utility rate of $0.06/kWh, there is an annual cost saving of $58,000.

This "quick start guide" will help building owners and energy managers reduce PPL energy use in their facilities. This brochure provides an overview of PPLs in office buildings and describes the process and strategies needed to cost-effectively reduce their energy impact. It packages extensive PPL research into an easy-to-use set of instructions and provides quick references to useful tools, websites, and databases. It is also intended to guide the procurement of new equipment that incorporates strategies and technologies to significantly reduce energy consumption.

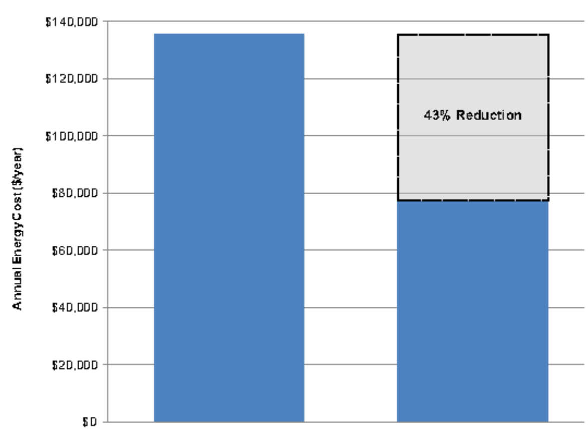

Figure 2. A 43% reduction in PPL energy use saves $58,000 annually. *Graph by Chad Lobato, NREL*

NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

Plug and Process Loads Reduction Process ▼

Step 1: Establish a Plug and Process Load Champion

The first step in addressing PPLs is to establish a PPL champion (or a team of champions) to initiate and help with the process. This person needs to understand basic energy efficiency opportunities and design strategies and be able to independently and objectively apply cost justifications. He or she must be willing and able to critically evaluate, address, and influence the building's operations, institutional policies, and procurement processes.

Historically, PPLs have not been targeted as an energy consumer such as lights or HVAC, and are considered a function of the building—in some ways, something you cannot do anything about. There are huge opportunities in understanding and managing these loads. Not only do they save energy directly, but cooling energy is also saved by not removing the heat generated by PPLs. PPLs are often specified by many parties, so equipment and efficiency strategies are rarely handled by one decision maker. The champion will make sure that all decision makers are on the same page about PPLs and that their decisions save energy and integrate well with other building systems.

Step 2: Institutionalize Plug and Process Load Measures

The day-to-day energy efficiency of any building depends largely on the decisions of occupants, facility managers, and owners, all of whom play key roles in whole-building energy consumption. Therefore, one key step in reducing PPL energy use is to institutionalize PPL measures through procurement decisions and policy programs (refer to **ENERGY STAR®** for guidance). To do this, the champion must identify decision makers who can institutionalize programs based on identified PPL efficiency measures. Policies must be improved as needed to stay current with technologies.

Step 3: Benchmark Current Equipment and Operations

For a building that is representative of multiple buildings in a portfolio, the benchmarking process is required for only one building. The applicable strategies can then be implemented across the portfolio.

Step 3a: Perform a Walkthrough

A building walkthrough to identify and inventory PPLs will establish a benchmark of current equipment and operations. You can **download a workbook** to help in the inventory process and to estimate PPL energy use and costs. In this workbook, use the sheet named "Office PPL Inventory" to inventory the PPLs in your building. Use the sheet named "Office PPL Calculator" to determine which PPL strategies will offer the greatest savings in your building.

The champion will assess all PPLs, noting the various types of equipment and the quantity of each type. The champion needs to identify PPLs that are common throughout the building, and those that are present in limited quantities. At this stage, the champion will also engage the PPL users to learn how and why each device is used, and if the device is critical to health, safety, or business operations.

Frank et al. (2010) provided a detailed example of how a PPL walkthrough is conducted.

Step 3b: Develop a Metering Plan

A metering plan identifies energy-saving strategies by quantifying the energy use of PPLs. Such a plan saves time and money because only a representative sample of common items needs to be metered. For example, if every cubical has the same type of monitor, only a small sample needs to be metered. The PPLs that are present in limited quantities, that have unknown use patterns, or that are otherwise unique should all be metered if possible. The metering can be carried out, in part, with many commercially available PPL power meters. If metering is possible, the collected data can be used to understand when equipment is operated and highlight opportunities to turn off the equipment when it is not needed. If metering is not possible, either because the PPLs are hard-wired to the electrical system or because their voltage and current requirements are too great, you can **download a workbook** or refer to ASHRAE (2009), to estimate in-use power draws. You can then multiply an estimate by the hours of use to derive an estimate of actual energy use.

Another part of the metering plan is to identify PPLs that cannot be de-energized. Some PPLs cannot be de-energized because of:

- Health and safety concerns
- Interruptions to business operations
- Reductions in sales
- Shutdown procedures
- Reconfiguration requirements on startup.

If the PPL cannot be de-energized, use **the workbook** or ASHRAE (2009) to estimate the device's in-use power draw.

Step 3c: Select a Plug Load Power Meter

Many meters are commercially available to measure plug loads. A meter should have the following features:

- Ability to measure and log one week of electrical power (Watts) data. This offers a more accurate picture of energy use compared to a meter that provides only instantaneous readings.
- Sampling interval of 30 seconds
- Designed for the type of circuit to be metered (e.g., 120 Volt, 15 amp, 60 Hertz)
- Ability to accurately meter loads of 0–1800 W
- External display
- Internal clock that timestamps each data point
- Underwriters Laboratories listing
- Ability to download stored data.

Step 3d: Meter the Plug Loads

The steps to execute the metering plan for a given plug load are:

1. Assure the users that the purpose of the metering effort is to gather data about the building's energy performance, and not to monitor their personal or business activities.
2. If a business function will be interrupted by installing the meter, consider waiting until nonbusiness hours to do so.
3. If applicable, install any necessary computer software so the meter can be configured and the measured data can later be downloaded and analyzed.
4. Set up the meter to measure electrical power at a sampling interval of 30 seconds, if possible. Intervals as long as 15 minutes are acceptable. If necessary, clear the memory on the meter and go through any other initial setup, such as setting the date and time.
5. Power down and unplug the device to be metered, plug the device into the meter, plug the meter into an outlet, and power on the device.
6. Meter the device all day, every day for at least one entire work week. Time and budget permitting, meter for longer periods for more accurate annual energy use estimates and to capture seasonal use patterns.
7. Download the metered data for analysis. Calculate the average load during business and nonbusiness hours.

Step 4: Develop a Business Case for Addressing Plug and Process Loads

To gain buy-in from all parties involved, the champion must develop a business case that justifies measures to reduce PPLs.

In most projects, the initial business case is based on energy cost savings. Energy savings alone may not be sufficient to justify the most efficient PPL reduction strategy, so nonenergy benefits should be highlighted. For example, it is often difficult to justify purchasing low-energy laptop computers with energy cost savings alone. Laptops can be justified, however, because they enable users to work from home and to take their computers on travel. If mobility is not necessary, mini-desktops are available that have the efficiency of laptops without their added costs and security concerns.

Another example is centralized multifunction devices (compared to individual printers, copiers, and fax machines), which have reduced costs for maintenance and supporting unique toner cartridges. Minimizing, centralizing, and standardizing document services greatly simplify the implementation of robust standby power configurations and significantly lower service costs. Moreover, volatile organic compounds from the printer toners can be isolated to a few copy rooms with dedicated exhaust to improve indoor air quality. Depending on the building layout and function, as many as 300 printers can be replaced with as few as 20 widely distributed multifunction devices.

Step 5: Identify Occupants' True Needs

Identify occupants' and institutional true equipment needs. A true need is required to achieve a given business function; a perceived need is often based on past experience without consideration for more efficient strategies to accomplish the same function.

To reduce PPLs, the champion must understand what the occupants produce as part of their jobs and what tools they require. He or she must be diplomatic enough to help them do their jobs energy efficiently without making them feel that the purposes of their jobs are being questioned. This can be challenging, because every occupant, including those working in sensitive operations (e.g., security, information technology, upper management), should be accounted for. Determining occupant needs will reveal any nonessential equipment. A business case should be made for continued use of this equipment; otherwise, it should be removed. Exceptions can be made, especially for equipment that preserves occupant health and safety.

Certain PPLs may not be true needs, but are highly desirable. For these, the champion will need to work to meet the need with a shared, centralized piece of equipment and reduce or eliminate personal devices. For example, a shared, centralized coffee maker can meet employee demand and eliminate numerous personal coffee makers.

Step 6: Meet Needs Efficiently

Once the list of true needs is determined, each must be met as efficiently as possible. You should research the **ENERGY STAR** and **EPEAT**® databases to find energy-efficient equipment; however, these alone will not maximize cost-effective energy savings. Nonrated equipment should be researched to find the most efficient model. This will require the champion to work with equipment manufacturers and suppliers to determine the available options. Once a model is selected, it should be turned off when not in use, if possible.

A significant fraction of many PPLs' energy use is from parasitic loads, which is the power draw when a device is not performing useful work. Parasitic loads result in wasted energy, even if the equipment is energy efficient.

Step 7: Turn It All Off

Office buildings are unoccupied for two-thirds of the year. A key step in any PPL reduction program is to reduce energy use during nonbusiness hours, as it is generally wasted. Figure 3 shows a comparison between measured daily energy consumption for an **ENERGY STAR**-rated ice machine before and after timer control was implemented. Nearly $150/year was saved by installing a $20 electrical outlet timer—and the users still had all the ice they needed.

For detailed information about how to control PPLs, refer to **Lobato et al. (2012)**.

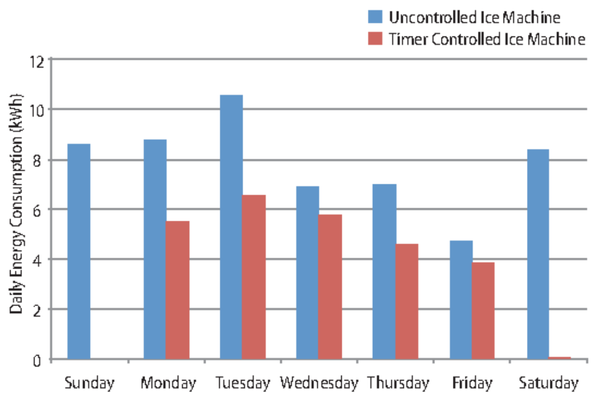

Figure 3. Ice machine daily load profile. *Graph by Chad Lobato, NREL*

Step 8: Address Unique Plug and Process Loads

Some equipment is not specified by building owners or employees. For example, outside contractors or vendors typically control food service areas, but the building owner covers their energy costs. For such situations, the owner should contractually require or provide the most efficient equipment available. Refer to **ENERGY STAR** and **EPEAT** for efficient options.

Energy-efficient gym equipment and ATMs may not be available and may be restricted from being turned off. These particular PPLs should be addressed on a case-by-case basis with the manufacturers to identify any possible solutions.

Step 9: Promote Occupant Awareness

A crucial step in reducing PPL energy use is to promote employee awareness of efficiency measures and best practices. Figure 4 is an example of a sticker that could be placed on computers and monitors to remind employees to turn off their equipment when it is not being used. Employee awareness can come in such forms as:

- Training
- Informational letters
- Emails
- Signage
- Videos
- Periodic reminders or updates.

Step 10: Address Plug and Process Loads (Design Team)

New construction and retrofit projects bring additional PPL reduction opportunities that the design team should address. The champion should work with the design team to question standard specifications, operations, and design standards that limit energy savings opportunities. One key role the design team plays in reducing PPLs is maximizing space efficiency, which increases the ratio of occupants per building area or piece of equipment. Increasing space efficiency decreases areas of dense PPLs, such as break rooms, common print areas, and cafeterias. Equipment in these areas is more efficiently used, and PPLs are reduced.

The design team has the opportunity to further reduce energy use by integrating PPL control strategies into the building's electrical system. Early in the design phase, the design team can build features into the electrical system to control the outlets at workstations and in common areas. This strategy can be as simple as installing switches, vacancy sensors, or timed disconnects for outlets, or as sophisticated as controlling outlets through the building management system.

The design team is typically responsible for specifying equipment such as elevators and transformers. The stairs should be designed to be as inviting and convenient as possible so employees want to use them. Elevators should then be carefully scrutinized to find the most efficient model. Some important features are reduced speed, occupancy-controlled lighting and ventilation, and smart scheduling.

The design team is also responsible for process cooling systems in areas with concentrated plug loads, such as information technology closets. These systems should use, where applicable, economizers, evaporative cooling, and waste heat recovery.

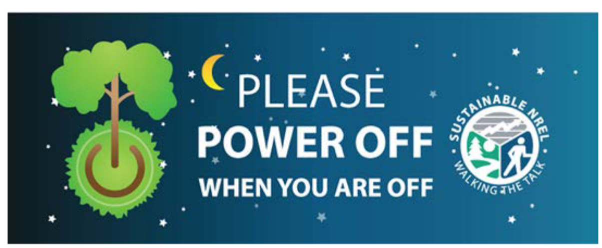

Figure 4. Sticker used at NREL to promote occupant awareness. *Illustration by Marjorie Schott, NREL*

Strategies ▼

The following best practices should be implemented to cost-effectively reduce PPL energy use without sacrificing functionality. When the following strategies recommend equipment replacement, refer to **ENERGY STAR** and **EPEAT** for energy-efficient options.

Note: The savings shown in the following strategies assume a utility rate of $0.10/kWh and an operating schedule of 10 business hours/day.

Strategies

Break Rooms and Kitchens

Refrigerators

For refrigerators in break rooms and kitchens, implement the following:

- ☐ Remove underused refrigerators to save $40–$80/year/refrigerator.
- ☐ Replace aging, inefficient refrigerators with the most efficient compliant refrigerators to save $40/year/refrigerator.
- ☐ Consolidate multiple mini-refrigerators into a full-size refrigerator to save $35/year/mini-refrigerator.
- ☐ Replace glass door refrigerators with similarly sized solid door refrigerators to save $60/year/glass door refrigerator.

Small Kitchen Appliances

- ☐ Upgrade items such as coffee pots, toasters, and microwaves with units that have limited parasitic loads from light-emitting diode (LED) lights or displays to save $1/year/item.
- ☐ Control these items with electrical outlet timers so they are powered down during nonbusiness hours to save $3/year/item.

Vending Machines

Vending machines have an approximate energy cost of $350/year/refrigerated machine. Implement the following strategies to reduce vending machine energy consumption:

- ☐ Remove underused machines to save $350/year/machine.
- ☐ Replace aging, inefficient vending machines with the most efficient equipment to save $150/year/machine.
- ☐ Remove the display lighting to save $65/year/machine.
- ☐ Implement a load-managing device (**Deru et al. 2003**) to save $95/year/machine.
- ☐ Set contractual requirements for vendors to use only delamped, energy-efficient vending machines that have a load-managing device preinstalled.

Drinking Fountains

- ☐ Disconnect or remove drinking fountain coolers and bottled water coolers.
- ☐ Replace aging drinking fountains and bottled water coolers with noncooled drinking fountains to save $55/year/cooler.

Workstations

Workstations represent a significant fraction of office building PPLs and overall building energy use. Figure 5 is an example of a low-energy workstation.

Computers

- ☐ Replace standard desktop computers with miniature desktop, laptop, or thin client computers to save as much as $60/year/computer.
- ☐ Disable screensavers and enable computer power management settings to save as much as $50/year/computer with use of the computer management features (**ENERGY STAR 2011**).
- ☐ Configure computers so users can manually trigger standby or sleep mode via:
  - ☐ The computer power button
  - ☐ The laptop docking station power button
  - ☐ Designated keyboard buttons
  - ☐ A standby icon on the computer desktop
  - ☐ Other external standby triggering devices.

Monitors

- ☐ Replace aging monitors with LED backlit liquid crystal display (LCD) monitors to save as much as $13/year/monitor (**Lobato et al. 2011**).

Task Lights

- ☐ Replace incandescent or fluorescent-tube task lighting with efficient compact fluorescent lamps (CFLs) or LED task lighting to save $15/year/task light.

Phones

- ☐ Replace standard phones with low-power (2-W maximum) voice over Internet protocol (VoIP) phones to save $10/year/phone.

Figure 5. Diagram of an example low-energy workstation.
Illustration by Matthew Luckwitz, NREL

Strategies

Printers, Copiers, Scanners, and Fax Machines

- ☐ Consolidate multiple personal devices into a single multifunction device to save $8/year/personal device.
- ☐ Enable the power option settings on the multifunction devices to go into standby after 15 minutes of idle time.

Parasitic Loads

- ☐ Implement power management surge protectors at work stations to reduce or eliminate the parasitic loads of equipment during nonbusiness hours.
- ☐ For detailed information about how to control PPLs, refer to **Lobato et al. (2012)**.

Vertical Transport

Elevators

Elevator car lighting and ventilation are typically powered whether or not the car is occupied.

- ☐ Control elevator lighting and ventilation with occupancy sensors to save as much as $100/year/elevator.

Stairs

Building occupants should be encouraged to use stairs to reduce energy use and improve health.

Escalators

Escalators generally operate continuously during business hours, and in some cases continuously during nonbusiness hours.

- ☐ Control escalators so that they operate only during business hours or when needed to save as much as $900/year/escalator.

Small-Scale Food Service Areas

As with the break rooms and kitchens, replacing aging, inefficient equipment with the most efficient **ENERGY STAR** equipment will save energy. Food service areas present unique challenges because they are often outfitted and operated by outside vendors. It is important to work with the vendor to supply energy-efficient PPLs that meet their needs.

Refrigerators

- ☐ Remove underused refrigerators to save$40–$80/year/ refrigerator.
- ☐ Replace aging, inefficient refrigerators with the most efficient compliant refrigerators to save $40/year/refrigerator.
- ☐ Consolidate multiple mini-refrigerators into a full-size refrigerator for a savings of $35/year/mini-refrigerator
- ☐ Replace glass-door refrigerators with similarly sized solid-door refrigerators to save $60/year/glass-door refrigerator.
- ☐ Set contractual requirements for vendors to use only the most efficient commercial refrigerators.

Nonrated Equipment

For equipment that is not rated by ENERGY STAR, or similar organizations, those responsible for specification and procurement should work directly with manufacturers to determine the most efficient option. Many manufacturers offer low-energy equipment options.

Small Kitchen Appliances

- ☐ Upgrade items such as coffee pots, toasters, and microwaves with units that have limited parasitic loads from status LED lights or displays to save $1/year/item.
- ☐ Control these items with electrical outlet timers so they are powered down during nonbusiness hours to save $3/year/item.
- ☐ Set contractual requirements for vendors to use only the most energy-efficient items.

Parasitic Loads

Food service equipment can have large parasitic loads during nonbusiness hours.

- ☐ Control equipment with electrical switches, or a similar method, to easily disconnect power to all nonessential equipment during nonbusiness hours.
- ☐ Set contractual requirements for vendors that will ensure that the equipment is disconnected and powered down during nonbusiness hours.

Strategies

Conference Room Equipment

Conference rooms are subject to varying use schedules.

- ☐ Implement controls that disconnect or turn off equipment when the space is unoccupied. Electrical outlet timers can be used to power down equipment during nonbusiness hours. Occupancy sensors can be used to disconnect power when the rooms are unoccupied during business hours.
- ☐ Outfit the space with energy-efficient equipment. LED backlit LCD televisions and energy-efficient projectors should be used for display purposes.

Server Room Equipment

- ☐ Implement an uninterruptible power supply that has the following features:
  - ☐ At least 95% energy efficiency
  - ☐ Scalable design
  - ☐ Built-in redundancy
  - ☐ End user serviceable
  - ☐ Sufficient uptime until the backup generator starts
  - ☐ Meets the efficiency guidelines of the **Server System Infrastructure** initiative, which sets open industry specifications for server power supplies and electronic bays.
- ☐ Load the uninterruptible power supply so it operates at peak efficiency.
- ☐ Use energy-efficient power distribution units.
- ☐ Use blade servers with variable-speed fans and energy-efficient power supplies.
- ☐ Implement virtualization software.
- ☐ Implement a hot aisle/cold aisle configuration.
- ☐ Implement hot aisle containment .
- ☐ Depending on climate zone, implement economizers and evaporative cooling.
- ☐ Capture waste heat from the servers for use in other areas of the building.

NREL (2013) and **Sheppy et al. (2011)** provide more details about energy reduction strategies in server rooms and data centers.

Telecommunications Room Equipment

Typical telecommunications rooms provide continuous power to all Ethernet switches and ports.

- ☐ Power these switches and ports based on occupant needs.

Additional Strategies

For office buildings that have large file storage needs, motorized compact shelving units should be replaced with manual hand crank compact shelving units to save energy.

Management policies should be implemented to address PPLs. These policies should minimize or eliminate the use of personal electronic equipment (coffee makers, fans, heaters, mini-refrigerators, decorative lighting, etc.) at the workstations. The policies should establish a standardized list of the energy-efficient equipment to be used in the building. They should provide a process for addressing atypical circumstances that may warrant what would otherwise be excessive PPL energy use.

For items that have not yet been addressed, refer to Lobato et al. (2011b) for the process required to power down PPLs when not in use. Items such as lobby displays, ice machines, and exercise equipment can be effectively controlled by commercially available control devices. The devices should be configured so the equipment is powered only during business hours.

For new construction and extensive retrofits, it is good practice to aggregate plug loads onto dedicated electrical panels. With dedicated plug load panels, the circuits can be integrated with the building control system to turn off all plug loads during nonbusiness hours. These panels also allow for easy energy submetering, which can be used to develop a building PPL energy use display system that can provide feedback to the building occupants.

Recommended Plug Load Energy Reduction Strategies for Office Buildings

Shown on the following page is a sample of the workbook available for **download** in full as an Excel file. It will help you identify potential energy savings by reducing plug loads.

For each strategy listed, answer the question "Is your building doing this?" If your response is "No" for any strategy, fill out the adjacent cells to the right to determine the total approximate savings that the given strategy could yield in your building. Strategies that are listed without savings numbers are highly variable depending on the office building being assessed.

Strategies

	Is your building doing this?			If you answered "NO," enter the quantity for each piece of equipment below to determine the approximate savings in your building.		
Strategies	**YES**	**NO**	**N/A**	**Potential Energy Savings per Piece of Equipment**	**Quantity in Your Building**	**Potential Annual Savings for Your Building (kWh)**
▸ Break Rooms and Kitchens						
Remove underused refrigerators	☐	☐	☐	**400 kWh/year** for every underused refrigerator that is removed	x___=	
Replace aging, inefficient refrigerators with one of the most efficient, full-size ENERGY STAR® refrigerators for every 60 people	☐	☐	☐	**400 kWh/year** for every inefficient refrigerator that is replaced	x___=	
Consolidate personal mini-refrigerators into a full-size shared refrigerator	☐	☐	☐	**350 kWh/year** for every mini-refrigerator that is removed	x___=	
Replace glass-door refrigerators with similarly sized solid-door refrigerators	☐	☐	☐	**600 kWh/year** for every glass-door refrigerator that is replaced	x___=	

NOTE: Potential energy savings are based on an assumption of 10 hours of operation per work day

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After-hours Power Status of Office Equipment and Energy Use of Miscellaneous Plug-Load Equipment

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To download this paper and related data go to:
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Abbreviations, Acronyms, and Glossary of Terms

As Used in This Report

CRT — cathode ray tube (monitor)

CPU — central processing unit

ICS — integrated computer system, in which computer and monitor share a power cord, (e.g., an LCD monitor powered through a computer) and may also share a housing (e.g., an Apple iMac)

ILPS — in-line power supply: a type of external power supply found on the cord between the plug and the device; aka "fat snake" because it looks like the power cord swallowed a box or cylinder

LBNL — Lawrence Berkeley National Laboratory (aka LBL or Berkeley Lab)

LCD — liquid crystal display (monitor)

ME — miscellaneous (plug-load) equipment

MFD — multi-function device: a unit of digital equipment that can perform at least two of the following functions: copy, fax, print, scan

OE — office equipment

OEM — original equipment manufacturer

OS — operating system (e.g., Windows XP or Mac OS X)

PC — personal computer: a generic term that includes laptop computers, desktop computers and integrated computer systems; it includes both Apple and Intel-architecture machines

PDA — personal digital assistant; a cordless (i.e., rechargeable) hand-held computer device

PIPS — plug-in power supply: a type of external power supply that is incorporated into the cord's plug; aka "wall wart"

PM — power management: the ability of electronic equipment to automatically enter a low power mode or turn itself off after some period of inactivity; PM rate is the percent of units *not off* that are in low power.

PM rate: — the extent to which a given sample or type of equipment is *actually found* to have automatically entered a low power mode or turned itself off.

PM Enabling rate: — the extent to which *settings in the user interface* of a given sample or type of equipment indicate the equipment is set to automatically enter low power or turn itself off.

XPS — external power supply: a power supply external to the device that it powers; a voltage regulating device incorporated into either the power cord or the wall plug of a device

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Abstract

This research was conducted in support of two branches of the EPA ENERGY STAR program, whose overall goal is to reduce, through voluntary market-based means, the amount of carbon dioxide emitted in the U.S. The primary objective was to collect data for the ENERGY STAR Office Equipment program on the after-hours power state of computers, monitors, printers, copiers, scanners, fax machines, and multi-function devices. We also collected data for the ENERGY STAR Commercial Buildings branch on the types and amounts of "miscellaneous" plug-load equipment, a significant and growing end use that is not usually accounted for by building energy managers. For most types of miscellaneous equipment, we also estimated typical unit energy consumption in order to estimate total energy consumption of the miscellaneous devices within our sample. This data set is the first of its kind that we know of, and is an important first step in characterizing miscellaneous plug loads in commercial buildings.

The main purpose of this study is to supplement and update previous data we collected on the extent to which electronic office equipment is turned off or automatically enters a low power state when not in active use. In addition, it provides data on numbers and types of office equipment, and helps identify trends in office equipment usage patterns. These data improve our estimates of typical unit energy consumption and savings for each equipment type, and enables the ENERGY STAR Office Equipment program to focus future effort on products with the highest energy savings potential.

This study expands our previous sample of office buildings in California and Washington DC to include education and health care facilities, and buildings in other states. We report data from sixteen commercial buildings in California, Georgia, and Pennsylvania: four education buildings, two medical buildings, two large offices (> 500 employees each), three medium offices (50-500 employees each), and five small business offices (< 50 employees each). Two buildings are in the San Francisco Bay area of California, nine (including the five small businesses) are in Pittsburgh, Pennsylvania, and five are in Atlanta, Georgia.

Introduction

Since the 1980s there has been continual growth in the market for electronic office equipment, particularly personal computers and monitors, but also printers and multi-function devices, which are replacing discrete copiers, fax machines and scanners in some office environments. According to 2003 projections by the Department of Energy, annual energy use by personal computers is expected to grow 3% per year, and energy use among other types of office equipment is expected to grow 4.2%; this growth is in spite of improvements in energy efficiency, which are expected to be offset by "continuing penetration of new technologies and greater use of office equipment" (EIA 2003).

In 1992 the US Environmental Protection Agency (EPA) launched the voluntary ENERGY STAR program, designed to curb the growth of CO_2 emissions by labeling the most energy-efficient electronic products for the mutual benefit of manufacturers, consumers, and the environment.[1] The first products to be labeled were computers and monitors; printers were added in 1993, fax machines in 1994, copiers in 1995, and scanners and multi-function devices in 1997 (EPA/DOE 2003). Continued improvement in energy savings among office equipment remains a focus of the ENERGY STAR program, which updates its product specifications as necessary to respond to changes in technology, energy consumption, and usage patterns.

ENERGY STAR labeled office equipment reduces energy use primarily through power management (PM), in which equipment is factory-enabled to automatically turn off or enter low power (any power level between off and on) after some period of inactivity, usually 15 or 30 minutes. Most office equipment is idle more often than it is active; among equipment that users tend to leave on when not in use, such as shared and networked devices, PM can save significant energy. ENERGY STAR devices have a large market share, but the percentage that actually power manage is lower for several reasons. Power management is sometimes delayed or disabled by users, administrators, or even software updates that change the factory settings in the interface; in addition, some network and computing environments (e.g., the Windows NT operating system) effectively prevent PM from functioning.

To accurately estimate energy savings attributable to the ENERGY STAR program, and target future efforts, current data are needed on the extent to which each type of office equipment is turned off or successfully enters low power mode when idle. Combined with measurements of the energy used in each power state, we can estimate typical unit energy consumption (UEC), which, combined with number of units currently in use, provides an estimate of total energy use, and program savings (Webber, Brown et al. 2002).

In our ongoing technical support of the ENERGY STAR program, the Energy Analysis Department at Lawrence Berkeley National Lab (LBNL) has conducted after-hours surveys (aka night-time audits) of office equipment in commercial buildings. Our previous series of surveys was conducted during the summer of 2000; it included nine buildings in the San Francisco Bay area and two in the Washington DC area. We recruited and surveyed a diversity of office types and documented just over 100 computers per site, on average. We collected data on the types, power states and PM delay settings of ENERGY STAR labeled office equipment (computers, monitors, copiers, fax machines, printers, scanners and multi-function devices). The methods and results of that study were reported previously (Webber, Roberson et al. 2001).

---

[1] The ENERGY STAR® program has expanded to include residential appliances and heating and cooling equipment, consumer electronics, building materials and components, refrigeration equipment, commercial buildings and new homes. Since 1996 it has been jointly administered by the U.S. EPA and DOE (http://energystar.gov/).

In that study we also recorded (but did not report) numbers of some 'miscellaneous office equipment,' such as computer speakers, external disk drives, portable fans and heaters, boomboxes, and battery chargers.

In this report, we present the results of our most recent (2003) after-hours survey of commercial buildings, which expanded on the previous study to include:

buildings in Pittsburgh, Pennsylvania and Atlanta, Georgia,
education buildings, health care buildings, and small offices, and
an inventory of miscellaneous plug-load equipment.

As part of our ongoing effort to improve the accuracy of data used to evaluate the ENERGY STAR program, we wanted to capture data from a wider range of commercial building types and geographic regions. While our sample is not large enough to distinguish regional differences in equipment night-time or after-hours power status, we hope to improve the robustness of our data by increasing its geographic diversity. Also, because office equipment is not confined to offices or office buildings, we wanted to capture data from other types of commercial buildings, such as schools, which also have significant numbers of computers.

Collecting data on after-hours power status involves visiting buildings when most employees are gone. Given the difficulty of arranging after-hours access to most commercial buildings, we used this opportunity to simultaneously collect data for the ENERGY STAR Commercial Buildings program on the types and numbers of miscellaneous plug-load equipment, and to develop a taxonomy by which to categorize them. These data allow us to begin to better characterize the large 'plug-load' building energy end use category.

Methodology

The protocol used in this series of surveys changed from that of 2000 because of the need to develop a data collection protocol for miscellaneous equipment, and then integrate it with our office equipment protocol.

Building Sample

Table 1 below outlines the buildings in our sample, which are identified by a letter; for this purpose the small businesses are aggregated into one 'small office.' Appendix A describes them in more detail, but only in generic terms, to preserve the anonymity of occupants. As in 2000, our initial target was to collect data on at least 1,000 computers. In selecting types and numbers of commercial buildings to comprise that sample, we referred to data on computer densities provided by the Commercial Building Energy Consumption Survey (CBECS) (EIA/CBECS 2002). According to CBECS, in 1999, 74% of the U.S. population of computers were found among office, education, and health care buildings; therefore, our building recruitment effort focused on these three types of buildings. CBECS further characterizes offices by number of employees: 0-19 (small), 20-499 (medium), and 500+ (large).

To familiarize ourselves with what to expect (in recruitment effort and equipment found) in schools and health care buildings, we began by surveying a high school and a medical clinic in the San Francisco area. We then recruited and surveyed a variety of buildings in Pittsburgh in April, and Atlanta in June 2003.

Site recruitment is one of the most difficult and time consuming aspects of commercial building surveys. Usually it involves cold-calling from a list of prospective business or building types (e.g., high schools), briefly describing our research activity, and trying to connect with the person who is able and willing to grant after-hours access, which involves providing a key and/or escort. Most facilities have real concerns about safety, security, and privacy (e.g., of client or patient records), which of course must be addressed.

In each building, we surveyed as much area as possible in four hours or until we covered the area accessible to us, whichever came first. At two sites we surveyed a single floor, at four sites we surveyed the entire space available to us, and at the remaining six sites we surveyed portions of two or three floors. In general, the greater the density and variety of equipment found, the less area we covered in four hours. Floor areas are approximate gross square feet, based on floor plans or information from facility managers.

Table 1. Building Sample and Computer Density

site	state	building type	occupancy	in area surveyed (approximate no.)			computer density per	
				computers	ft^2	employees	1000 ft^2	employee
A	GA	education	university classroom bldg	171	28,000	n/a	6.1	n/a
B	PA	medium office	non-profit headquarters	182	55,000	128	3.3	1.42
C	GA	large office	corporate headquarters	262	28,000	120	9.4	2.18
D	CA	education	high school	112	40,000	n/a	2.8	n/a
E	GA	medium office	business consulting firm	37	22,000	70	1.7	0.53
F	PA	education	high school	248	100,000	n/a	2.5	n/a
G	CA	health care	outpatient clinic	177	45,000	n/a	3.9	n/a
H	GA	medium office	information services dept	153	24,000	76	6.4	2.01
J	PA	health care	private physicians' offices	56	26,000	n/a	2.2	n/a
K	PA	small office	5 small businesses combined	117	20,000	77	5.9	1.52
M	PA	large office	corporate headquarters	73	40,000	125	1.8	0.58
N	GA	education	university classroom bldg	95	20,000	n/a	4.8	n/a
			total	**1,683**	**448,000**	n/a = not available		

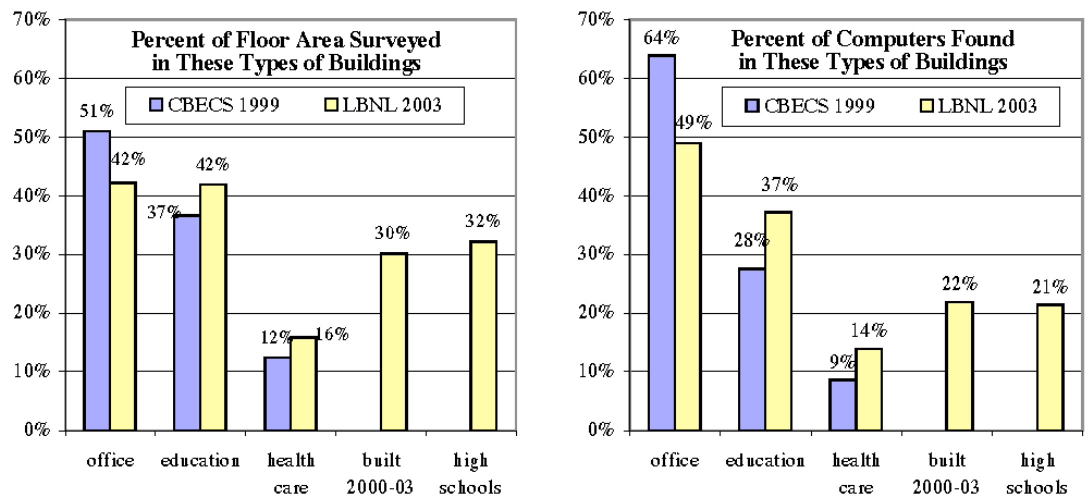
Our characterization of offices differs slightly from that of CBECS. By our definition a small office has <50 employees, a medium office has 50-500 employees, and a large office has >500 employees on site. Also, CBECS appears to classify offices by the number of employees per building, while we classify them by the number of employees per location. For example, our site E is a 'medium office' (50-500 employees) that occupies one floor of a high-rise office tower; however, CBECS might consider the same office to be part of a 'large office' (over 500 employees) that includes all offices within the entire building.

Our 'small office' is actually aggregated results for five small businesses in three different buildings: (1) a graphics and printing business, (2) an environmental consulting firm, (3) a commodity brokerage firm, (4) a software development firm, and (5) an engineering firm. Their number of employees ranged from 4 to 25, with a collective total of 77 employees.

For the six offices in our sample, Table 1 also shows the approximate density of computers by gross square feet as well as per employee. We do not have number of employees (or computer density per employee) for education and medical facilities. For high schools, where the number of students is known, equipment density per student could be a useful metric if we had surveyed the entire building, which we did not. The number of students regularly using a university classroom building, as well as the number of employees in both education and medical buildings is much more variable and difficult to determine.

Although we used the CBECS data as a starting point in our building selection and recruitment efforts, our resulting building sample does not necessarily correspond to the much larger CBECS building sample. Figure 1 below compares our building sample to CBECS, based on the sum of floor area surveyed and number of computers found among all office, education, and health care buildings in each sample. Compared to CBECS, offices are somewhat under-represented in our current sample, while education and health care buildings are somewhat over-represented. In addition, new buildings and high schools may be over-represented in our building sample, though we don't have corresponding CBECS data for comparison.

Figure 1. Comparison of LBNL and CBECS Commercial Building Samples



Survey Protocol

Each survey takes four people up to four hours to complete, and occurs on a weekday evening or weekend. We usually work in two teams of two people, with one calling out information and the other recording it. Using a floor plan, clipboard, flashlight and tape measure, we systematically record each plug-load device. The flashlight helps in tracing cords to plugs, and the tape is used to measure TV and monitor screen sizes. Our data collection is as unobtrusive as possible; we don't turn computers on or off or access any programs, settings, or files. If a workspace is occupied or obviously in use, we skip it and return later, if possible.

Office Equipment Data Collection

For our purposes in this study, office equipment includes the following equipment categories and types:

computers: desktop, laptop (notebook or mobile), server, and integrated computer system (ICS);
monitors: cathode ray tube (CRT), and liquid crystal display (LCD);
printers: impact, inkjet, laser, thermal, solid ink, and wide format;
fax machines: inkjet, laser, and thermal;
copiers;
scanners: document, flatbed, slide, and wide format; and
multi-function devices: inkjet and laser.

For each unit of office equipment, we recorded the make (brand) and model as it appears on the front or top of the unit (we did not record information from the nameplate on the bottom or back of the unit). We recorded the diagonal measurement, to the nearest inch, of monitor screens, except those of laptops (note: for CRT monitors this measurement is smaller than the nominal screen (or tube) size). For laser printers and MFDs we scrolled through the menu options available in the user interface to find the "power save delay setting," which usually ranges from 15 minutes to "never."

We tried to record each unit of office equipment that had an external power supply (XPS). These devices offer significant potential for energy efficiency improvement because they draw power even when the unit of which they are part is turned off or disconnected (e.g., when a laptop computer or cell phone is removed from its charger, which remains plugged in). We distinguish two types of external power supply: a plug-in power supply (PIPS), in which an AC/DC voltage transformer is incorporated into the plug, and an in-line power supply (ILPS), which is incorporated into and appears as an enlarged part of the power cord. We also tried to record whether or not each printer, copier, and MFD was connected to a network via cable (to the extent that networks become wireless, network connection will become more difficult to determine).

The power state of each unit was recorded as on, low, off, or unplugged (exception: we did not record units that were unplugged if it appeared they were never used). Although some office equipment, particularly copiers, may have features that enable them to turn off automatically or enter low power manually (by user action), we assume that the vast majority of units found off were turned off manually (i.e., by a user) and that units found in low power entered that state automatically (i.e., without user action).

If a monitor/computer pair were both on, we recorded the screen content; the most common occurrences are a screensaver, application, log-in or other dialog box (e.g., "It is now safe to turn off your computer"). When a monitor is off and the computer to which it is connected is not, it can be difficult to tell whether the computer is on or in low power. The method we used to determine a PC's power state is outlined in Appendix B; in short, a clampmeter is used to measure relative current in the computer power cord before and after initiating a computer wake function, such as touching the mouse or keyboard (McCarthy, 2002).

The power state of a laptop computer is usually difficult to determine, unless it is in use and obviously on. A closed laptop has few external indicators, and those that are present are often ambiguous and inconsistent (e.g., between brands or models). In terms of improving our estimates of laptop unit energy consumption, the most relevant data are the amount of time each laptop spends plugged in, and how often its battery is (re)charged. Therefore, we recorded, at a minimum, whether or not each laptop was plugged in.

In this report the term 'computer workstation' refers to any combination of computer(s) and monitor(s) physically used by one person at a time; generally, there is a workstation associated with each office chair. Workstation configurations vary widely; most common is one desktop computer connected to one monitor, but we have noticed growing numbers of other configurations, including multiple computers with one monitor, multiple (usually LCD) monitors with one computer, and laptops used with a docking station and monitor. In this series of surveys, we identified each computer workstation by a unique number; i.e., all components of each workstation were identified by the same number. We did this for two reasons: first, to facilitate subsequent analysis of the relationship between computer and monitor power states; and second, to be able to characterize the variety of workstations found. These analyses are discussed in the Results.

Miscellaneous Equipment Data Collection

'Miscellaneous equipment' (ME) refers to plug-load devices whose energy use is not usually accounted for by building energy managers because they are portable, often occupant-provided units whose number, power consumption and usage patterns are largely unknown. All ME in this report, including lighting, is plug-load, as opposed to hard-wired, although for some equipment (e.g., commercial refrigerators) we did *assume* a plug. The sheer variety of ME necessitates development of a taxonomy by which it can be categorized and summarized. Appendix C presents our current miscellaneous equipment taxonomy.

For each unit of miscellaneous equipment we recorded any information (e.g., power state or rated power) that could be used to estimate unit energy consumption. For lighting we recorded lamp type (e.g., halogen), wattage, and fixture type (desk, floor, track, etc.). For battery chargers, we noted the portable component (drill, oto-opthalmoscope, walkie-talkie. etc.) and whether the charger was empty or full. For vending machines, we recorded temperature and product (e.g., cold beverage) and any lighting. For unknown equipment we noted make and model for later determination of identity and power specifications.

As with office equipment, we noted if there was a PIPS or ILPS. We also recorded PIPSs and ILPSs that were plugged in but unattached to equipment (such as a PIPS used to charge an absent cell phone) and those whose equipment could not be identified, such as among a maze of cords in a server room. Nevertheless, we undoubtedly missed some, so our reported number of PIPSs and ILPSs is actually a conservative estimate.

Limitations of This Methodology

One advantage of conducting after-hours building walk-throughs to collect data on office equipment power status is that a good variety and number of buildings can be recruited and surveyed. On the other hand, the data collected represent a snapshot in time, and do not capture variations in user behavior over time, which would require automated long-term time series metering of equipment power state and power levels.

This is our most robust sample of buildings to date for collecting data on the after hours power status of office equipment. It includes data on 1,683 computers (including desktops, ICSs, laptops and servers) and about 448,000 ft^2 in 12 commercial buildings, including schools and health care facilities in California, Georgia, and Pennsylvania. (In comparison, our previous (2000) survey included 1,280 computers in 11 office buildings in California and Washington DC.) However, we do not suggest that this sample is representative of commercial buildings as a whole or in part (e.g., by type, size, age, or location), or that the results presented here are statistically significant. It is a record of what we found that we hope will be of use to policy makers, researchers, and building managers.

Results and Discussion

Equipment Density

Table 2 shows the number and density, per 1000 approximate gross square feet, of office equipment, miscellaneous equipment, and the sum of OE and ME in each building, and for all buildings. Our survey captured data on over 10,000 units of equipment, including almost 4,000 units of office equipment.

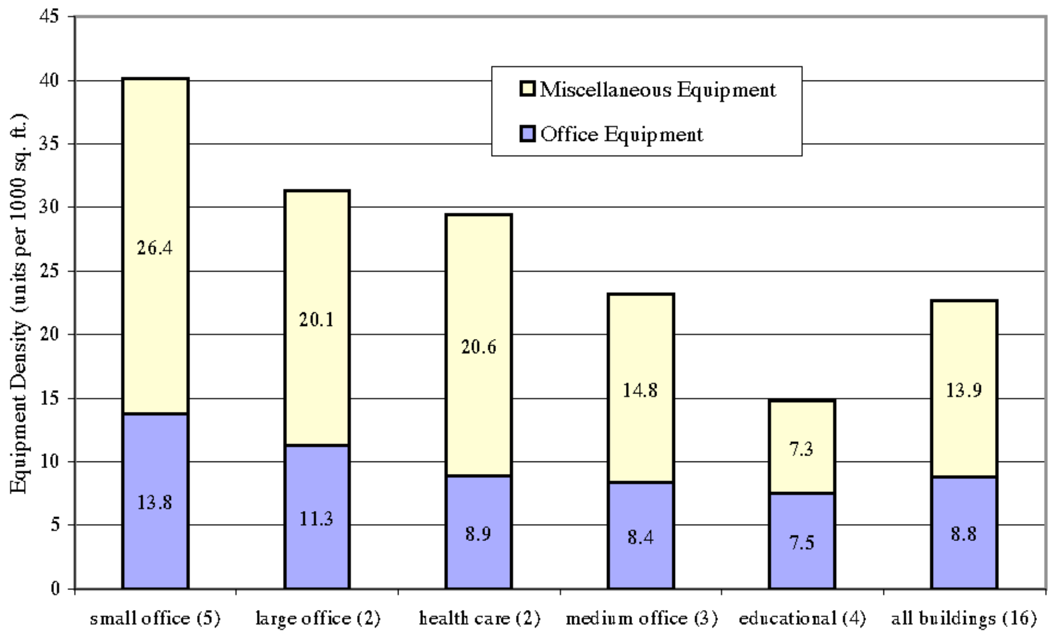
Table 2. Office and Miscellaneous Equipment: Number of Units and Density
sorted by Density of Office Equipment (units/1000 ft^2)

		Number of Units			Density (units/1000 ft^2)			Density (units/employee)		
bldg type	**site**	**OE**	**ME**	**OE+ME**	**OE**	**ME**	**OE+ME**	**OE**	**ME**	**OE+ME**
medium office	**E**	98	441	**539**	4.5	20.0	**24.5**	1.4	6.3	7.7
education	**F**	574	596	**1,170**	5.7	6.0	**11.7**			
large office	**M**	227	753	**980**	5.7	18.8	**24.5**	1.8	6.0	**7.8**
education	**D**	258	291	**549**	6.5	7.3	**13.7**			
health care	**J**	171	458	**629**	6.6	17.6	**24.2**			
medium office	**B**	410	422	**832**	7.5	7.7	**15.1**	3.2	3.3	**6.5**
education	**N**	204	234	**438**	10.2	11.7	**21.9**			
health care	**G**	460	1,002	**1,462**	10.2	22.3	**32.5**			
education	**A**	377	259	**636**	13.5	9.3	**22.7**			
small office	**K**	275	528	**803**	13.8	26.4	**40.2**	3.6	6.9	**10.4**
medium office	**H**	340	630	**970**	14.2	26.3	**40.4**	4.5	8.3	**12.8**
large office	**C**	540	612	**1,152**	19.3	21.9	**41.1**	4.5	5.1	**9.6**
all buildings		**3,934**	**6,226**	**10,160**	**8.8**	**13.9**	**22.7**	**3.2**	**5.7**	**8.9**

Note that the numbers of miscellaneous equipment units in Table 2 are lower than those in Appendix D because Table 2 does not include plug-in and in-line power supplies, while Appendix D does.

Figure 2 illustrates office and miscellaneous equipment density (per 1000 square feet), by building type.

Figure 2. Office and Miscellaneous Equipment Density, by Building Type (and number)



From Table 2 we see that the two buildings with the lowest combined equipment density are high schools, and Figure 2 shows that education buildings in our sample had the lowest equipment densities overall. Among our sample of 12 buildings, building types with the highest densities are small and large offices. We suggest that small offices may have high equipment density because every office needs certain devices (e.g., copier, fax machine, microwave oven, refrigerator), regardless of how many (or few) people share it. Medium offices exhibited a range of density (see Table 2, sites B, H), but on average their office equipment density is similar to and their miscellaneous equipment density is lower than that of health care facilities.

Closer examination of the results for each building reveals some underlying trends. For example, the only two buildings with a computer density less than 2 per 1000 ft^2 (from Table 1) were offices (one medium, one large) whose employees tend to rely on laptop computers, most of which were absent during our visit; one of these companies *requires* employees to take their laptops home or lock them up when not at work.

Office Equipment

Our sample includes data on the power state of 1,453 desktop computers (well above our target of 1,000), 1,598 monitors, 353 printers, 89 servers, 79 MFDs, 47 fax machines, 45 ICSs, 34 scanners, and 33 copiers. Among printers, our discussion of results will focus on the 158 laser and 123 inkjet printers found.

Among all buildings, computer density ranges from 1.7 to 9.4 per 1000 ft^2 gross floor area, (see Table 1). Among office buildings only, computer density ranges from 0.53 to 2.18 per employee. Office equipment density ranges from 4.5 to 19.3 units per 1000 ft^2 gross floor area, with an average of 8.8 (see Table 2). Among offices, office equipment density ranges from 1.4 to 4.5 units per employee, with an average of 3.2.

When analyzing the numbers of equipment in each power state, we are primarily interested in two values: turn-off rates and power management rates. 'Turn-off rate' is the percent of each equipment type that is turned off, while 'PM rate' is the percent of those *not off* that are in low power.

Table 3 shows the numbers of each type of office equipment, and their after-hours power state. Table 3 does not include laptop computers, units that were unplugged, or units whose power state was unknown.

Table 3. Office Equipment: After-hours Power States

Equipment		Number				Percent			
Category	**Type**	**on**	**low**	**off**	**sum**	**on**	**low**	**off**	**PM rate**
computers	desktop	869	60	524	1453	60%	4%	36%	6%
	server	87		2	89	98%	0%	2%	n/a
	ICS	7	11	27	45	16%	24%	60%	61%
monitors	CRT	259	648	422	1329	19%	49%	32%	71%
	LCD	56	164	49	269	21%	61%	18%	75%
printers	laser	53	81	24	158	34%	51%	15%	60%
	inkjet	86		37	123	70%	n/a	30%	n/a
	impact	16		6	22	73%	n/a	27%	n/a
	thermal	31		7	38	82%	n/a	18%	n/a
	wide format	2		6	8	25%	0%	75%	0%
	solid ink	1	3		4	25%	75%	0%	75%
MFDs	inkjet	9	4	3	16	56%	25%	19%	31%
	laser	36	14	13	63	57%	22%	21%	28%
copiers	all	12	5	16	33	36%	15%	48%	29%
fax machines	all	44	3		47	94%	6%	0%	6%
scanners	all	8	12	14	34	24%	35%	41%	60%

Note: "PM rate" is the percent of units *not off* that were in low power.

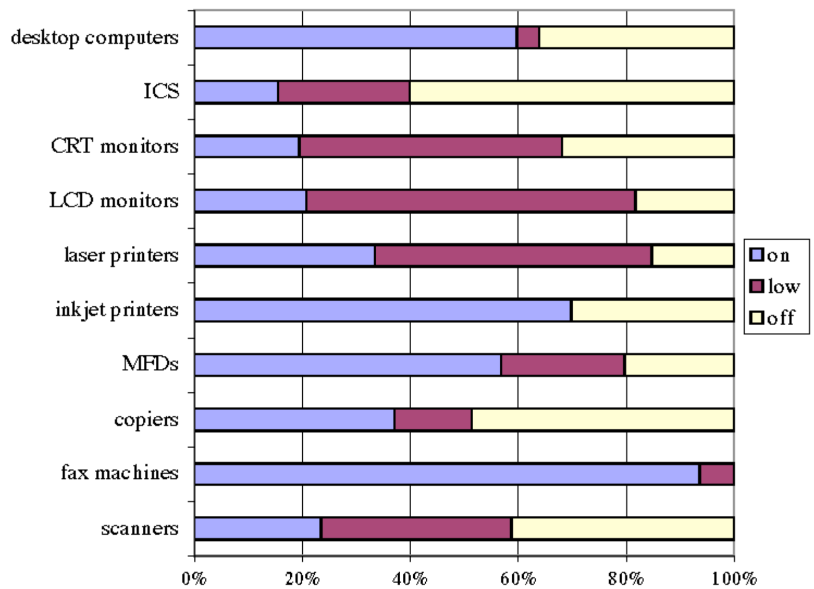
Not surprisingly, turn-off rates were lowest among fax machines and server computers. Turn-off rates were highest for integrated computer systems (60%), copiers (48%), and scanners (41%). PM rates were highest among LCD monitors (75%), CRT monitors (71%), ICSs (61%), scanners (60%), and laser printers (60%).

The lowest power management rates were among desktop computers and fax machines (6% of each). Because copiers and MFDs often have long (2-4 hour) PM delay settings that may not have elapsed at the time of our visit, PM rates in Table 3 for this equipment should be considered a minimum or lower bound. Figure 3 (below) graphically shows the breakdown by power state of each major type of office equipment.

Computers

We categorized computers as either desktop, integrated computer systems, servers, or laptops. Among 1,453 desktop computers the turn-off rate was 36%; it ranged from 5% (at Site E, medium office) to 67% (at Site B, medium office). Only 6% of all desktop computers that were not off were in low power. This PM rate is similar to the 5% rate found in a previous study (Webber, Roberson et al. 2001). Among the 45 ICSs in Table 3 the turn-off rate was 60%, and the PM rate was 61%. However, it is possible that of the 11 ICSs found in low power, only the display (but not the CPU) was in low power.

Figure 3. Office Equipment Power States



Among education buildings in our sample, the majority of the desktop computers, monitors and ICSs were found in classrooms clearly dedicated to computer-based learning. These "computer labs" typically have a 1:1 ratio between computers and chairs. Among the two high schools, 65% of desktop computers and ICSs were found in computer labs with at least 15 (and up to 77) computers each; among the two university classroom buildings, 68% of desktop computers and ICSs were found in computer labs with at least 15 (and up to 57) computers each. Because a single instructor likely controls the after-hours power status of all equipment in these rooms, and also because school buildings in general experience more 'after-hours' per year than other buildings, computer labs present a target for energy-efficiency efforts in schools.

Laptop Computers

There are 50 laptop computers in our sample, and we recorded information on the power state of 37. Of those 37, all but two (or 95%) were plugged in, either through their power cord or a docking station. Nine (or 24%) of the 37 laptops were clearly on; i.e., their display showed a desktop, application, or login screen.

Sixty percent (60%, or 21) of the 35 laptops that were plugged in were plugged into docking stations.[2] Of 107 docking stations found, 20% (21) were 'full', i.e., contained laptops, while 80% (86) were 'empty,' or without laptops. Those empty docking stations are evidence of at least 86 more laptops that were absent at the time of our visit. In addition, we found 35 power cords with ILPSs that we identified as "laptop charger, empty" (which we consider in the 'power' category of ME). Combined with 50 laptops and 86 empty docking stations found, we conclude that at least 171 laptop computers are in use among our sample of buildings. Of course, this number does not include (and we did not attempt to estimate) the number of people who take both their laptop and its power cord/battery charger home or lock them up at night.

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[2] Docking stations are in our 'peripheral' miscellaneous equipment category; laptop computers are office equipment.

If we compare this minimum number of laptop computers to the total number of non-server computers in our sample, from Table 3 (1,453 desktops + 45 ICSs, + 171 laptops = 1669 total), laptops comprise approximately 10% of non-server computers found in our survey; again, this is a conservative estimate.

Some offices appear to have largely switched from desktop to laptop computers. Table 4 shows that in two (of six) offices in our sample – one large and one medium office – the sum of laptop computers, empty docking stations and empty laptop battery chargers (ILPSs) outnumbered the desktop computers found.

Table 4. Ratio of Laptop to Desktop Computers at Two Sites

Site	no. of desktop computers	number of laptop computers			
		laptops found	empty docking stations	empty laptop chargers	**estimated total**
E	**20**	4	11	9	**24**
M	**41**	26	40	9	**75**

Monitors

The average turn-off rate among 1,329 CRT monitors was 32%; it ranged from 17% at Site E (medium office) and N (university) to 62% at Site D (high school). 71% of CRT monitors that were not off were in low power. Among the 269 LCD monitors in Table 3 the turn-off rate was 18% and the PM rate was 75%.

Assigning a unique number to each computer/monitor workstation enabled us to analyze the relationship between computer power state and monitor power state. Table 5 shows the results of that analysis. (Note: Table 5 does not include monitors connected to more than one computer.)

Table 5. Analysis of Monitor Power Management by Computer Power State

						Monitor Power Management *	
			Monitor Power State			Monitor PM Rate (computer is off or in low power)	PC-initiated Monitor PM Rate (computer is on)
Computer	**Computer Power state**	**No.**	**Off**	**Low**	**On**		
Desktop	Off/no signal	433	184	244	5	98%	
	Low	59	4	53	2	96%	
	On	689	154	286	249		53%
Laptop **	Absent or empty docking station	55	13	42	0	100%	
	Plugged-in or in docking station	23	4	15	4	79%	
Server	On	32	14	10	8		56%

*Monitor Power Management is the percent of monitors *not off* that are in low power

** These data refer to external monitors connected to laptop computers, not to the laptop display.

Computers can initiate low power modes in ENERGY STAR monitors. Power management settings in the computer operating system (OS) control panels determine if and when the computer sends a signal to the monitor that causes the monitor to enter low power. If an ENERGY STAR monitor is attached to a computer that is on, it will enter low power only if it receives this signal. "PC-initiated monitor PM rate" refers to the share of systems in which the computer signals the monitor to initiate PM, and the monitor responds. We can infer this rate only among systems in which the computer is on and the monitor is not turned off.

An ENERGY STAR monitor can also enter low power if there is no video signal from the computer, either because the computer is off, it is in low power, or the monitor is disconnected from the computer. "Monitor PM rate" refers to the share of monitors that power manage in the absence of a signal from the computer.

Among monitors that were not turned off, those connected to computers that were off or absent had monitor power management rates of 98% (with desktop computers) and 100% (with laptops); monitors not off and connected to desktop computers that were in low power had a 96% monitor PM rate. In the remaining cases, the monitor may have been incapable of power managing (i.e., it was non-ENERGY STAR). Monitors not off and connected to desktop or server computers that were on had PC-initiated monitor PM rates that were much lower: 53% (for desktop computers) and 56% (for servers). Clearly, monitors that depended on a computer signal to initiate power management were much less likely to enter low power.

In our 2000 study we did not uniquely identify each workstation and so could not conduct this analysis. However, our 2003 monitor "PC-initiated PM rate" differs from the monitor "PM enabling rate" of another recent but unpublished study. In 2001, researchers at Energy Solutions in Oakland CA (O'Sullivan 2003) used **EZ Save** software[3] to remotely obtain (via local area networks) the PM *settings* of over 7,000 computer monitors at 17 commercial and institutional sites in the San Francisco Bay area. They found that monitor PM settings in the computer OS control panel were enabled for 44% of monitors. We would expect the share of monitors that *actually* power manage when the computer is on to be lower than the share of computers *enabled* to power manage their monitors (because some monitors may not be ENERGY STAR, there may be network interferences with PM, etc). However, our "PC-initiated PM rate" of 53% for desktop computers is higher than the 44% "PM enabling rate" found by Energy Solutions. There are several possible explanations for this:

1) Energy Solutions' 2001 sample contained significantly more computers using the Windows NT OS (which does not support PM and is no longer supported by Microsoft) than LBNL's 2003 sample,
2) Newer computers may be more successful at initiating monitor power management, and newer computer equipment (like newer buildings) may be over-represented in our 2003 sample,
3) Our PC-initiated PM rate is calculated from a subset of monitors (those left on and attached to a PC left on), while Energy Solutions' enabling rate represents all monitors. If turn-off and enabling rates are not independent (i.e., if people who leave their devices on at night are more likely to enable than those who turn their devices off), that could explain part or all of the discrepancy.
4) PC-initiated monitor PM rates actually have risen, as individuals and organizations respond to ENERGY STAR or other educational programs about the energy savings potential of monitor PM, or
5) Our 2003 sample includes a wider variety of commercial building types and locations, and so is more representative than data collected only from office buildings in California,.

In any case, the ability of computers to power manage monitors deserves further scrutiny and improvement.

In the report on our 2000 office equipment field surveys (Webber, Roberson et al. 2001) we speculated that monitors in low power might be thought by users to be off. Among buildings in this report, Site M, a large office, offers anecdotal evidence regarding user (mis)interpretation of monitor power state. According to the facility manager, this company's strict policy is that employees turn their monitors off before leaving, and security personnel turn off any monitors found left on. Our data show that only 4% of monitors were on, but only 29% were actually off; the remaining 65% were in low power mode. This confirms our field observations that if a display is black or blank, users often assume the monitor is off, even though the front panel power indicator (which is amber and/or blinking when the unit is in low power) indicates otherwise.

LCD monitors were not even mentioned in the report on our 2000 field surveys of office equipment, but in 2003, LCDs were 17% of all monitors. As shown in Table 6, at three sites (including two high schools, D and F) we found no LCD monitors, but at two sites (E, medium office; A, university building), LCD monitors outnumbered CRT monitors, and at three others (B and H, both medium offices; and J, health care) LCDs were over 25% of all monitors found.

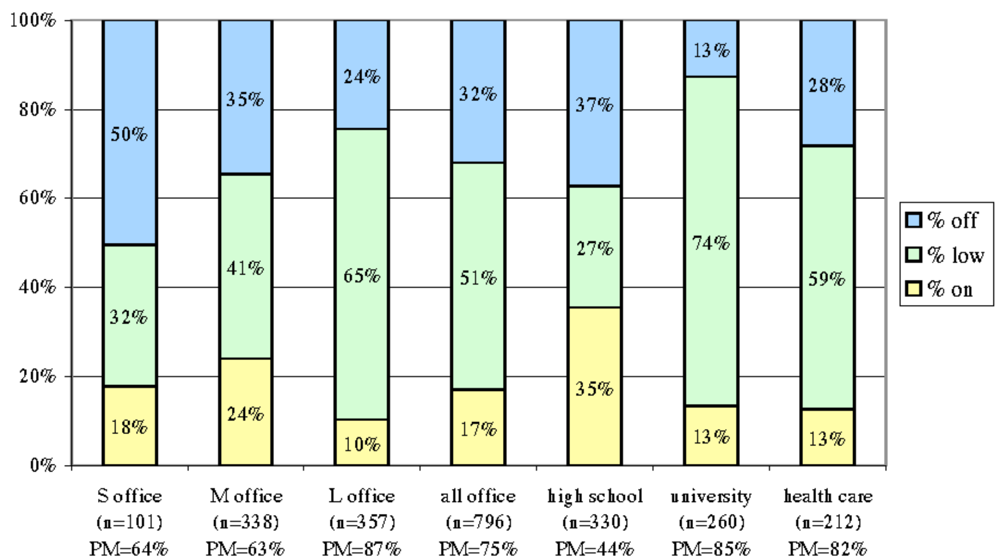
[3] **EZ Save** software was developed by the Department of Energy and adapted by the EPA ENERGY STAR program.

Table 6. Number and Percent of LCD Monitors, by Site
sorted by percent of LCD monitors

site	D	F	C	M	G	K	N	J	H	B	A	E	all
LCDs	0	0	2	4	12	14	13	18	40	66	96	21	286
CRTs	89	248	254	97	162	88	76	46	104	111	79	12	1366
total	89	248	256	101	174	102	89	64	144	177	175	33	1652
% LCDs	0%	0%	0%	4%	7%	14%	15%	28%	28%	37%	55%	64%	17%

While our building sample is not large enough to draw reliable conclusions about office equipment power management based on building type, we did some analysis within our sample. Figure 4 shows the after-hours power status of monitors (both CRT and LCD) based on building type. (A similar analysis for desktop computers and ICSs is not shown here because almost all the computers found in low power were in a single (health care) building, which may be anomalous.)

Figure 4. Monitor After-hours Power Status, by Building Type

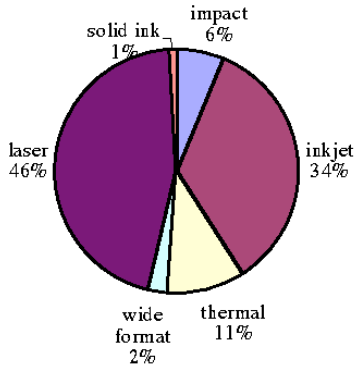


In our sample, monitor PM rates were by far the lowest in high schools (44%) and highest in university buildings (85%) and large offices (87%). Monitor turn-off rates were lowest in university buildings (13%) and highest in small offices (50%). In addition to the low monitor PM rate, a relatively high number (35%) of monitors were on in high schools, where all monitors found were CRTs, which use significantly more power when on than LCDs (Roberson, 2002). This strengthens the evidence that there is significant energy savings potential among office equipment in computer classrooms, and particularly those in high schools.

Printers

We categorize printers based on imaging technology: laser, inkjet, impact, thermal, wide format, solid ink.[4] Figure 5 shows the composition of our sample. Of 385 printers, 45% (174) were laser, 34% (132) were inkjet, 11% (41) were thermal, 6% (25) were impact, 2% (8) were wide format, and 1% (4) were solid ink.

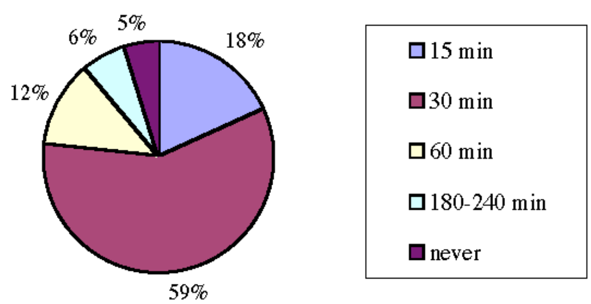
Figure 5. Printer Sample, by Technology



Of 158 laser printers in our sample, 15% were off, and 60% of those not off were in low power mode. Among the 123 inkjet printers the turn-off rate was 30%; we found no inkjet printers in low power. Of 38 thermal printers, which do not power manage, the turn-off rate was 18%. Of four solid ink printers none were off, but three (75%) were in low power.

For laser printers we tried to record "powersave" (i.e., low power) delay settings and whether or not they were networked. We did not record delay settings for laser printers that were off, or for those that did not have user interactive menus. Of 78 laser printers for which we actually recorded delay settings, 18% (14) were set to 15 minutes, 59% (46) were 30 minutes, 12% (9) were 60 minutes, 6% (5) were 180-240 minutes, and 5% (4) were set to "never" or off. Figure 6 displays this graphically.

Figure 6. Laser Printers: Powersave Delay Settings



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[4] Wide-format is not an imaging technology, but rather an ENERGY STAR category for printers that accommodate 17"x 22" or larger paper. Of 8 wide format printers in our sample, 7 used inkjet, and one used impact technology.

Among printers for which we recorded the presence or absence of a network connection, 63% of laser printers but only 7% of inkjet printers were networked.

Only 60% of laser printers not off were actually found in low power (see Table 3). Not all laser printers can power manage (i.e., they are not ENERGY STAR), and so do not have powersave delay settings. Among laser printers that can power manage, there are several reasons they might be found on during our survey: (1) the printer has a long (3-4 hour) powersave delay setting, which had not elapsed, (2) the printer was recently used, and (3) the printer is in error mode, which effectively prevents it from entering low power.

Multi-Function Devices

The ENERGY STAR Office Equipment program distinguishes 'digital copier-based MFDs,' which are covered by their MFD program, from printer- and fax-based MFDs, which are covered by their printer program. In this study, we identify any multi-function device as an MFD, and distinguish between them on the basis of imaging technology (inkjet or laser), which we think is most relevant to power consumption.

Many units of office equipment that we identified in the field as copiers, fax machines, or printers turned out, on later examination of their specifications, to actually be multi-function devices. Among the 80 MFDs eventually identified, 80% (64) used laser technology, and the remaining 20% (16) were inkjets. Turn-off and PM rates were similar for laser and inkjet MFDs. Of 63 laser MFDs in Table 3 the turn-off rate was 21%, and 28% of those that were not off were in low power. Of 16 inkjet MFDs (at least some of which can power manage) the turn-off rate was 19%, and 31% of those not off were in low power.

Copiers

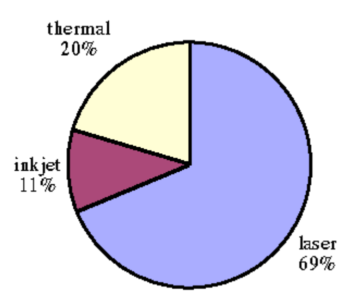
Of the 33 copy machines in Table 3, 48% were off and 29% of those that were not off were in low power. This low PM rate may be due in part to the fact that copiers often have powersave delay settings of two hours or more, and some of the copiers that we found on would eventually have entered low power.

Our 2000 field surveys of office equipment included 34 copiers and 11 'digital copier-based MFDs,' which yields a copier to 'digital copier-based MFD' ratio of 3:1. Our current sample includes 33 copiers and 64 laser or 'digital copier-based MFDs,' which yields a 2003 copier to 'digital copier-based MFD' ratio of 0.5:1. These numbers confirm our field observations that MFDs are replacing copiers in the marketplace.

Fax Machines

It can be difficult to tell whether a fax machine is on or in low power. Also, many units meet ENERGY STAR's low power requirement when on but idle or 'ready', and so do not need a separate low power mode. In this study, unless a fax machine gave a visual indication that it was in low power, we recorded it as being on. Of the 47 units in our sample and in Table 3, none were off and 6% (3) were in low power. Of the 44 fax machines whose technology we were able to determine, 69% (30) were laser, 20% (9) were thermal, and 11% (5) were inkjet. Figure 7 displays this graphically.

Figure 7. Fax Machine Technology



Scanners

Of the 34 scanners in Table 3, 41% were off and 60% of those that were not off were in low power. Of the total 37 scanners in our sample, 76% (28) were flatbed scanners, 14% (5) were specialized document scanners, 5% (2) were wide format, and 5% (2) were slide scanners. Among flatbed scanners only, 18% (5) were on, 43% (18) were in low power, 29% (8) were off, and 11% (3) were unplugged. All five document scanners were off; both wide format scanners were found in the same room, and were on.

Office Equipment: Comparison of 2000 and 2003 Turn-off and PM Rates

A primary goal of this study is to update information on office equipment turn-off and power management rates from previous studies, and to broaden the range of buildings in which this data is collected. Table 7 compares the office equipment turn-off and PM rates from this series of surveys to those from our 2000 field surveys of office buildings in California (Webber, Roberson et al. 2001).

In most cases, our 2003 field data yield turn off and PM rates that are virtually the same as those found in 2000. Notable exceptions are that monitor PM rates were higher (72% in 2003 c.f. 56% in 2000) and MFD PM rates were much lower in 2003 than in 2000 (29% in 2003 c.f. 56% in 2000). Also, copier and scanner turn-off rates were higher in 2003 than in 2000.

Table 7. Office Equipment Turn-off and Power Management Rates

			Turn-off Rate		PM Rate	
Category	**Type**	**no. in 2003**	**2000**	**2003**	**2000**	**2003**
computers	desktop + ICS	1,498	44%	37%	5%	7%
	desktop	**1,453**		**36%**		**6%**
	ICS	45		60%		61%
monitors	**all**	**1,598**	**32%**	**29%**	**56%**	**72%**
	CRT	1,329		32%		71%
	LCD	269		18%		75%
printers	all	353	25%	23%	44%	31%
	monochrome laser		24%		53%	
	high-end color		15%		61%	
	laser	**158**		**15%**		**60%**
	inkjet	**123**	**31%**	**30%**	**3%**	**0%**
	impact	22	31%	27%	0%	0%
	thermal	38		18%		0%
	wide format	8	57%	75%	32%	0%
	solid ink	4		0%		75%
MFDs	**all**	**79**	**18%**	**20%**	**56%**	**29%**
	inkjet	16		19%		31%
	laser	63		21%		28%
copiers	all	33	18%	49%	32%	28%
fax machines	all	47	2%	0%		6%
scanners	all	34	29%	41%		60%

For computers, the 2003 PM rate of 6% is similar to the estimated 2000 rate of 5%, but the 2003 turn-off rate of 36% for desktop computers is lower than the 2000 turn-off rate of 44% for all computers.

The 2003 turn-off rate of 32% for CRTs matches the 2000 turn-off rate for all monitors, but the 2003 turn-off rate of 18% for LCD monitors is much lower. In 2003 we found a much higher PM rate for both CRT and LCD monitors (71% and 75%, respectively) than the 56% PM rate reported for all monitors in 2000.

For all laser printers (of which <2% are color) our 2003 turn-off rate of 15% is lower than the 2000 rate of 24% for monochrome laser printers. The 2003 turn-off rates for inkjet (30%) and impact (27%) printers are similar to the 2000 rates for both (31%). Among our small sample of 8 wide format printers in 2003, the 75% turn-off rate is significantly higher than the 57% reported in 2000. The 2003 turn-off rate of 0% for (a sample of four) solid ink printers is lower than the 2000 turn-off rate of 15% for high-end color printers.

The 2003 PM rate of 60% for laser printers is similar to the 2000 rate of 61% for "high end color" printers. In 2000 some inkjet and wide-format printers were in low power, but in 2003 we found none.

The 2000 study did not report on thermal or solid ink printers, probably because few or none were found. Solid ink is not a widespread printer technology; in 2003 we found four, all in the same building. Of 41 thermal printers in our 2003 sample, only 15% were found in offices; another 15% were in education buildings, but 70% were found in health care buildings. For thermal printers the 2003 turn-off rate is 18%; for solid ink printers it is 0%. The 2003 PM rate for thermal printers is 0%; for solid ink it's 75%.

In 2003 we distinguish between laser and inkjet MFDs, but their turn-off rates (19 and 21%, respectively) are similar to the 2000 rate of 18% for all MFDs. However, in 2003 the PM rate for both inkjet and laser MFDs (31 and 28%, respectively) are significantly lower than the 2000 rate of 56% for all MFDs.

Copiers had a much higher turn-off rate in 2003 (49%) than in 2000 (18%), but their PM rate in 2003 (28%) is slightly lower than in 2000 (32%). Because of confusion about fax machine power state, no PM rate was reported in 2000; however, in 2003, at least 6% of fax machines were in low power. For scanners, the turn-off rate rose from 29% in 2000 to 41% in 2003; the 2003 PM rate was 60%.

Miscellaneous Equipment

Miscellaneous Equipment: Numbers and Density

Miscellaneous equipment outnumbered office equipment in all buildings except one (a university, site A); at one medium office (site E), the ratio of miscellaneous equipment to office equipment exceeded 4:1. For all buildings combined, if external power supplies are included as miscellaneous equipment, the ratio of miscellaneous equipment units (7,668, Appendix D) to office equipment (3,934, Table 2) is almost 2:1.

For all buildings combined, the most numerous equipment types in each ME category are as follows:

audio/visual:	television (27% of audio/visual category), VCR (23%), overhead projector (14%)
food/beverage:	microwave oven (16%), undercabinet refrigerator (15%), coffee maker (12%)
portable hvac:	8-16" diameter fan (35%), heater (21%), < 8" diameter fan (20%)
laboratory:	scale (24%), spectrophotometer (18%), tabletop centrifuge (13%)
lighting:	fluorescent undercabinet lamp (60%), 13W compact fluorescent lamp (15%)
medical:	oto-opthalmoscope charger (25%), exam light (18%), x-ray light box (12%)
networking:	switch (30%), hub (22%), modem (14%)
office misc.:	clock and/or radio (22%), compact audio system (18%), pencil sharpener (17%)
peripheral:	computer speaker pair (52%), laptop docking station (12%), PDA dock (11%)
power:	lighted power strip (36%), plug-in power supply (35%), in-line power supply (8%)
telephony:	powered phone (42%), headset with network box (13%), conference phone (11%)
maintenance:	vacuum cleaner (21%), floor polisher (14%), clothes washer or dryer (12%).

Appendix D lists the number of miscellaneous equipment units, by category, found in each building. For all sites combined, the most numerous miscellaneous equipment categories are power (including external power supplies, which are discussed in the following section), lighting, and computer peripherals. The least numerous categories of plug-load miscellaneous equipment are money exchange and security. Figure 8 shows the relative numbers of each category of miscellaneous equipment, by type of building, and Figure 9 shows the density of each equipment category, in number of units per 1000 ft^2 of floor area surveyed.

Figure 8. Miscellaneous Equipment Numbers, by Category and Building Type

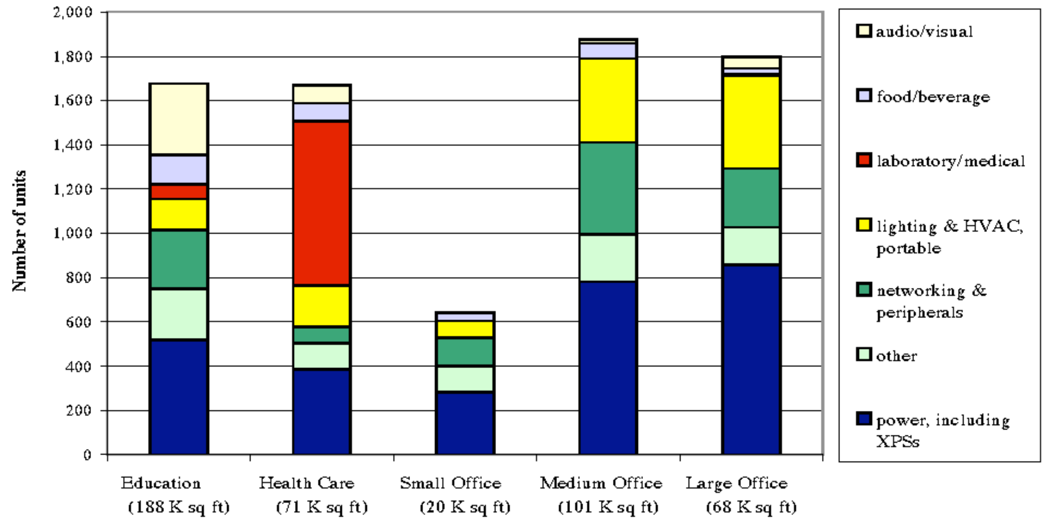
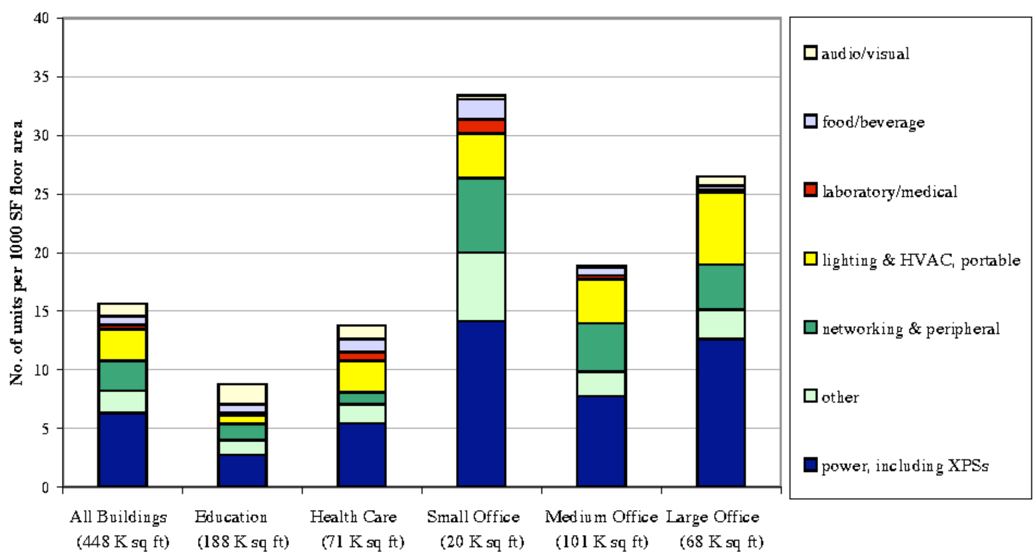


Figure 9. Miscellaneous Equipment Density, per 1000 ft² Floor Area



In Figures 8-11, some miscellaneous equipment categories have been combined for easier comparison. Specifically, we combined laboratory with medical and medical specialty, portable lighting with portable HVAC, and networking equipment with computer peripherals; 'other' combines the categories of money exchange, office miscellany, security, telephony, and utility/maintenance.

Not surprisingly, laboratory and medical equipment is the largest miscellaneous equipment category (in terms of number of units) in health care buildings, and audio/visual equipment is a significant category in education buildings. Networking equipment appears to be a smaller category in large offices; however, this result may be because we did not have access to network closets in the two large offices in our sample.

Miscellaneous Equipment: Relative Energy Consumption

An inventory is a necessary starting point, but does not reveal the relative total energy consumption (TEC) of ME found in our survey. For that we must first estimate the typical UEC of each type of equipment, which, when multiplied by number of units found, yields an estimate of TEC. We were able to estimate the UEC and TEC for over 70% (230 of 321 types) of ME found among buildings in this survey.

Typical unit energy consumption is the sum of the products of the power consumed in each power state (unplugged, off, on, active) and the likely number of hours per year (or percent time) spent in each state. We used data from previous metering projects and other available sources to estimate both parameters. In some cases we found UEC estimates in the literature. To estimate power consumed in each power state, we relied primarily on metering data by LBNL and others, online and published sources, and comparison to similar devices for which we have data (AD Little 1996, Cadmus 2000, USDOE 1995, Wenzel 1997).

In all cases, for both power levels and usage patterns, we recorded the basis of our estimates in order to facilitate subsequent evaluation and revision of our estimates based on new information or assumptions. To estimate the portion of time each type of miscellaneous equipment typically spends in each power state, we used data on as-found power states collected in this survey, supplemented by educated guesswork and personal experience. Here are some examples:

- we assumed that refrigerators, freezers, and refrigerated vending machines are always on,
- we estimated that microwave ovens in office lunchrooms are used 5 hours/week on average,
- 80% of VCRs found were on; we assume they are always on and estimated additional 10% usage,
- 60% of over 450 computer speaker pairs in our survey were found on; we used that data without adjustment, assuming that speakers found off during our survey were virtually always off.

Of course, for each type of equipment, usage and UEC may vary depending on the setting in which it is found. For example, a TV in a high school classroom is likely to be used less often that it would in a home. Similarly, a coffee maker is likely to be used more often in a typical office than it would in a typical home. Our UEC estimates apply to the buildings that we surveyed and do not necessarily apply in other situations.

We prioritized the considerable effort of estimating UECs by focusing on the most numerous and most energy-intensive equipment types. Miscellaneous equipment for which we do *not* have UEC (and therefore TEC) estimates include some specialized medical equipment and other equipment we could not meter and for which we could find no power specifications. That we do not have estimates of power use for some equipment does not mean that their consumption is insignificant, only that we were unable to estimate it at this time. Examples of equipment for which we have no estimate (with the number of them found) are:

- audio/visual category: video switch (9), power distribution & lighting system (5),
- food & beverage category: hot beverage dispenser (4), steam trays (3),
- peripheral category: keyboard/video/mouse (KVM) switch (27), pen tablet (17)
- power category: battery backup system (3), power amplifier (2)

For the 230 types of miscellaneous equipment for which we have estimates of both power consumption and time spent in each power mode, it is a simple matter to calculate typical unit energy consumption and (multiplying UEC by the number of units found) to calculate their total energy consumption. Obviously, any error in the UEC estimate is compounded (multiplied) by the number of units found. Also, the more power consumed and the more time spent on, the larger the potential error in our (absolute kWh) estimates.

Our UEC estimates ranged from 1 kWh/yr for pencil sharpeners to 7,008 kWh/yr for kilns; TEC estimates ranged from 1 kWh/yr (e.g., for one shaver) to almost 80,000 kWh/yr for 24 refrigerated vending machines.

Networking equipment in our survey, primarily ethernet hubs and switches, ranged from 1 to 80 ports each. Our inventory distinguishes these equipment by the number of ports (e.g., we list the number of 12-, 16-, 24-, 48-, and 80-port hubs separately), but our estimates of UEC and TEC are based on the sum of all ports, regardless of unit configuration. We found a total 2,120 ethernet switch ports and 451 ethernet hub ports.

Of the miscellaneous equipment for which we have UEC and TEC estimates, Table 8 shows the total energy consumption of miscellaneous equipment according to our categories. The top 50 in unit energy consumption are listed in Table 9 and the top 50 in total energy consumption are listed in Table 10.

The food & beverage category appears to dominate miscellaneous equipment in terms of *unit energy consumption*; eleven of the top 15 equipment types in terms of UEC are in the food & beverage category, which are shaded in Tables 9 and 10. The food & beverage category also dominates in terms of *total energy consumption*, accounting for half (50%) of total energy consumed. Table 10 shows that among our survey of commercial buildings the top ten types of food & beverage equipment in terms of TEC are:

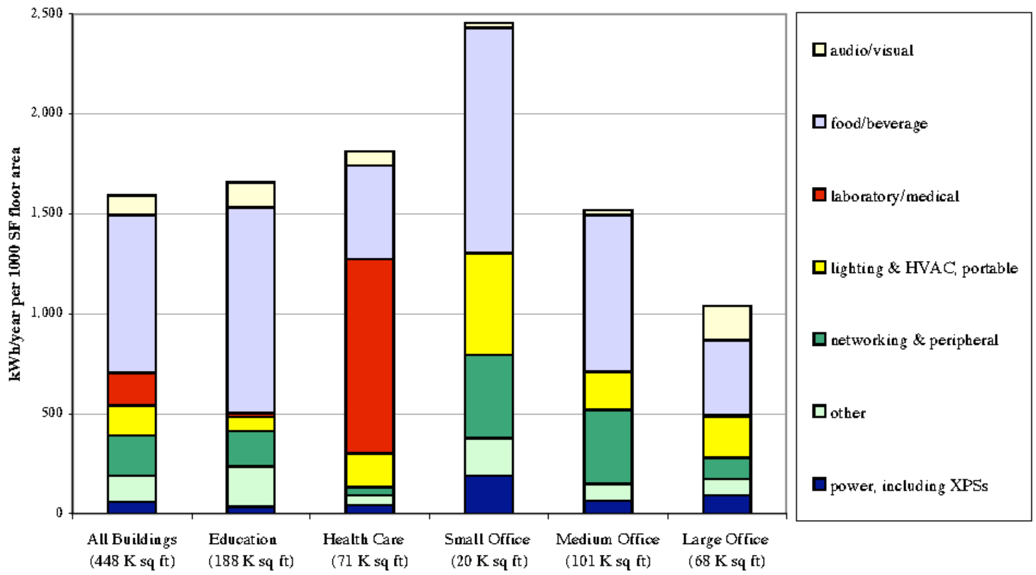
1) refrigerated vending machines
2) commercial refrigerators
3) commercial freezers
4) microwave ovens
5) coffee makers, commercial or specialty
6) hot food cabinets
7) coffee makers, residential models
8) small (undercabinet) refrigerators
9) room temperature vending machines
10) visi-coolers

While each ethernet switch port has a UEC of just 17 kWh/yr, the over 2,000 units have a collective TEC of over 35,000 kWh/year, which suggests this equipment is a good target for energy efficiency measures. We estimate that computer speaker pairs collectively account for almost 10,000 kWh/yr in these buildings; because these units are seldom used, their consumption represents a considerable energy savings potential.

Table 8. Total Energy Consumption of Miscellaneous Equipment, by Category

Miscellaneous Equipment Category	TEC (kWh/yr)	% of Sum
food/beverage	354,406	50%
laboratory/medical	72,583	10%
networking	53,775	8%
audio/visual	43,036	6%
lighting, portable	42,417	6%
computer peripherals	35,549	5%
other (money exchange, security, specialty, utility/maintenance)	38,285	5%
hvac, portable	26,731	4%
power, including XPSs	26,079	4%
office miscellany	13,114	2%
telephony	7,616	1%
All Miscellaneous Equipment Found in Survey	**713,591**	**100%**

Figure 10. TEC of Miscellaneous Equipment, Normalized by Floor Area (kWh/yr per 1000 ft^2)



Figures 8-10 show that although small offices have the lowest numbers of miscellaneous equipment, they have the highest *density*, in both numbers and TEC, in all categories except audio/visual. This is consistent with Figure 2, in which small offices have the highest density of both office and miscellaneous equipment.

Figure 11. TEC of Miscellaneous Equipment, as Percent of Building Type

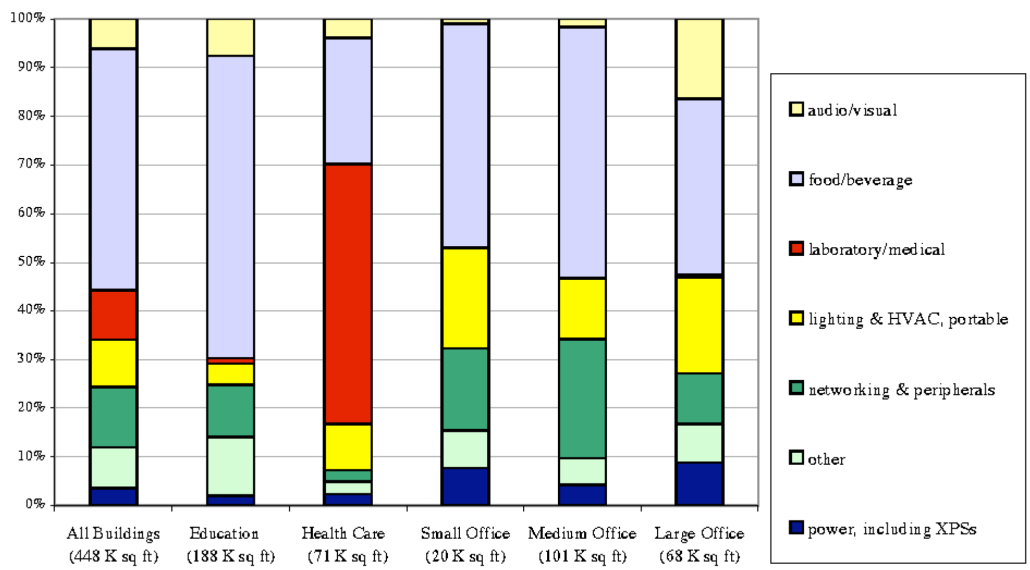


Table 9. Top 50 Miscellaneous Equipment Types, by Unit Energy Consumption

Note: Shading indicates equipment in the food & beverage category
Note: * indicates equipment for which we found and used published UEC values.

	Miscellaneous Equipment		Power Use (W)		Estimated Usage (percent time)			Unit Energy Consumption (UEC) kWh/yr
	Category	Type	On	Off	On	Off	Unplugged	
1	specialty	kiln	8000		10%	0%	90%	7,008
2	food & beverage	fryer						* 5,884
3	food & beverage	freezer, commercial						* 5,200
4	food & beverage	hot food cabinet						* 4,700
5	food & beverage	refrigerator, commercial						* 4,300
6	laboratory	autoclave	1500	0	30%	50%	20%	3,942
7	food & beverage	visi-cooler						* 3,900
8	food & beverage	vending machine, cold beverage						* 3,318
9	food & beverage	ice maker						* 2,167
10	food & beverage	vending machine, room T snack	205		100%	0%	0%	1,796
11	food & beverage	coffee maker, commercial or specialty	2595		6%	74%	20%	1,349
12	laboratory	drying oven or steam incubator	300	0	50%	50%	0%	1,314
13	food & beverage	refrigerated case						* 1,214
14	audio/visual	LED display sign, networked	135	15	100%	0%	0%	1,183
15	food & beverage	soda fountain pump or smoothie maker	100	0	100%	0%	0%	876
16	networking	switch, fiberoptic, 24 port	96		100%	0%	0%	841
17	food & beverage	bottled water tap, hot & cold						* 799
18	food & beverage	water cooler, hot & cold						* 799
19	HVAC, portable	air cleaner						* 761
20	utility/maintenance	clothes washer						* 704
21	food & beverage	refrigerator, L (full-size)						* 701
22	food & beverage	refrigerator/freezer						* 701
23	peripheral	external drive, tape backup	100		80%	10%	10%	701
24	audio/visual	system control, rack-mount	79	5	100%	0%	0%	692
25	audio/visual	power/volume controller	79	5	100%	0%	0%	692
26	HVAC, portable	room air conditioner						* 630
27	utility/maintenance	clothes dryer						* 622
28	specialty	bookshelves, mobile	70	0	100%	0%	0%	613
29	utility/maintenance	pump, water treatment chemical	70	0	100%	0%	0%	613
30	food & beverage	refrigerator, M (apt-size)						* 567
31	utility/maintenance	exhaust fan, industrial	125	0	50%	50%	0%	548
32	laboratory	refrigerator, S	60	0	100%	0%	0%	526
33	laboratory	freezer	60	0	100%	0%	0%	526
34	lighting, portable	incandescent tracklight, 50 lamps each	2000	0	3%	97%	0%	520
35	telephony	phone/PBX centrex system	55.5		100%	0%	0%	486
36	food & beverage	coffee maker, residential model	865	0	6%	69%	25%	450
37	food & beverage	microwave oven	1620	3	3%	97%	0%	447
38	medical specialty	charger, suction pump	50	3	100%	0%	0%	438
39	peripheral	disk array	50		100%	0%	0%	438
40	networking	tape drive	100		50%	50%	0%	438
41	medical specialty	sterilizer, hot bead	90		50%	50%	0%	394
42	audio/visual	digital video camera	70	3	60%	40%	0%	378
43	networking	router	40		100%	0%	0%	350
44	peripheral	external drive, other	50		80%	20%	0%	350
45	medical specialty	charger, defibrillator	50	3	75%	25%	0%	335
46	HVAC, portable	heater	750		5%	48%	48%	329
47	peripheral	external drive, hard disk	50		67%	25%	8%	292
48	food & beverage	refrigerator, S (undercabinet)						* 277
49	networking	video processor, rack-mount	30		100%	0%	0%	263
50	lighting, portable	incandescent studio lamp, 500W	500	0	6%	94%	0%	260

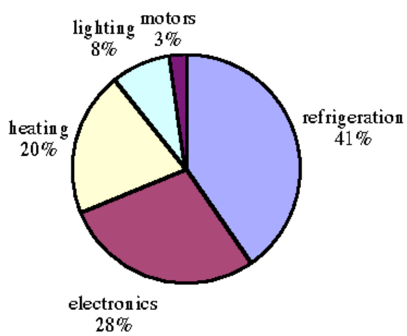
Finally, we characterized the top 50 miscellaneous equipment types in Table 10 according to these broader end-use or technology categories: electronics, heating, lighting, motors, and refrigeration. For equipment that could belong in more than one of these categories, we categorized it based on its primary technology or consumption. For example, refrigerated vending machines are a 'refrigeration' end use, while room temperature vending machines are 'lighting;' microwave ovens and computer projectors are categorized as 'electronics' although they might alternatively be categorized as 'heating' and 'lighting,' respectively. Figure 12 shows the relative consumption of equipment in Table 10 according to these end-use categories.

Table 10. Top 50 Miscellaneous Equipment Types, by Total Energy Consumption

Note: Shading indicates equipment in the food & beverage category

	Miscellaneous Equipment		number	Energy Consumption, kWh/yr	
	Category	Type	found	per Unit	Total
1	food & beverage	vending machine, cold beverage	24	3,318	79,632
2	food & beverage	refrigerator, commercial	18	4,300	77,400
3	networking	switch, ethernet, total no. of ports	2120	17	35,285
4	food & beverage	freezer, commercial	5	5,200	26,000
5	food & beverage	microwave oven	53	447	23,675
6	specialty	kiln	3	7,008	21,024
7	lighting, portable	fluorescent undercabinet lamp, ave 24"	626	33	20,833
8	food & beverage	coffee maker, commercial or specialty	15	1,349	20,241
9	laboratory	autoclave	5	3,942	19,710
10	food & beverage	hot food cabinet	4	4,700	18,800
11	food & beverage	coffee maker, residential model	39	450	17,542
12	food & beverage	refrigerator, small (undercabinet)	50	277	13,860
13	food & beverage	vending machine, room T snack	7	1,796	12,571
14	food & beverage	visi-cooler	3	3,900	11,700
15	HVAC, portable	heater	33	329	10,841
16	power	plug-in power supply (PIPS), attached	878	11	9,999
17	peripheral	computer speakers (pair)	464	21	9,836
18	food & beverage	refrigerator, M (apt-size)	17	567	9,641
19	food & beverage	bottled water tap, hot & cold	12	799	9,588
20	food & beverage	ice maker	4	2,167	8,668
21	HVAC, portable	air cleaner	11	761	8,371
22	networking	router	23	350	8,059
23	lighting, portable	incandescent desk/table lamp, 75W ave	99	78	7,722
24	peripheral	external drive, tape backup	11	701	7,709
25	audio/visual	VCR	113	64	7,214
26	audio/visual	LED display sign, networked	6	1,183	7,096
27	medical specialty	charger, defibrillator	21	335	7,036
28	audio/visual	TV (all sizes)	130	53	6,941
29	audio/visual	projector, overhead	68	96	6,524
30	peripheral	projector, computer	32	204	6,523
31	food & beverage	fryer	1	5,884	5,884
32	laboratory	refrigerator, S	11	526	5,782
33	power	UPS (uninterruptible power supply)	137	36	4,983
34	medical	exam table w/ heated drawer	38	130	4,940
35	networking	hub, ethernet, all sizes, total no. ports	451	11	4,938
36	office miscellany	adding machine	81	58	4,730
37	medical	charger, oto/opthalmoscope	116	39	4,573
38	telephony	phone, powered	98	42	4,116
39	peripheral	external drive, hard disk	13	292	3,796
40	office miscellany	typewriter	32	116	3,700
41	medical specialty	vital signs monitor	24	153	3,679
42	specialty	bookshelves, mobile	6	613	3,679
43	HVAC, portable	fan, medium (8-16" diam)	56	62	3,495
44	audio/visual	system control, rack-mount	5	692	3,460
45	food & beverage	refrigerator, L (full-size)	4	701	2,803
46	medical specialty	sterilizer, hot bead	7	394	2,759
47	medical	exam light	87	31	2,714
48	networking	video processor, rack-mount	10	263	2,628
49	laboratory	drying oven or steam incubator	2	1,314	2,628
50	peripheral	external drive, other	7	350	2,450
				SUM	**607,780**

Figure 12. End-Use Breakdown of Top 50 Miscellaneous Equipment Types, by TEC

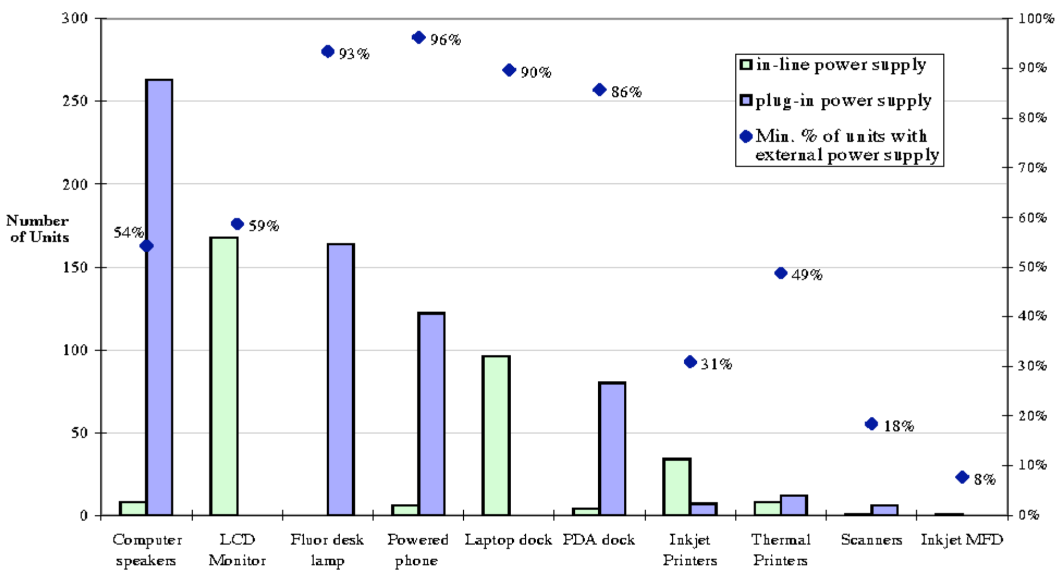


External Power Supplies

Figure 13 shows the types of equipment we found with external power supplies, the number of units of each equipment type that had an XPS, the type of power supply (ILPS or PIPS), and the minimum percent of each equipment category that had an XPS. It is a minimum value because although we tried to record every occurrence of an XPS, we did not capture all of them.

The most numerous XPSs were among computer speakers, LCD monitors, fluorescent desk lamps (whose PIPS included a magnetic ballast), powered phones (including conference and speaker phones), laptop and PDA docking stations. The highest percentage of units with XPSs were among powered phones, fluorescent desk lamps, laptop and PDA docking stations. ILPSs were prevalent among LCD monitors and laptop docking stations, while PIPSs prevailed among computer speakers, fluorescent desk lamps, powered phones and PDA docks. Equipment among which we found both ILPSs and PIPSs (though not on the same unit) were computer speakers, powered phones, PDA docks, inkjet printers, thermal printers, and scanners.

Figure 13. External Power Supplies: Number, Type and Frequency



Conclusions

For all buildings combined, the average plug-load equipment density in *units per 1000 gross ft^2*, was about 9 for office equipment and 14 for miscellaneous equipment, for a sum of about 23 units per 1000 gross ft^2. Educational buildings, where large floor areas are devoted to classrooms, had the lowest density of both office and miscellaneous equipment. However, two-thirds of computers and monitors found in educational buildings (and thus most of the energy savings potential) were concentrated in computer-based classrooms.

Among offices only (for which we were able to estimate number of employees, or occupants), the average equipment density, in *units per employee*, was approximately 3 units of office equipment and 6 units of miscellaneous equipment per employee, for a sum of about 9 electrical plug-load devices per employee; note that this includes equipment found in common areas such as kitchens, print centers, and utility closets. Because we have not attempted to estimate equipment density before, these data represent a baseline for reference and comparison with future data.

Office Equipment

A good overview of our results regarding office equipment power states is provided by Figure 3 (page 10), which allows a visual comparison of the percent of units found on, in low power, or off, by equipment type. Power management, indicated by the middle segment of each bar, is most successful among monitors and laser printers; and least successful among desktop computers, inkjet printers, copiers, and fax machines. Turn-off rates, indicated by the right segment of each bar, are highest (≥ 40%) among integrated computer systems, copiers, and scanners; and lowest (≤ 20%) among laser printers, LCD monitors, and MFDs.

This is the first field study in which we analyzed the effect of computer power state on monitor power state. Only 6% of desktop computers in this study of commercial buildings were found in low power, and only 53% of those that were on successfully initiated power management in monitors. Computers in homes (where fewer are networked) may have higher enabling rates, but we have no data from residences. Clearly there is significant room for improvement in power management of computers, and more data are needed to identify the parameters that affect the ability of computers to power manage themselves and their monitors.

In contrast, 96-98% of monitors connected to computers that were not on were found in low power, so a very high proportion of monitors are ENERGY STAR compliant, or capable of power managing themselves.

This report presents evidence of the growing use of laptop computers. Because of their inherent portability, accounting for laptops is difficult, especially during an after-hours survey, but our conservative estimate is that laptops comprise at least 10% of the non-server computers in our sample. We also estimate that laptops outnumbered desktop computers at two sites: one medium and one large office. To the extent that relatively energy-efficient laptops are replacing desktop computers, significant electrical energy is saved. However, more work is needed to characterize laptop usage patterns and energy consumption, which can vary widely depending on how often they are used when plugged in and how often the battery is charged. Laptop power state data from this survey can be useful in developing a typical unit energy consumption for laptop computers, but needs to be supplemented by data not available from after-hours surveys.

LCD monitors, which use significantly less energy when on than CRT monitors, are also penetrating the market. They outnumbered CRT monitors at two of the twelve sites in our sample: a medium office and a university classroom building. In contrast, we found no LCD monitors at three sites: two high schools and a large office. We expect the market share of LCD monitors to continue to grow as older CRT monitors are replaced and LCD monitor technology improves and becomes more affordable due to economies of scale.

For both types of education buildings in our sample (high schools and university classroom buildings), two-thirds of computers and monitors found were in "computer labs," or classrooms with a 1:1 ratio between computer workstations and chairs.[5] Some university computer labs had LCD monitors, but all the high school computer labs we visited had CRT monitors, many of which were found on after-hours. With so many workstations located in one room, and (presumably) controlled by one or very few instructor(s), we suggest efficiency efforts in high schools focus on reducing power consumed by equipment in these rooms.

Among our sample of printers, 46% were laser and 34% were inkjet. The turn-off rate was twice as high (30%) for inkjet printers as for laser printers (15%); inkjet printers are more likely to be turned off than laser printers because they are much less likely to be networked. Among laser printers, 77% had power management delay settings of 30 minutes or less, and only 5% were disabled (i.e., set to "never"). This indicates a high market penetration for ENERGY STAR laser printers; however, for reasons discussed above (including error messages and after-hours network use), the actual PM rate for laser printers is lower than indicated by PM delay settings. Nevertheless, the 2003 PM rate of 60% for laser printers is higher than the 2000 PM rate of 53% for monochrome laser printers, suggesting improvement in actual PM rates.

Eighty percent (80%) of multi-function devices that we found used laser imaging technology; the other 20% were inkjet. For both types, the average turn-off rate was about 20%, and the average PM rate was 30%, significantly lower than the 56% PM rate for MFDs observed in 2000. Power management rates among MFDs are important because MFDs appear to be replacing copiers in the workplace; the ratio of digital copier-based MFDs to copiers rose from 1:3 in our 2000 survey of office equipment to 2:1 in the 2003 survey reported here. However, while most MFDs can also fax, print, and scan, we did not observe a corresponding decrease in the relative number of fax machines, printers and scanners.

Miscellaneous Equipment

The inventory and energy consumption estimates of miscellaneous plug-load equipment presented in this report represent a first step toward characterizing the electrical demand of this large end-use category. Miscellaneous equipment outnumbered office equipment in our sample by a factor of almost two to one. While some energy-intensive devices, such as commercial refrigeration equipment, have been the target of efficiency efforts, including ENERGY STAR labeling, other less consumptive but more numerous devices, such as networking equipment and external power supplies, may offer significant energy savings potential.

According to our system of taxonomy, by far the most numerous category of miscellaneous plug-load equipment was 'power,' including power strips, surge suppressors, and external power supplies. The second most numerous category was 'lighting,' particularly undercabinet and compact fluorescent lamps, and the next most numerous category was computer 'peripherals,' 52% of which were computer speaker pairs. However, the numbers of each type of equipment do not necessarily reflect their relative energy intensity. The next step was to estimate typical unit energy consumption for the most common types of miscellaneous equipment, and begin to sort out their relative contribution to plug-load end use.

We were able to derive UEC estimates and calculate TEC for just over 70% of the types of ME found in our survey. Among miscellaneous equipment for which we have TEC estimates, equipment types with the top 50 TEC account for 85% of the total TEC—about 608K of 714K kWh/year, respectively. The food & beverage category accounts for 50% of the estimated (714K kWh/yr) TEC for all miscellaneous equipment devices. This category includes refrigeration equipment (freezers, refrigerators, vending machines) that are always on, as well as ubiquitous and frequently-used devices such as coffee makers and microwave ovens.

[5] We do not necessarily assume a 1:1 ratio between chairs and people; occupancy rates may vary between classes.

Future Work

The low rate of power management in desktop computers causes concern and deserves further investigation to ascertain barriers to computer power management as well as the most effective ways to mitigate them. One possibility would be to conduct more in-depth case studies in several types of buildings to identify specific institutional or technological impediments and evaluate the efficacy of various counter measures. Increasing power management among PCs would yield significant savings in both computers and monitors.

The increasing use of laptop computers makes it important to characterize their unit energy consumption. This would likely involve visiting offices during working hours and asking laptop users about their usage patterns, including how often the laptop is powered from a wall outlet and how often the battery is charged. It would also be useful to estimate the extent to which laptops are used in addition to or instead of desktops.

Results of this study point to the savings potential among computers and monitors in computer classrooms. We should improve our assessment of computer usage patterns in schools and develop effective strategies for realizing these savings. It would then be possible to implement prospective energy-saving measures in several computer classrooms and schools, and conduct follow-up surveys to evaluate their relative efficacy.

It would be useful to supplement these survey results with automated, network-based collection of data regarding usage patterns and power management settings of computers, printers, fax machines, and MFDs. While the former provides more detail, the latter yields significantly more data over longer periods of time.

Now that we have UECs for most common types of miscellaneous equipment, it would be possible to calculate their relative energy intensity among all buildings in our sample, or between types of buildings. Given utility bills for an individual building, we could work with building managers to estimate the portion of building energy load attributable to miscellaneous plug-load and to identify energy saving opportunities.

Additional after-hours building surveys could improve our understanding of office equipment usage and miscellaneous plug loads. Surveying a single building more than once (e.g., at weekly, monthly intervals) would help us to assess the robustness of the results from a single survey. The representativeness of our office equipment sample would be improved (compared to CBECS, for example) by visiting more large offices, and the completeness of our miscellaneous equipment inventory could be improved by ensuring that we survey their common or service areas such as network, phone and other utility closets. Furthermore, now that we have a baseline inventory of miscellaneous equipment, additional surveys and device metering would enable us to track changes in numbers and types of miscellaneous equipment, as well as their after-hours power status, and begin to characterize the typical 'plug-load profile' for various types of buildings.

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Appendix A: Building Descriptions

Site A

University classroom building, Atlanta GA
Urban, downtown campus; 4-story, circa 1970
Area surveyed includes chemistry and computer laboratory/classrooms, faculty offices, lecture hall, lobby, and storage.

Site B

Medium office, Pittsburgh PA
Headquarters of a national non-profit organization
Suburban office park, 3-story, new in 2002
Area surveyed includes computer lab/shop, conference, cubicles, custodial, kitchen, lounge, network closet, offices, print/copy centers, reception, server room, shipping & receiving.

Site C

Large office, Atlanta GA
National headquarters of an internet company
Midtown office building, 8-story, circa 1970s
Area surveyed includes customer call center, computer classrooms, break room, conference, cubicles, .offices, and print/copy centers.

Site D

Urban high school, CA
3-story main building, new in 2001
Area surveyed includes administrative offices, audio/visual studio, bookroom, classrooms, computer classrooms, conference, library, teachers lounge, network closet, print/copy center, utility/mechanical. Most computers are found in a few rooms, including computer classrooms and the library.

Site E

Medium office, Atlanta GA
Branch office of an international consulting firm
One floor of a 1990s suburban office tower
Area surveyed includes break room, conference, cubicles, lounge, offices, print/copy centers, server room. This office had a high percentage of laptop computers, which must be locked up or taken home at night. Only administrative staff have desktop computers, which are left on at night for backups and updates.

Site F

Urban high school, Pittsburgh PA
3-story main building, remodeled in 1990s
Area surveyed includes auditorium, cafeteria, classrooms (including art, band, language, computer classrooms, conference, library, teachers lounge, network closet, offices, storage, and A/V workroom. Most computers are found in a few classrooms and the library.

Site G

Outpatient clinic, San Francisco CA
10-story urban medical campus building
Area surveyed includes conference, cubicles medical labs, library, lounges, exam rooms (including E/N/T, general medicine, ophthalmology, pediatric), nurses stations, offices, patient registration, phone bank, medical utility, treatment rooms, and waiting. Each exam and treatment room had a computer/monitor.

Site H

Medium office, Atlanta GA
Information services department of a university
6-story urban campus building, circa 1970s
Area surveyed includes break room, conference, copy/print center, cubicles, custodial, lounge, network closet, offices, server room , and utility/mechanical.

Site J

Medical office building, Pittsburgh PA
Suites of physicians in private practice
5-story suburban building,
Area surveyed includes break room, conference, exam rooms (including cardiology, E/N/T, endocrinology, ophthalmology, sleep disorders, urology), kitchen, labs, offices, server room, storage, utility, and waiting.

Site K

Small office, Pittsburgh PA
5 small businesses in 3 different suburban buildings
Area surveyed includes break room, conference, copy/print center, cubicles, electronics shop, network closet, offices, server room , and storage.

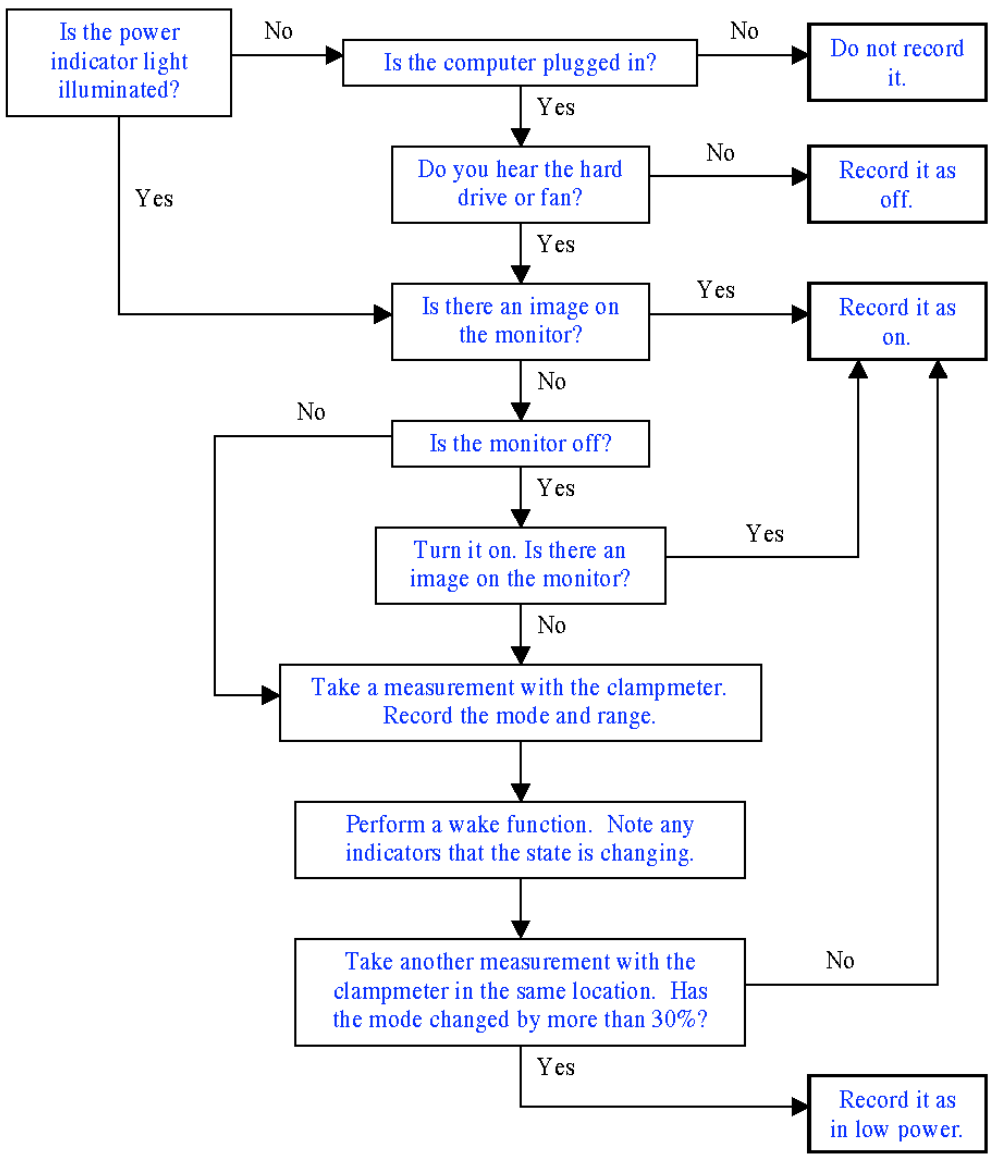
Site M

Large office, Pittsburgh PA
Corporate headquarters of a major manufacturer
Urban downtown office building, 6-story, new in 2001
Area surveyed includes conference, copy/print centers, cubicles, kitchen, lounge, health center, offices. Many employees in this office use laptop computers. Company policy is to turn monitors off at night (to prevent fires); special permission is required to bring in or use small appliances (fans, heaters, lamps, etc).

Site N

University classroom building, Atlanta GA
Urban, downtown campus; 4-story, circa 1960
The area surveyed included computer laboratories and classrooms, other classrooms, and offices of faculty, staff, and graduate students.

Appendix B: Flowchart for Auditing Desktop Computer Power State



Appendix C: Miscellaneous Equipment Taxonomy

Category	Equipment Type (not an exhaustive list)
audio/visual	television, video cassette player/recorder, overhead projector, audio amplifier, compact disk audio device, digital video disk device, slide projector, video monitor, audio mixer, audio tape device, LED display sign, receiver, speaker, tuner, digital video camera, video conferencing device, microfilm viewer, scan converter, public address system, set-top box
food & beverage	microwave oven, refrigerator (all sizes), coffee maker, toaster/toaster oven, vending machine, hot/cold bottled water tap, hot pot/kettle, water cooler, freezer, hot beverage dispenser, hot food cabinet, ice maker, coffee grinder, drinking fountain, fryer/griddle, steam trays, visi-cooler, meat slicer, mixer, soda fountain pump, blender, refrigerated case
hvac, portable	fan, heater, air cleaner, room air conditioner
laboratory	scale, spectrophotometer, tabletop centrifuge, temperature monitor, lab refrigerator, microscope, autoclave, shaker/stirrer, lab freezer, hot plate/warmer, drying oven, timer
lighting	fluorescent undercabinet lamp (by size), desk/table/floor lamp (by lamp type and power use), incandescent spotlight or studio lamp, decorative lamp, strand or cable lights, fluorescent light box, incandescent or halogen track light or recessed lamp, exterior fluorescent sign
medical	oto-opthalmoscope charger, exam light or headlamp, x-ray light box, exam chair or table, body scale, hospital bed, utensil sterilizer, blood pressure monitor, IV cart
medical specialty	vital signs monitor, respirator, defibrillator charger, EKG machine & accessories, pulse oxymeter, eye chart projector, lensmeter, glucometer charger, hot bead sterilizer, suction pump charger, hearing test device, retinal scanner, fundus camera, hyfrecator, sonoscope
money exchange	credit card reader, cash register, bar code scanner, change or stamp vending machine
networking	modem, router, hub, printer hub, switch, print controller/server, video processor, wireless access point, audio/video modulator, tape drive, broadband distribution amplifier, driver
office miscellany	clock and/or radio, boombox or compact audio system, pencil sharpener, adding machine, shredder, typewriter, stapler, postage meter or scale, hole punch, laminator, time stamper, binding machine, microfiche reader
peripheral	computer speakers (pair), laptop docking station, personal digital assistant dock, computer projector, keyboard/video/mouse switch, external drive (CD, zip, hard disk, tape backup), pen tablet, digital whiteboard,
power	power strip, surge protector, PIPS, ILPS, uninterruptible power supply, charger (for laptop computer, cell or cordless phone, power tool), power conditioner, battery backup system
security	badge reader, book demagnetizer, shoplifting sensor, article surveillance system
specialty	pottery wheel, mobile bookshelves, oscilloscope, shrinkwrapper, bench wheel, soldering iron
telephony	conference or speaker phone, answering machine, intercom, phone switch, phone jack or box, dictation machine, PBX phone line converter, voice control box, switchboard phone, integrated voice server
utility/maintenance	vacuum cleaner, floor polisher, dishwasher, ultrasonic cleaner, water purifier, clothes washer or dryer

Appendix D: Miscellaneous Equipment Numbers, by Category and Site

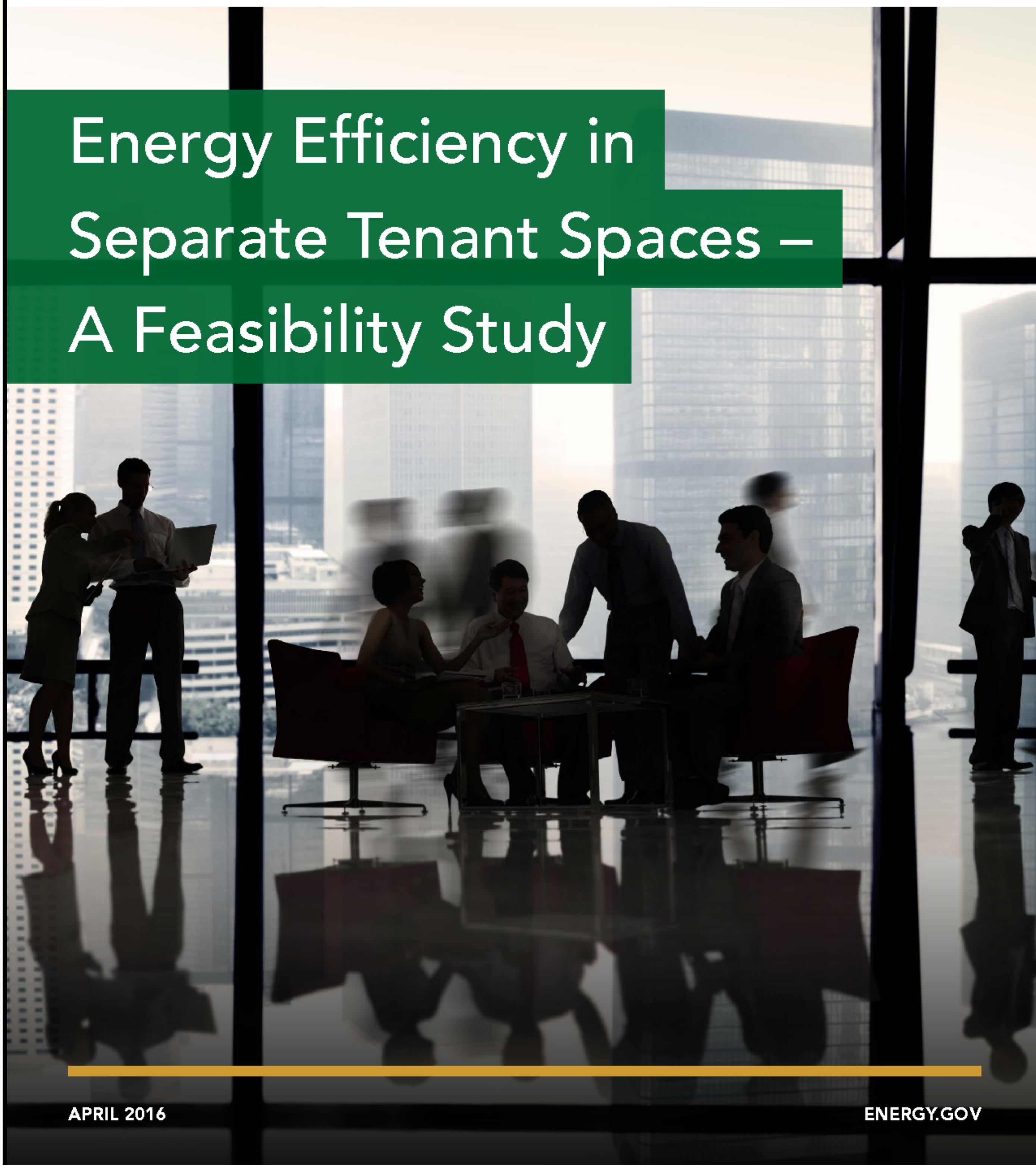
Sorted in descending order

site code	G	M	C	H	F	K	E	J	B	A	D	N	All
bldg type	medical	L office	L office	M office	school	S office	M office	medical	M office	school	school	school	
ME Category													**sum**
power	114	220	205	174	57	167	87	64	139	36	44	86	**1393**
lighting	85	226	179	158	70	52	172	51	15	8	10	20	**1046**
plug-in power supply	92	123	221	111	34	84	76	35	88	60	24	42	**990**
peripheral	13	104	150	125	85	82	87	9	118	36	30	44	**883**
audio/visual	58	28	24	8	144	7	8	27	2	65	90	23	**484**
office miscellany	28	68	6	34	38	86	18	56	86	9	33	19	**481**
medical	393	5						76					**474**
in-line power supply	25	72	16	69	27	32	29	56	10	95		13	**444**
food/beverage	29	9	15	31	71	33	14	51	24	19	30	14	**340**
networking	27	8	8	48	43	46	31	21	6	4	11	11	**264**
telephony	5	76	15	26	49	10	20	8	12	3	1	8	**233**
medical specialty	149	3			2			70					**224**
hvac, portable	41	1	13	24	7	24	5	11	6	3	20	4	**159**
laboratory	44	1						10		63			**118**
utility/maintenance	3			2	14	4	2	2	4	9	8	4	**52**
specialty	1	2			13	14			3	1	9	1	**44**
money exchange	12	1			3	3		2	6	3	3		**33**
security		1	1		1				1		2		**6**
sum	**1119**	**948**	**853**	**810**	**658**	**644**	**549**	**549**	**520**	**414**	**315**	**289**	**7668**

Note; Plug-in and in-line power supplies are listed separately, but are actually part of the power category

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Energy Efficiency in Separate Tenant Spaces – A Feasibility Study



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1. Executive Summary

Commercial buildings account for 20% of energy used in the United States economy,[1] with leased spaces representing approximately 50% of all commercial building energy use.[2] Increasingly, market pressures such as rising energy costs, new requirements to publicly disclose energy usage, and increased attention on energy efficiency as a means to combat climate change are motivating tenants, building owners, and other commercial building stakeholders to explore new ways to reduce energy consumption.

Traditionally, efforts to encourage energy efficiency in commercial buildings have focused on building owners rather than tenants. While building owners generally have control over building systems and operations, tenants play a critical role in achieving lasting reductions in energy intensity. In recognition of this collaborative role, the Energy Efficiency Improvement Act of 2015 mandated the development of a voluntary tenant space recognition system similar to the successful ENERGY STAR® buildings program. Additionally, the legislation mandated a feasibility analysis, presented here, regarding the implementation of tenant-specific energy efficiency measures. In response, this paper presents best practices, resources, and policies that could serve as the backbone for future tenant energy efficiency programs.

The energy consumption at a representative large, multi-tenant building can be partitioned into energy attributable to common areas (such as atriums, lobbies and garages), shared mechanical systems (such as central heating, fans, and cooling towers), and tenant spaces. In a typical arrangement, certain segments are clearly controlled by the owner, such as the garage lighting. Other segments are clearly controlled by the tenant, such as plug loads in tenant spaces. However, ultimate responsibility for managing the energy consumed in a multi-tenant space is often balanced between tenants and owners. Circumstances differ based on lease structure, but in a typical arrangement, neither owner nor tenant has complete control.[3] Instead, the energy usage and associated emissions are under the joint control of the owner and tenant, and the significant reductions in energy consumption require collaboration between the two parties.

Achieving greater levels of energy efficiency in tenant spaces is feasible through the use of technologies that exist in the market today. However, historic challenges have prevented wide-spread adoption of separate space efficiency measures. First, the timing and process of leasing - characterized by infrequent design windows, multiple stakeholders, design and budget constraints, and the dynamics of fluctuating negotiating leverage between owners and tenants - have largely prevented rapid advancement of energy efficiency in separate tenant spaces. Second, many owners, tenants, and brokers remain unaware or uninterested in the financial benefits and opportunities afforded by energy efficiency within leased spaces. Third, the majority of tenants in the market are small, disparate, and hard to reach with overarching energy efficiency strategies. Fourth, owners and tenants are hesitant to invest in tenant space energy efficiency measures due to the "split-incentive" problem. This "split-incentive" refers to the financial disconnect of investments in energy efficiency that can result from how costs and benefits of energy efficiency are allocated to different parties. And fifth, the inability to collect tenant-specific energy data from whole building consumption, in order to validate the benefits of energy efficiency investments, limits owners and tenant insight into the value of energy efficiency, further dampening interest.

1 U.S. Energy Information Administration. (2006). 2003 CBECS Detailed Tables – Table C4A: Expenditures for Sum of Major Fuels for All Buildings. https://www.eia.gov/consumption/commercial/data/archive/cbecs/cbecs2003/detailed_tables_2003/2003set14/2003html/c4a.html

2 NRDC. (2013). High Performance Tenant Demonstration Project. http://www.josre.org/wp-content/uploads/2013/02/CMI-PPT-on-Tenant-Energy-Performance.pdf

3 As an example, while the owner may select and maintain the central heating system, the tenant may have control over the thermostat controlling the leased space and the adjoining common corridor. Together, the choices made by the owner and tenant determine the energy consumption at the building.

Increased education and awareness materials, collection of tenant-specific energy consumption data, and a re-alignment of leasing cost structures targeted toward building owners, tenants, and brokers, may help overcome these challenges and encourage widespread uptake of tenant space energy efficiency measures. This paper highlights a variety of potential ways to address these needs including:

Submetering of tenant spaces – Metering tenant-specific energy use offers the ability to separate out individual tenant-level energy usage from common area usage. This "submetering" helps ensure that each tenant pays for their own energy consumption, and receives the full benefit of energy cost reductions on their part.

Easy comparison of energy efficient technologies – Technologies exist to increase the energy efficiency of tenant spaces. However, understanding the costs and benefits of utilizing such technologies is often complicated and time consuming, requiring tenants to understand not only the energy saving attributes of individual products, but also interactive effects between technologies. Improving the ability to readily compare packages of technologies through interactive tools or build-out guidance checklists is one potential way to increase the uptake of energy efficient technology in tenant spaces.

Recognizing the business case for energy efficiency – Many businesses recognize the ways in which energy efficiency can improve their bottom line. There are opportunities to help even more businesses see these benefits, including the role of energy efficiency in reducing total cost of occupancy, making spaces more comfortable and attractive, contributing to improved worker performance, and increasing asset value at time of sale. Even in lease structures with a split incentive for energy efficiency, building owners can benefit from increased energy efficiency through market differentiation – and in certain markets command higher rents and longer tenures. A growing body of research has shown that energy efficient buildings rent for an average premium of 2-6%,[4] can sell for a premium of as much as 16%,[5] attract high-quality tenants,[6] and have lower default rates for commercial mortgages.[7]

Low-cost energy simulation models for tenant spaces – Tenants can compare different energy efficiency measures through energy simulations and decide which options are most appropriate for the individual space. Energy modeling is most often used today in large spaces (greater than 20,000 square feet) where the return on investment from energy efficiency measures more than covers the upfront costs of modeling. Continued investments in both guidance and software to make advanced modeling more accessible and targeted at tenant spaces will help smaller tenant applications (less than 20,000 square feet) to use designs that benefit from energy modeling.

Improving leasing language and broker engagement – energy efficiency-aligned language can be added to traditional building leases to create "green leases" that mitigate the landlord-tenant split-incentive problem. To increase the use of green leases, which in turn can help tenants realize financial benefits, industry trade organizations can continue to highlight examples of successful green leases, collect and publish best practices, and create case studies that illustrate the benefits and market opportunity for green leasing strategies. Education that increases energy efficiency literacy among real estate brokers will help them to better respond to tenant requests for energy efficient spaces and leases.

4 Eichholtz, P., Kok, N., & Yonder, E. (2012). Portfolio greenness and the financial performance of REITs. Journal of International Money and Finance, 31(7), 1911-1929. http://www.fir-pri-awards.org/wp-content/uploads/Article-Eichhiltz-Kok-Yonder.pdf

5 Eichholtz, P., Kok, N., & Yonder, E . (2010). Doing Well by Doing Good? American Economic Review. http://urbanpolicy.berkeley.edu/pdf/AER_Revised_Proof_101910.pdf

6 Eichholtz, P., Kok, N., & Quigley, J. M. (2009). Why do companies rent green? Real property and corporate social responsibility. Real Property and Corporate Social Responsibility (August 20, 2009). Program on Housing and Urban Policy Working Paper, (W09-004). http://www.ucei.berkeley.edu/PDF/EPE_024.pdf.

7 An, X., & Pivo, G. Default Risk of Securitized Commercial Mortgages: Do Sustainability Property Features Matter? (2015). http://capla.arizona.edu/sites/default/files/faculty_papers/Default%20Risk%20of%20Securitized%20Commercial%20Mortgages%20and%20Sustainability%20Features%2C%202015.pdf

Creation of a federal tenant space recognition system – By allowing for direct peer-to-peer comparison of buildings based on energy or sustainability performance, recognition systems provide the market with greater insight to evaluate building performance. This can help owners, tenants, and brokers to broadcast the value of energy efficiency measures, and distinguish high-performance buildings from the rest of the market. Simplifying efficiency to an accessible metric can give market participants a "scorecard" to measure higher levels of performance, and often drives activity across the industry as a whole through competitive forces and peer comparison. There will be several possible ways to design a recognition program for leased spaces. Options range from recognition based on outcome-focused gross metrics like those used by the Australian government (energy use intensity), to detailed metrics focused on design and operational inputs like the government in Singapore (lighting level, temperature ranges) to energy simulation-based approaches or simpler checklist-based approaches. Further research is warranted to assess the metrics, structure, and market viability of a potential system to best support the U.S. market.

2. Introduction, Definition of Scope and Existing Efforts

2.1 Introduction and Legislative Mandate

Over the past 20 years, many of the energy efficiency gains in commercial buildings in the United States have occurred as a result of a focus on improved technologies and owner-oriented tactics, while tenants have so far received relatively little pressure or support to improve energy efficiency measures within their spaces. As such, congress passed the Energy Efficiency Improvement Act of 2015 on April 23, 2015 to foster greater attention and collaboration on tenant space energy management.

The Energy Efficiency Improvement Act requires completion of this study to determine the feasibility of: (1) significantly improving energy efficiency in commercial buildings through the design and construction of separate spaces with high-performance energy efficiency measures, and (2) encouraging owners and tenants to implement such measures in separate spaces. The legislation also requires the Secretary to publish this study on the website of the Department of Energy (DOE).

2.2 Definition of Scope

This study investigates the feasibility of significantly improving energy efficiency in commercial buildings through the design and construction, by owners and tenants, of separate spaces with high-performance energy efficiency measures. For the purposes of this study: "significant improvement" is defined as an excess of 20% improvement, "separate spaces" are spaces that tenants are leasing, and "high-performance energy efficiency measures" are combinations of tools, practices, and technologies that when applied drive energy efficiency improvements in excess of 20%, either separately or in combination.

In addition, this study investigates the feasibility of encouraging owners and tenants to implement high-performance energy efficiency measures in separate spaces. For the purposes of this study: "encouraging" is the development, distribution, and adoption of tools, resources and policies that enable owners and tenants to implement energy efficiency measures.

3. Benefits of Achieving Energy Efficiency in Tenant Spaces

Reducing the energy used in tenant spaces would provide significant benefits to the economy and environment of the United States. Fundamentally, both owners and tenants affect the energy consumed and resulting emissions from leased spaces, and as a result, this section discusses the energy and emissions of the commercial real estate sector accordingly.

3.1 Energy and Emissions in Tenant Spaces

The energy consumption at a representative large, multi-tenant building can be partitioned into energy attributable to common areas (such as atriums, lobbies and garages), shared mechanical systems (such as central heating, fans, and cooling towers), and tenant spaces. In a typical arrangement, certain of these segments are clearly controlled by the owner, such as the garage lighting. Other segments are clearly controlled by the tenant, such as plug loads in tenant spaces. However, ultimate responsibility for managing the energy consumed in a multi-tenant space is often balanced between tenants and owners. Circumstances differ based on lease structure, but in a typical arrangement, neither owner nor tenant has complete control.[8] Instead, the energy and associated emissions are under the joint control of the owner and tenants, and significant reductions in energy costs can best be captured through their collaboration.

For purposes of scale, this section quantifies the total energy consumed by office, retail, and flex (a mix of office, warehouse, and light industrial) spaces. While multifamily spaces are also leased, they typically are not designed and constructed for each new tenant, and have a different set of considerations that are outside the scope of this report.

As a whole, commercial buildings account for 20% of the energy used in the United States Economy.[9] Of this number, office, warehouse, and retail spaces in the United States occupy 26.5 billion square feet of space, consume 4,700 trillion Btu of energy (major fuels and electricity), and spend $25 billion annually on energy costs. The office, retail, and warehouse sectors produce over 970 million metric tons (MMT) of carbon dioxide equivalent emissions (CO_2e).[10] While these estimates encompass all office and retail space, leased space accounts for more than 50% of an office building's total energy use.[11] Making a conservative assumption that energy use associated with retail and warehouse leased space is also 50% of total building energy use, leased spaces account for more than 490 MMT of emissions, and 2,350 trillion Btu of energy consumption annually.

8 As an example, while the owner may select and maintain the central heating system, the tenant may have control over the thermostat controlling the leased space and the adjoining common corridor. Together, the choices made by the owner and tenants determine the energy consumption at the building.

9 U.S. Energy Information Administration. (2006). 2003 CBECS Detailed Tables – Table C4A: Expenditures for Sum of Major Fuels for All Buildings. https://www.eia.gov/consumption/commercial/data/archive/cbecs/cbecs2003/detailed_tables_2003/2003set14/2003html/c4a.html

10 EIA. (2003). Commercial Buildings Energy Consumption Survey (CBECS) – 2003 CBECS Survey Data. CBECS website http://www.eia.gov/consumption/commercial/data/2003/

11 NRDC. (n.d.). High Performance Tenant Demonstration Project. http://www.josre.org/wp-content/uploads/2013/02/CMI-PPT-on-Tenant-Energy-Performance.pdf

3.2 Potential Benefits

There are quantifiable financial and environmental benefits associated with increasing energy efficiency. As a quick estimate of benefits, if current energy use in retail, warehouse, and office space was reduced by 20%, the country could save:

- 940 trillion Btu of energy, roughly the quantity of electricity consumed by Mexico.[12]
- $5 billion in annual expenditures.
- 190 MMT of CO2e, or the emissions from 370 billion miles of automobile travel.

3.3 Effects of Energy Efficiency on Employment

A recent literature review and analysis by the Pacific Northwest National Laboratory (PNNL) evaluates the impact of improved energy efficiency on employment and the economy.[13] [14] The study evaluated two primary vectors of energy efficiency job creation:

1. Long-run, economy-wide job creation due to energy efficiency freeing up money that would otherwise have been spent on energy. The study concluded that spending money made available by reducing energy expenditures for alternative goods and services generates a net gain of about 8 jobs per million dollars of consumer bill savings.
2. Immediate, sector-specific job creation due to investments in energy efficiency. The study concluded that initial investments in energy efficiency generate about 11 jobs per million dollars of investment. These activities include the purchasing and installing of measures for retrofit or for new construction and also jobs in other sectors "induced" by this economic activity.

Common Types of Lease Structures

While there are many lease structures, a few of the most common are briefly described below, in order to illustrate the ranges of responsibility:

- In a triple-net lease, the costs of maintenance, insurance, taxes, and utilities are borne by the tenant. In this case, the owner has little control or financial interest in the energy consumption of the leased area.
- In a gross lease, the costs of maintenance, insurance, taxes, and sometimes utilities are paid by the owner. The tenant pays a flat fee covering these expenses. In this case, the owner has more control and financial interest in the energy consumption of the leased area.
- In a pro rata share scenario, tenants are responsible for a percentage of total utility bills proportional to the percentage of the building's area which they occupy, and are billed through a monthly recovery fee.
- The vast majority of lease structures resemble one of these three models, with tenants directly or indirectly covering energy usage costs associated with their use (such as plug loads), and paying proportionally for the use of shared systems or energy costs for common area spaces, lobbies, etc.

12 EIA. (2014). Total Petroleum and Other Liquids Production – 2014. http://www.eia.gov/beta/international/

13 Anderson, D. M., Belzer, D. B., Livingston, O. V., & Scott, M. J. (2014). Assessing National Employment Impacts of Investment in Residential and Commercial Sector Energy Efficiency: Review and Example Analysis (No. PNNL-23402). PNNL, Richland, WA (US). http://www.pnnl.gov/main/publications/external/technical_reports/PNNL-23402.pdf

14 Further explanation of the PNNL study methodologies and results are referenced in section 5.1 of the appendix.

4. Feasibility of Achieving Energy Efficiency in Tenant Spaces

The technologies exist to improve energy performance in separate spaces; however, historic challenges have prevented wide-spread adoption of separate space efficiency measures. While challenges do exist, there are a variety of opportunities that mitigate these barriers and encourage the uptake of energy efficiency in tenant spaces. The following discussion summarizes current research and strategies to improve tenant spaces energy efficiency.

4.1 Challenges

While the potential benefits of energy efficiency in separate tenant spaces were described in Section 3, several challenges have historically prevented large-scale adoption of such measures. These systemic barriers discourage the implementation of energy efficient technologies during design and construction. Broadly speaking, these challenges can be categorized as issues of Timing and Process, Education and Awareness, Tenant Market Demographics, Cost Structures, and Data Availability.

4.1.1 *Timing & Process*

As background, the energy efficiency of a tenant space is determined primarily during two time windows:

- Design and fit-out, or the time leading up to and including construction of the tenant space.
- Occupancy, or the time in which tenants occupy the space.

Major tenant improvements are relatively infrequent – tied to the lease cycle, the time in-between can typically be 3-7 years or more – and as such the opportunity to influence the design and selection of major systems and technologies in the space are limited to these intermittent windows.[15] While some energy efficiency strategies are available during occupancy, the largest-scale gains are typically achievable in the infrequent design window, with moderate additional energy savings obtainable during occupancy. Generally speaking, these gains apply to office, retail and warehouse buildings, whereas other space types such as data centers and manufacturing have an entirely different relationship where the operational energy in the space is much greater than that of the building. Figure 1 below provides a generalized overview of the leasing and tenant improvement process, noting the sequence of these "windows" in a typical project:

15 The greatest opportunity to implement energy efficiency in separate tenant spaces is during the new construction process and in particular, during a build-to-suit development. During new construction, the greatest systemic changes can be implemented, including customized design of the HVAC system, metering schema, and building envelope. While the opportunities are greater during this stage, the considerations are highly similar to those discussed in this section.

FIGURE 2 – THE TENANT IMPROVEMENT PROCESS

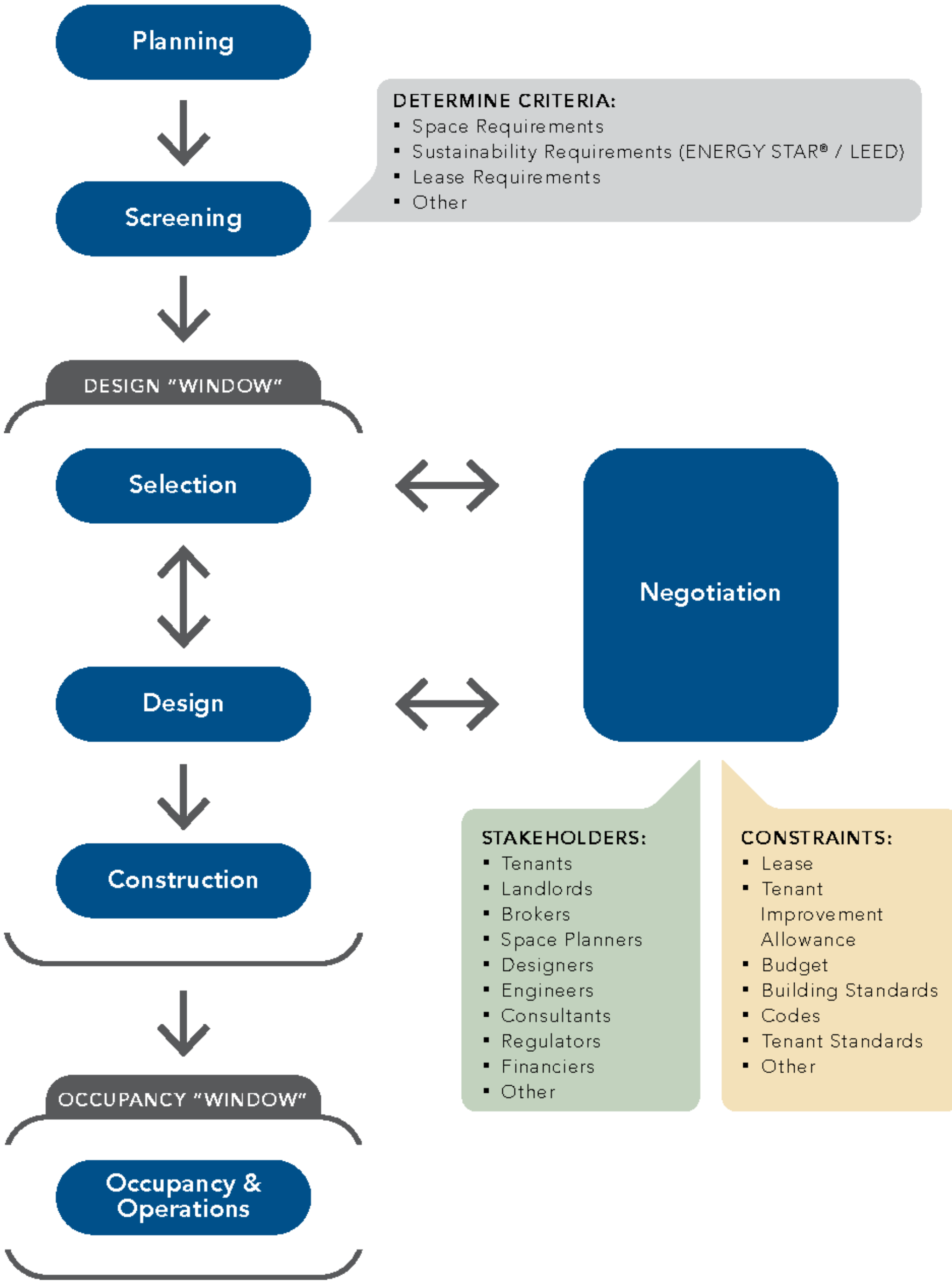


Table 1 details each of the steps shown in Figure 1, noting key activities and processes that can influence the implementation of energy efficiency initiatives throughout the tenant improvement process:

TABLE 1 – THE KEY PHASES OF THE TENANT IMPROVEMENT PROCESS

PHASE:	DESCRIPTION AND ACTIVITIES:
Planning	▪ Decision that new space is needed ▪ Criteria development ▪ Office search and design team formation, can include: tenant representative (broker), designer, architects, and space planners
Screening	▪ Initial review of candidate properties ▪ Preliminary matching against space criteria ▪ Development of a "short list" of properties for initial negotiations
Selection	▪ Final decision on property, depending on outcome of negotiations and design
Negotiations	▪ Finalizing lease terms, conditions, rental rates, tenant improvement allowances, length, and other considerations
Design	▪ Space planning ▪ Aesthetic and functional design of tenant suite
Construction	▪ Build-out, furnishing, and commissioning of infrastructure, systems, and equipment
Occupancy & Operations	▪ Building operations and maintenance ▪ Tenant business operations

The energy performance of tenant spaces is influenced in multiple ways across each of the above phases. Factors including owner attitudes, financial situation, and negotiating position can foster or inhibit energy performance considerations in decision-making. For example, in the planning phase, tenants can establish environmental and energy performance targets for their space, guiding which buildings become eligible through the screening process. As a result, tenants may screen building ownership for their sustainability practices and attitudes, or limit their searches to LEED or ENERGY STAR® certified spaces in an effort to find a collaborative partner for saving energy. These, and other decisions at earlier stages of the tenant improvement process, can have significant influence on the ultimate efficiency of the space.

The Design Window

The design window consists of three phases (2): selection, negotiation, and design. Depending on the market, the size of the leased space, the sophistication of the parties, and the specifics of the project, these phases can occur simultaneously or sequentially.[16] Through the three stages parties iteratively negotiate, examining proposals and counter-proposals, evaluating competing bids, and revising financial projections. Timing pressure and budget constraints are intense components of this process, as owners and tenants both wish to avoid lost revenues or unnecessary costs due to a long leasing process. As such, energy efficiency measures may be rushed or dropped altogether, as the parties often perceive that they have more pressing considerations.

While the three phase design window is the process used by many tenants, other tenants may go through a simpler process. In its simplest form the process may involve identifying a nearby space (avoiding the selection phase), negotiating terms directly with the owner (avoiding the broker), and moving in with little fit-out. Again, energy efficiency may be de-prioritized as tangential in this process.

Throughout this entire design window, multiple stakeholders (and motivations) come into play, each with varying levels of influence depending on the situation:

- Brokers, motivated by commissions, often leave out energy efficiency topics in negotiations as they often seek quick and simple deal closure, and try to eliminate any extraneous factors from complicating negotiations.
- Tenants, often facing "sticker shock" at the expenses involved in leasing space or dealing with day-to-day business requirements, are faced with adding additional up front expenses of incorporating energy efficiency measures into their operations.
- Designers, consultants, and engineers all must keep abreast of negotiations and budgets in addition to client energy efficiency demands, and translate tenant criteria and space constraints into a workable plan.[17] Energy efficiency can be pushed aside relative to other client priorities.

The Deep-Retrofit "Window"

In addition to the design and occupancy windows described here, a major opportunity to improve energy performance arises through a "Deep Retrofit." Defined as an integrated, whole-building modernization program, Deep Retrofits can reduce energy consumption by 40% or more by enacting a holistic set of energy efficiency strategies across both common areas and tenant spaces.

Deep Retrofits often make sense when real estate owners, developers, and investors seek to "reposition" an older, dated property to be more competitive in the market, when significant tenant turnover is expected, or when large centralized systems such as a chiller or window glazing need to be replaced. By acting on this Deep Retrofit window - and integrating energy performance strategies throughout tenant spaces and building common areas - building owners can achieve a multiplier effect in terms of energy savings potential. However, these windows are infrequent, often 20-50 years apart.

16 Critically, tenants often will enter into negotiations with multiple building owners at the same time, attempting to achieve pricing leverage or to examine multiple options or locations. Designers often must look at the available space and produce a "test fit" preliminary design to ensure that the tenant requirements could be met by a particular property, and to check the impacts to the tenant improvement budget. Building owners put forward an initial proposal at this stage including rental rates, terms, and tenant improvement allowances.

17 Constraints also guide the ultimate space design. Large, national tenants or chains and franchisees may have brand standards and design criteria, specifying lighting technologies, illumination levels, or other aesthetic requirements that may compete with energy efficiency strategies. Building codes, project budgets, or unique leasing terms regarding maintenance practices may all combine to limit designers. Further, building ownership may have tenant improvement guidelines or building standards that specify systems, technologies, or operational constraints that impact energy performance opportunities. Each of these options needs to be evaluated by the parties in the transaction, and resolved through negotiations and by designers.

- Building owners, in a highly competitive market, have a valuable product and may suspend complex negotiations involving energy efficiency when a more attractive tenant - with simpler demands - appears.

Once design of a tenant space begins in earnest, timing considerations add pressure to decision making. At this juncture, both tenants and owners likely have financial and other resources committed to the deal, and any delays can result in additional costs:

- Tenants and owners often forego energy efficiency analyses - such as engineering studies, energy modeling, or technical pilots –so as to not disrupt the project's timing.
- Tenants may not be able to justify the financial and time costs of analysis by consultants, engineers, or other design professionals in comparison to the amount of energy costs that may be saved, particularly in smaller spaces.
- Owners often avoid perceived risks of "new" or "different" requirements are included, as this adds further complexity and uncertainty to the deal.
- In many cases, the initial costs of more efficient lighting, HVAC, or other equipment exceed that of standard technologies, further burden project financing and strain negotiations.

Ultimately, what gets installed and built in a tenant improvement project can depend on negotiating leverage. In a high-vacancy, tenant friendly market, a national credit-worthy tenant can demand and often receive significant concessions from property owners. Alternatively, in a low-vacancy, owner friendly market, building owners may provide minimal tenant improvement allowances (if any) or charge rent premiums. Such a market discourages the inclusion of energy efficient measures due to the ability of owners to easily identify alternative, less-demanding tenants.

Given these process related aspects – the phases of the design window, the multiple stakeholders and design constraints, and the dynamics of fluctuating negotiating leverage – significant advancements in achieving energy efficiency in separate tenant spaces has been slow to materialize.

When energy efficient technologies are implemented in the tenant improvement process, the most common improvements are items localized to the separate space, such as interior lighting upgrades and/or enhancements, efficient power supplies, efficient data center power and cooling systems, and tenant-specific HVAC systems that may or may not interact with central building systems. In larger leases, where a tenant has leverage through potential occupancy of a significant portion of a building, tenant improvements and leasing requirements may also include envelope enhancements, specify operating hours and practices by building management, set expectations on sustainability certifications such as LEED or ENERGY STAR®, or control other operational aspects.

The Occupancy Window

Once a tenant begins occupancy, some potential for significant energy savings diminishes. Tenants have limited control over central systems and in-suite equipment to improve efficiency, and only control limited building operations, if any. Owners, having secured the tenant for the life of the lease and having financed all or part of the cost of the tenant improvement, are hesitant to consider additional upgrades while mid-stream in the lease. Likewise, tenants in a shorter lease or mid-stream in their lease will resist spending resources on energy efficiency projects as they will not be able to fully benefit from the generated cost savings by the time their lease is up. At this point, the utility costs are paid by either the tenant or the owner as designated in the lease, and any cost savings achieved through energy efficiency may not be realized by the party that is making the investment. Further, the business needs and requirements of a tenant may preclude changes in technology or system operations for the purposes of energy efficiency – for example, while one might typically try to restrict operating system use during traditional business hours, tenant operations might require extended operations of HVAC equipment.[18] Owners are also reluctant to conduct large-scale energy efficiency upgrades that may disrupt tenants due to construction activities. As a result, both the owner and tenants may have limited appetite to pursue major energy savings projects during occupancy.

During occupancy, owners are generally operating and maintaining shared building systems, such as HVAC, exterior lighting, elevators, and building amenities. Depending on the leasing arrangements, the owner may also be maintaining select equipment within tenant spaces, such as replacing lights, or operating dedicated HVAC systems. Yet doing so still requires significant coordination between building ownership and tenants. The ultimate result is that during occupancy, most owners focus energy efficiency efforts on shared building systems under their purview, while tenants implement plug-load and behavior change strategies within their own spaces, if they act at all.

4.1.2 *Education, Awareness, and the Role of the Broker*

While timing pressures during the lease negotiation process decrease the prioritization of energy efficiency, the challenge is compounded by the fact that for many in the industry, energy efficiency in tenant spaces is not yet a common topic of discussion. While leading property owners and managers have become increasingly aware of the financial and competitive benefits of energy-efficient buildings, the owner has historically been the main driver of energy efficiency in commercial real estate. As discussed earlier in this section, the leasing terms have typically allowed the owner to dictate energy efficiency measures.

As a result, a vast number of potential tenants remain unaware or uninterested in the financial benefits and opportunities afforded by energy efficiency within leased spaces. Market inertia, competing priorities, information overload, and financial concerns can crowd out the "mindspace" of a potential tenant, leaving little time to investigate energy efficiency opportunities. For example, when examining a new space for lease, most tenants are primarily focused on location, rent, space suitability, and amenities. Energy efficiency is a distant fifth or lower on the list of priorities. This is reinforced by the relative costs of energy and rent. At a typical major city office building, energy will cost between $2 and $4 per SF. By contrast, rent may be as much as:

18 An example of necessary extended operating system hours could be an accounting firm requesting HVAC services for after hours during tax season.

TABLE 2 – RENT IN MAJOR MARKETS

CITY:	AVERAGE CLASS A OFFICE ANNUAL RENT ($/SF)
Manhattan, NY	$77 [A]
New York, NY (City Average)	$49 [B]
Washington, DC	$45 [C]
Austin, TX	$43 [D]
Denver, CO	$34 [E]
Tulsa, OK	$16 [F]

A Mashayekhi, R. (2015). Manhattan office vacancy rate hits six-year low. The Real Deal. http://therealdeal.com/2015/07/21/manhattan-office-vacancy-rate-hits-six-year-low/

B LoopNet. (2015). New York, NY Market Trends. http://www.loopnet.com/New-York_New-York_Market-Trends/?Trends=AskingRentsFL,NumberOfListingsFL,ProfileViewsFL,TotalSFAvailableFL,DaysOnMarketFL&PropertyTypes=Multifamily,Office,Industrial,Retail

C LoopNet. (2015). Washington, DC Market Trends. http://www.loopnet.com/Washington_District-of-Columbia_Market-Trends?Trends=AskingRentsFL,NumberOfListingsFL,ProfileViewsFL,TotalSFAvailableFL,DaysOnMarketFL&PropertyTypes=Multifamily,Office,Industrial,Retail

D Davidson, C. (2015). Austin Office Market Report – Q1 2015. The Tenant Advisor. http://www.coydavidson.com/office/austin-office-market-report-q1-2015/

E API Global. (2015). High Lease Rates and Low Vacancies a Hard Pill to Swallow for Tenants. Denver Metropolitan Commercial Real Estate Update. http://sg-realty.com/wp-content/uploads/2010/03/news-mid-year-20155.pdf

F CBRE. (2015). Tulsa Office MarketView H1 2015. Market Reports USA Tulsa/Oklahoma. http://www.cbre.us/o/tulsa/Pages/market-reports.aspx

One potential barrier to raising awareness is the role of the real estate advisor or brokerage community. Brokers "…hold the keys to what gets negotiated in the lease and what interests are being represented."[19] Working primarily for a commission based on the total rent and length of the lease, brokers facilitate negotiations covering terms, conditions, cost structures, tenant improvement allowances, and other logistical details.[20] When and if energy cost arrangements are discussed, they often constitute a minor element of negotiations, given the scale of energy costs in comparison to rent and other considerations. These same advisors are typically compensated when a deal is completed and have little incentive to complicate the transaction with discussions of sustainability. Thus, many tenants remain unaware of the relative efficiency of the tenant spaces they are considering.

Various real estate advisors – brokers, designers, property managers – play a particularly prominent role because the average tenant improvement project is driven by a non-real estate professional. The typical small to medium business owner who is seeking new space will designate a member of the staff to manage the process. Often, a human resources manager, business executive, or the owner themselves will act as project champion. Their leasing experience may represent the only time they engage in this type of transaction, resulting in a heavy reliance on their leasing representative and prospective owners for information and guidance.

It then falls to the real estate advisors to inform prospective tenants on the value of energy efficiency improvements. Brokers in particular play a critical role in interpreting, explaining, and advising their clients on the lease terms. But many real estate advisors will not take the time to educate tenants unless energy efficiency or sustainability is a goal expressed in preliminary discussions by the prospective tenant. Likewise, many tenants simply do not know what questions to ask related to energy efficiency. Unless an active effort is made by the tenant or owner sides to introduce energy efficiency and sustainability into leasing discussions, many projects will continue to move ahead without capitalizing on the opportunities.

4.1.3 *Tenant Market Demographics*

The tenant space market is comprised of a minority of national tenants with the ability to implement portfolio-wide energy efficiency changes. Conversely, the majority of tenants in the market are small, disparate, and hard to reach with overarching energy efficiency strategies. The National Association of Realtors and CoStar Group provide visualization of these market demographics:

- "In terms of inventory, commercial real estate markets are bifurcated, with the majority of buildings (81%) being relatively small, while the bulk of commercial space (71%) is concentrated in larger buildings."[21]
- Tenant demand is strongest for small leased properties of 5,000 square feet (SF) or less - these properties represent 75% of all leased properties in the United States. While demand for large spaces of 50,000 SF and above represent less than 15% of leased properties (Figure 2).[21]
- The average office lease for class A, B and C office buildings are about 8,000 sf, 3,500 sf, and 1,600 sf, respectively.[22]

19 Regulations.gov. (2015). Comment response to the published Request for Information (RFI). Shorenstein Realty Services. http://www.regulations.gov/#!documentDetail;D=EERE-2015-BT-BLDG-0012-0005

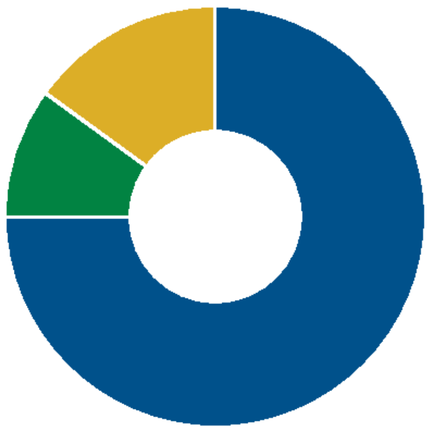
20 Brokers may also cover energy related items such as sustainability certifications, special HVAC cooling needs due to data centers or other unique equipment, operating hours, or energy and power source requirements due to intensive plug loads.

21 This number includes retail, office, and multifamily, and industrial space data. National Association of Realtors® Research Division. (2016). Commercial Real Estate Market Trends: Q4.2015. http://www.realtor.org/reports/2015-q4-commercial-real-estate-market-survey

22 Ponsen, A. (2015). Trends in Square Feet per Office Employee. Commercial Real Estate Development Association. http://www.naiop.org/en/Magazine/2015/Spring-2015/Business-Trends/Trends-in-Square-Feet-per-Office-Employee.aspx

- Lease terms of 36 and 60-months are most predominant in the market (59%).[21]
- Average lease prices vary with class A offices, class B and C offices, class A retail spaces, and class B and C retail spaces averaging $129/SF, $98/SF, $124/SF, and $91/Sf, respectively.[21]

FIGURE 2 – TENANT DEMAND FOR LEASED PROPERTIES REPRESENTED AS A PERCENTAGE OF THE U.S. MARKET.[21]



Efforts or programs targeting tenants will have an uphill battle due to the fragmented and diverse nature of the tenant population. These trends necessitate the creation, production, and distribution of resources and tools that can be effectively disseminated and communicated to tenants despite such variabilities.

4.1.4 *Cost Structures*

One of the most commonly cited barriers to the adoption of energy efficiency strategies in shared spaces remains the "split-incentive" problem. In a commercial building lease, all operational and maintenance costs associated with a building are paid by the owner, the tenant, or some combination thereof. These costs may include utilities, property taxes, security, insurance, janitorial services and more, and the lease legally defines who is responsible for these costs and any methodologies for cost-sharing or reimbursements.

In this context, the "split-incentive" refers to the accrual of costs and benefits of energy efficiency to different parties based on the separation of responsibilities for capital improvements and paying energy bills, or other bills associated with benefit streams such as operations and maintenance and worker salaries. In one typical scenario, capital costs are the responsibility of the owner, but operational costs are borne by the tenant. As an example, if a building owner invests in a more efficient lighting technology, the financial benefits of reduced energy consumption will flow partially or in whole to the tenant, depending on the lease structure. Likewise, tenants who will only occupy a building for a few years are hesitant to invest in a building system that lasts beyond that time horizon, or that ultimately becomes the building owner's property. Another form of the split-incentive can be found in space that is not submetered, but energy is included in the lease. With this structure, energy saving behavior by one tenant doesn't necessarily benefit that tenant – instead, the bill reduction is split across all tenants.

Numerous scenarios exist that determine to what extent, if any, owners or tenants both have a financial interest in reducing energy consumption. Specific lease types such as gross, net, fixed-base, or various permutations have different mechanisms for allocating energy costs. Gross leases typically specify that owners are responsible for energy costs, while net leases place that responsibility on the tenant. Various other approaches utilize mathematical formulas, cost ratios, common area maintenance (CAM) methodologies, or energy submeters to determine the timing, proportion, and ultimate responsibility for energy costs. Further, different property types traditionally use different methodologies – with industrial or retail properties, the tenant is typically responsible for all utilities, while office properties are typically have terms that reflect local norms.

In many leases, owners have the right to pass-through costs of upgrades to the building, *if that investment will lead to a financial benefit to the tenant.*[23] For example, if a lighting retrofit would cost $2,000, and as a result the tenant would receive energy cost savings of $200 a year, then the owner could approach the tenant and pass the $2,000 through to them, assuming the tenant would be in the space for over 10 years and would "break-even" at a minimum. Of course, both parties would need to agree to this course of action and the specifics of the lighting project, subject to the terms and conditions of the lease. Understandably, many tenants are hesitant to agree to these relatively unplanned costs – effectively a rent increase - as they are trying to manage their total cost of occupancy in the building as part of their business expenses. Likewise, owners may be unwilling or unable to effectively discuss these types of energy efficiency investments with tenants, due to the complexity of the cost allocations, a fear of potentially upsetting or losing the tenant, or simply because the perceived benefits are minimal.

The "split-incentive" market barrier is not new, and has been identified and acted on by a number of organizations, with some limited progress. BOMA released its Green Lease Guide in 2008[24] and has made several updates since

The Distinction between Value and Cost-Savings

The benefits of energy efficiency and sustainability in commercial buildings can take many forms, and an important distinction should be made between cost-savings and value. In the book Value beyond Cost Savings and through numerous other publications, Scott Muldavin, the Rocky Mountain Institute (RMI), and many others have articulated the numerous real estate, business, and corporate enterprise benefits that result from energy efficient, green, or sustainable buildings. These benefits include improved competitiveness, increased asset value, increased worker productivity, reduced risks, improved corporate image and branding, employee attraction and retention – all can directly or indirectly result from improved energy performance, and provide building owners, business enterprises, and tenants with tangible value.

To a large extent, these benefits are not subject to the split-incentive in the same manner as cost-savings, as the owner and tenant each directly benefits from these attributes. For example, an owner will benefit from increased asset value, while a tenant would benefit from increased productivity.

In viewing the larger value considerations beyond basic cost savings, more-compelling business cases and new, opportunities can emerge. As market participants – owners, investors, tenants, and businesses – become aware of and act on the greater value benefits beyond strict cost savings, investments in energy efficiency and sustainability may accelerate, and circumvent many of the market barriers and challenges described herein.

23 This is often referred to as a tenant cost recovery clause.

24 BOMA. (2010). Commercial Lease: Guide to Sustainable and Energy Efficient Leasing for High-Performance Buildings. BOMA website http://store.boma.org/products/commercial-lease-guide-to-sustainable-and-energy-efficent-leasing-for-high-performance-buildings

then. The Green Lease Guide and subsequent publications provide model leasing language and practices for optimizing lease language in a manner that, among other things, aligns owner and tenant interests in energy efficiency and sustainability initiatives. The Natural Resources Defense Council's (NRDC) Center for Market Innovation has also published Energy Efficiency Lease Guidance, and is participating with the City of New York Mayor's Office of Long-Term Planning and Sustainability to disseminate and craft model energy aligned lease language within the New York real estate market. Additionally, a tenant space energy efficiency program managed by the Urban Land Institute (ULI) seeks to deliver a replicable process that integrates energy efficiency into office tenant space design and construction within the tenant improvement cycle window (refer to section 4.2 below for more details on this program).

The Institute of Market Transformation (IMT) has launched several tools, resources, and programs promoting "green leasing" practices, most notably the Green Lease Leaders recognition program.[25] Over the past several years, the Rocky Mountain Institute (RMI), the General Services Administration (GSA), the Northwest Energy Efficiency Alliance (NEEA), the Penn State Consortium for Building Energy Innovation, the California Sustainability Alliance, and numerous other regional and national groups have developed tools and programs targeting leasing and "split-incentive" cost structure barriers in the commercial real estate market.[26] [27] [28] [29] [30]

4.1.5 *Data Availability*

Another major challenge in improving the energy efficiency of separate spaces is segregating the energy consumed by a particular tenant from the whole building's energy consumption. This inability to collect tenant-specific energy data hinders efficiency for two primary reasons:

- As discussed, owners hesitate to invest in energy efficiency improvements of shared systems as only the tenant benefits from reduced utility costs of such endeavors.
- Second, lack of individualized data results in a common-pool resource issue[31] as tenants have no incentive to reduce energy use if they are not held financially accountable for their actions. Changes in their personal energy consumption would be distributed across all tenants.

Metering tenant-specific energy use, a process known as submetering, serves as one potential solution to this data availability problem. Submetering is needed to ensure that each tenant pays for what they use and receives the full benefit of energy they save.

Comments from USGBC are illuminating about the prevalence of tenant space submetering. The 2009 LEED-CI rating system has credit language that rewards the measurement and verification of tenant spaces which includes the installation of submetering equipment to measure and record energy use within tenant spaces. USGBC data show that 54% or 1,900 projects certified under the 2009 LEED-CI rating system have achieved credits dealing with measurement and verification, of which submetering is among several compliance options. This achievement rate demonstrates that submetering is achievable in the tenant space but is not an industry norm.

25 Green Lease Library. (2015). Green Lease Leaders. http://www.greenleaselibrary.com/green-lease-leaders.html

26 Rocky Mountain Institute. (n.d.). Built Environment: Tools and Resources. http://www.rmi.org/tools_and_resources

27 GSA. (n.d.). Green Lease Policies and Procedures. http://www.gsa.gov/portal/category/108551

28 Northwest Energy Efficiency Alliance. (2009). Solving the Energy Efficiency Puzzle: Achieving Bigger Savings in the Pacific Northwest. http://www.nwenergy.org/data/NWEC_Solving-the-EE-Puzzle.pdf

29 Consortium for Building Energy Innovation. (n.d.). http://cbei.psu.edu/

30 California Sustainability Alliance. (n.d.). Green Leases Toolkit. http://sustainca.org/green_leases_toolkit

31 The tragedy of the commons denotes a situation where individuals acting independently and rationally according to each other's self-interest behave contrary to the best interests of the whole group by depleting some common resource.

As a matter of current practice, few buildings and markets in the country measure tenant-level energy use through submetering. Where submetering strategies are employed, meters are most commonly installed for the primary function of lease administration, or the proper billing of tenants for energy use. The vast majority of these installations are typically for the purposes of monitoring spaces characterized by above-average energy use, such as data centers, and separating out this use from total building energy consumption.

Submeters are usually installed as a single entity or as a small group of manually-read meters. Their measurement is typically restricted to electricity use of lighting and plug loads. Energy use from HVAC and other shared systems is not included in these measurements; it is instead billed to the tenant by the owner on a pro rata basis.

Building owners often utilize less sophisticated meters over utility-grade meters. These meters are less expensive and "get the job done" when it comes to simple and consistent measurement of energy use from a single space. These basic meters provide a simple number of kWh used by a separate space over a given period of time. Under this scenario, facilities staff or contractors read the submeter's energy use and apply appropriate multipliers to this number in order to subtract this usage from that of the whole building's demand-charged utility bill.

These same meters can be installed with technical options allowing electricity measurements to tie into systems mimicking utility tariff standards. Such sophisticated options are used for heightened accuracy of tenant energy use billback.

Installing permanent submeters is expensive, with prices often ranging from $700 to almost $5,000 depending on the type and number of meters installed.[32] [33] These costs discourage many owners and tenants from purchasing meters as an energy monitoring tool. While lower-cost wireless meters exist, they currently lack the ability to measure energy use over an extended period of time. Rather, they are most commonly used to temporarily monitor the energy use of a space in order to justify permanent submetering of above-average energy use spaces.

In the absence of nationwide regulation, the presence of submetering is influenced primarily by tenant profile, with large corporate renters, energy-intensive users, sustainability conscious tenants, and tenants vying for LEED-CI certification occasionally requiring submetering during lease negotiations. This disparity can often lead to a varied presence of submetering within markets and buildings, making it difficult to uniformly collect energy use data for individual tenant spaces.

Building owners such as Shorenstein Realty have emphasized the "all or none" problem with billing tenants for energy use.[34] In order to separate out common area usage from tenant usage for billback, owners need to understand the energy consumption of each tenant in the building. Distinguishing common area usage from tenant energy usage can only be accomplished by submetering every tenant in the building. The submetering of just one tenant does not solve this issue as the owner is left with the problem of partitioning the remaining energy use between tenants and common area usage.

32 National Science and Technology Council Committee on Technology. (2011). Submetering of Building Energy and Water Usage. https://www.whitehouse.gov/sites/default/files/microsites/ostp/submetering_of_building_energy_and_water_usage.pdf

33 GSA. (2012). Submetering Business Case: How to calculate cost-effective solutions in the building context. http://www.gsa.gov/portal/mediaId/156791/fileName/Energy_Submetering_Finance_Paper_Knetwork_2012_11_269(508).action

34 Regulations.gov. (2015). Comment response to the published Request for Information (RFI). Shorenstein Realty Services. Regulations.gov website http://www.regulations.gov/#!documentDetail;D=EERE-2015-BT-BLDG-0012-0005

4.2 Technical Opportunities to Improve Energy Efficiency in Tenant Spaces

Despite the variety of challenges to achieving energy efficiency goals in tenant spaces, the technologies exist to significantly improve energy efficiency in these spaces. Case studies and cost benefit analyses of many proven technologies clearly demonstrate the feasibility of improving the energy efficiency in tenant spaces under a variety of different space and use conditions.

Efficient technologies are traditionally considered on an individual basis by which an owner or tenant can choose between simple investment options, such as whether or not to install LED lighting or lighting controls, in order to increase the efficiency of their space. Through this process, the decision maker can draw a straight line from cost of investment to energy savings as only one, or a few, efficiency upgrades are implemented at a time.

It is becoming increasingly important to consider energy efficiency technologies as a package of solutions rather than individual entities during a tenant fit out. This is because high efficiency technologies oftentimes complement the energy reductions of one another (such as HVAC equipment selection and advanced monitoring and controls) and owners often make decisions on more than one type of technology at a time during a fit out. As such, an owner or whole-building tenant may consider their investment holistically during construction.

Choosing between packages of energy efficiency technologies becomes difficult to manage as the number of variables involved increases. In addition, the costs and benefits of technologies can vary significantly depending on the geography, construction, and operations of the building. As a result, owners and tenants sometimes rely on energy modeling and technical consultants to assist with the decision-making process. As such, there is a clear market need for user-friendly, inexpensive tools that allow for decisions to be made without additional burden of technical considerations. Such tools could come in the form of an excel based program, a simple download, or an application that would allow owners and tenants to input specifics about their property (location, size, layout and use), select packages of efficient technologies, and compare results of packages based on financial metrics (incremental cost, payback period, and return on investment).

Several resources which provide broad return on investment (ROI) estimates of recommended energy efficiency packages are available to the public, including the Advanced Energy Retrofit Guide for Office Buildings prepared for the U.S. DOE and case studies produced by the Tenant Energy Analysis and Metrics program. The results of these case studies demonstrate the feasibility of significantly improving the energy efficiency of tenant spaces.

The Advanced Energy Retrofit Guide (AERG) for Office Buildings prepared for the U.S. DOE by PNNL provides several insightful case studies illustrating the implementation of different energy efficiency packages in different locations and the associated financial benefits of the project results.

One AERG case study highlighted the GUND Partnership's 2008 Cambridge, MA office renovation project and attainment of LEED Gold for Commercial Interiors certification (LEED-CI). Specific measures in the selected energy efficiency technology package included: lighting retrofits and the installation of ENERGY STAR® computers, printers, and office equipment. The project's costs totaled $4,400, estimated annual electricity savings were calculated to be $3,000, and the simple payback period was 1.5 years.[35]

An additional AERG case study focused on the 2009 energy efficiency retrofit of the Wilson Blvd. Building in Arlington, VA. Key energy efficiency measures included in the efficiency technology package

35 Thornton, B.A., Wang, W., Lane, M.D., Rosenberg, M.I., and Liu B. (2011). Advanced Energy Retrofit Guides Office Buildings. http://www.pnnl.gov/main/publications/external/technical_reports/pnnl-20761.pdf

included: alternate HVAC rooftop units, upgraded pneumatic HVAC controls and air handler system compressors, the installation of LED downlights, and the promotion of a tenant energy awareness strategy. Project costs totaled $1,140,000, while estimated annual energy savings were calculated to be $250,000, and the simple payback period for the project was 3.9 years.[35]

The Tenant Energy Analysis and Metrics program (referred to as "the program" or "the process") seeks to deliver a replicable process to integrate energy efficiency into office tenant space design and construction within the tenant improvement cycle window.[36] The program, developed in partnership with the NRDC, now resides at and is managed by the Urban Land Institute (ULI). The Tenant Energy Analysis and Metrics approach outlines a 10-step process to guide tenants through the leasing, design, modeling, analysis, execution, and measurement and verification stages of their build-out and occupancy:

- Step 1: select an office space.
- Step 2: select a project team (architects, engineers, and contractors tasked to help with the build-out).
- Step 3: set energy performance goals and create a list of energy efficiency technologies and strategies.
- Step 4: create packages of energy efficiency technologies and model their projected energy performance.
- Step 5: review the incremental costs of the energy efficiency packages and available incentives to specific energy efficiency technologies.
- Step 6: conduct a financial analysis including the calculation of return on investment (ROI) and payback period for each package of energy efficiency measures.
- Step 7: review financial analyses and choose a package of energy efficiency measures.
- Step 8: build out the space with chosen package of energy efficiency measures.
- Step 9: measure and verify the actual energy performance of the space.
- Step 10: share the results on an ongoing basis.

This process is further supported through guidance documents which detail in-depth instructions to complete each of the 10-steps discussed above.

The program documented ten case studies of tenants using the 10-step process to choose between packages of energy efficiency solutions, and the results they observed. These case studies are described in brief below. Energy and cost savings projections detailed in these summaries are based on actual energy performance and delivered savings. Case study participants verified savings numbers by measuring the operational energy use of their space upon completion of the build-out.

Bloomberg LP, a leading provider of global business information, rented space in Manhattan's 120 Park Avenue. Bloomberg partnered with the program for the design and construction of their new office. The company selected the following package of high efficiency measures for their build-out: mechanical duct bridging, high-efficiency lighting, daylight harvesting, and NightWatchman Software (plug load management). Combined, these efficiency measures totaled $3.06/square foot in incremental implementation costs.[37] Over the course of Bloomberg's lease, the project is estimated to reduce electricity use by 10.5% and save more than $173 thousand in electricity costs with a ROI of 140% and a payback period of 2.5 years (Table 3).

36 Information related to the ULI tenant space energy efficiency program and the case study summaries discussed below will be hosted at http://uli.org/.

37 The incremental implementation cost includes deductions from rebates and incentives.

COTY Inc., a global leader in beauty products, designed a tenant space build-out for floors 16 and 17 of their Empire State Building headquarters in Midtown Manhattan. Using the 10-step process, COTY chose the following package of high efficiency technologies for their planned build-out: a LED lighting system, daylight controls, variable air volume (VAV) air handling units, demand control ventilation, elimination of noise traps on air handling units, and plug and process load reduction through the installation of ENERGY STAR® equipment. In total, these efficiency measures amounted to $0.71/square foot in incremental implementation costs.43 Over the course of COTY's 17-year-lease, this project is estimated to reduce electricity use by 30.7% and save more than $716 thousand in electricity costs with a ROI of 328% and a payback period of 2.7 years (Table 3).

Cushman & Wakefield, a global commercial real estate services company, rented space in the newly constructed One World Trade Center in 2015. The company chose to use the program to guide the design and construction of their office. Cushman & Wakefield selected the following efficiency measures for their build-out: LED lighting; daylight harvesting; no humidity control, raising of temperature set points, and allowing independent distribution facility (IDF) room ventilation to cycle off; high-efficiency tenant HVAC and motors; ENERGY STAR® office equipment; server power management; and temperature set points (77° cooling and 70° heating). All in all, incremental implementation costs for these efficiency measures totaled $3.25/square foot.43 Over the course of Cushman & Wakefield's 10-year-lease, this project is estimated to reduce electricity use by 47.5% and save more than $87 thousand43 in electricity costs with a ROI of 359% and a payback period of 1.7 years (Table 3).

The Estee Lauder Companies, a leading manufacturer and marketer of cosmetics, leased 10,000 square feet at 110 East 59th Street in Manhattan. Through their partnership with the program, the company selected a package of energy efficiency measures for their build-out, which included: high efficiency lighting (0.7 and 0.9 Watts/square foot), daylight harvesting, occupancy sensor lighting, ENERGY STAR® equipment, and plug loads shutdown (master shutoff switch). This package of energy efficiency measures totaled $1.29/square foot in incremental implementation costs.43 Over the course of The Estee Lauder Companies' 6-year-lease, this project is estimated to reduce electricity use by 12.1% and save more than $15 thousand in electricity costs with a ROI of 42% and a payback period of 3.7 years (Table 3).

Global Brands Group Holding Ltd. leased 137,000 square feet on Floors 7, 8, and 9 of the Empire State Building in Midtown Manhattan and used the program to guide the design and construction of their new office space. The company selected the following package of energy efficiency measures for their build-out: daylight harvesting lighting controls, high-efficiency lighting, optimized HVAC units, demand-controlled ventilation (CO2 sensors), low-velocity air handler units (AHUs), and plug load management. The project totaled $0.98/square foot in incremental implementation costs.43 Over the course of Global Brands' 15-year-lease, this package of efficiency measures is estimated to reduce electricity use by 11.8% and save more than $438 thousand in electricity costs with a ROI of 126% and a payback period of 4.6 years (Table 3).

LinkedIn Corp, the world's largest online professional network, leased 36,000 square feet on Floor 22 of the Empire State Building in Midtown Manhattan. The company partnered with the program to guide the build-out of their office. LinkedIn chose the following energy efficiency measures to be incorporated into their new space: high-efficiency lighting, advance lighting (daylight harvesting and occupancy sensors), no humidification and increased temperature set points in IDF, optimized air handlers, demand-controlled ventilation, ENERGY STAR® equipment, and occupancy sensor plug strips. The incremental implementation cost for this project totaled $2.63/square foot.43 Over the course of LinkedIn's 10-year-lease, this package of efficiency measures is estimated to reduce electricity use by 31.3% and save more than $153 thousand in electricity costs with a ROI of 23% and a payback period of 6.4 years (Table 3).

The New York State Energy Research and Development Authority (NYSERDA), a state agency that helps New Yorkers increase energy efficiency, leased office space at 1359 Broadway in Manhattan. The agency partnered with the program for their planned build-out. NYSERDA chose the following energy efficiency measures to be included in the design and construction of their new space: high-efficiency lighting, daylight harvesting, ENERGY STAR® equipment, computer shutoff software, energy recovery ventilator, natural ventilation, and a variable refrigerant flow (VRF) system. Project incremental implementation costs totaled $2.43/square foot.43 Over the course of NYSERDA's 14-year-lease, this package of efficiency measures is estimated to reduce electricity use by 39.0% and save more than $188 thousand in electricity costs with a ROI of 179% and a payback period of 3.6 years (Table 3).

Reed Smith, a leading international law firm, moved into their office in Philadelphia's Three Logan Square in 2014. The company utilized the 10-step process and chose the following energy efficiency measures for their new office space: energy efficient lighting design (0.84 Watts/square foot), daylight harvesting controls, bi-level lighting control, dimmable switching controls, ENERGY STAR® equipment, occupancy sensor power strips, manually controlled quad outlets, after-hours outlet control, and high-efficiency motors and variable frequency drives on air handling units (AHUs). Incremental implementation costs for this project totaled $1.31/square foot.43 Over the course of Reed Smith's 16-year-lease, this package of efficiency measures is estimated to reduce electricity use by 44.5% and save more than $1 million in electricity costs with a ROI of 410% and a payback period of 2.2 years (Table 3).

Shutterstock, a global provider of high-quality licensed media, leased approximately 60,000 square feet at the Empire State building in Midtown, Manhattan. The company applied the 10-step process to their office build-out. Shutterstock selected the following energy efficiency measures for their new space: as-designed lighting (0.986 Watts/square foot), daylight harvesting, local occupancy sensors, economization of data center space, demand-controlled ventilation, and a chilled water data center cooling unit. Project incremental implementation costs totaled $2.63/square foot.43 Over the course of Shutterstock's 11-year-lease, this project is estimated to reduce electricity use by 22.9% and save more than $369 thousand in electricity costs with a ROI of 40% and a payback period of 6.1 years (Table 3).

In 2013, TPG Architecture, an architecture and interior design firm, signed a lease for 40,000 square feet of office space in Midtown Manhattan's 31 Penn Plaza. TPG worked with program partners to identify key energy efficiency measures in the design of their office space. The company selected the following energy efficiency package in their tenant space build out: as-designed lighting (1.08 Watts/square foot), daylight harvesting, local lighting occupancy sensors, ENERGY STAR® equipment, demand-controlled ventilation, no humidification in the office data center, computer shut-off software, occupancy sensor plug strips, and high-efficiency lighting (0.8 Watts/square foot). In total, incremental implementation costs for the package were estimated to be $2.01/square foot.43 Over the course of TPG's 11-year-lease, this project is estimated to reduce electricity use by 21.6% and save more than $275 thousand in electricity costs with a ROI of 162% and a payback period of 3.2 years (Table 3).

TABLE 3 – ULI TENANT SPACE ENERGY EFFICIENCY PROGRAM CASE STUDY RESULTS[A]

COMPANY	LOCATION	LEASED AREA	INCREMENTAL IMPLEMENTATION COST ($ / SQ FT)	PHASE*	ENERGY REDUCTION	TOTAL ELECTRICITY SAVINGS OVER LEASE TERM	ROI	PAYBACK PERIOD
Bloomberg LP	120 Park Avenue, Manhattan	20,000 ft²	$3.06 / sq ft	Modeled Savings	10.9%	$182,208	152%	2.4 years
				Verified Savings	10.5%	$173,880	140%	2.5 years
COTY Inc.[B]	350 Fifth Avenue, Manhattan	80,000 ft²	$0.71 / sq ft	Modeled Savings	32.0%	$548,317	227%	3.5 years
				Verified Savings	30.7%	$716,148	328%	2.7 years
Cushman & Wakefield	One World Trade Center, Manhattan	7,500 ft²	$3.25 / sq ft	Modeled Savings	52.6%	$95,663	404%	2.2 years
				Verified Savings	47.5%	$87,862	359%	1.7 years
Estee Lauder Companies[C]	110 E. 59th St., Manhattan	10,000 ft²	$1.29 / sq ft	Modeled Savings	10.8%	$23,069	106%	2.5 years
				Verified Savings	12.1%	$15,862	42%	3.7 years
Global Brands Group	350 Fifth Avenue, Manhattan	137,000 ft²	$0.98 / sq ft	Modeled Savings	25.5%	$546,983	189%	3.7 years
				Verified Savings	11.8%	$438,090	126%	4.6 years
LinkedIn Corp.	350 Fifth Avenue, Manhattan	36,000 ft²	$2.63 / sq ft	Modeled Savings	34.2%	$284,195	129%	3.4 years
				Verified Savings	31.3%	$153,000	23%	6.4 years
NYSERDA	1359 Broadway, Manhattan	15,200 ft²	$2.43 / sq ft	Modeled Savings	34.2%	$180,277	168%	3.8 years
				Verified Savings	39.0%	$188,017	179%	3.6 years
Reed Smith	Three Logan Square, Philadelphia	117,000 ft²	$1.31 / sq ft	Modeled Savings	34.3%	$1,800,986	715%	1.4 years
				Verified Savings	44.5%	$1,126,498	410%	2.2 years
Shutterstock Inc.	350 Fifth Avenue, Manhattan	58,600 ft²	$2.63 / sq ft	Modeled Savings	23.5%	$354,861	34%	6.3 years
				Verified Savings	22.9%	$369,897	40%	6.1 years
TPG Architecture LLP	31 Penn Plaza, Manhattan	40,000 ft²	$2.01 / sq ft	Modeled Savings	20.2%	$188,447	79%	4.7 years
				Verified Savings	21.6%	$275,372	162%	3.2 years

* "Modeled Savings" numbers represent original project savings estimates (step 4 of the 10-step process) while "Verified Savings" numbers represent verified project savings estimates (step 9 of the 10-step process).

A The numbers outlined above are the results of the Tenant Analysis and Metrics program which documented ten case studies of tenants using the 10-step process to choose between packages of energy efficiency solutions.

B Differences in modeled savings and verified savings energy reductions may be attributed to baseline and assumption adjustments and actual energy use documented during the measurement and verification process.

C Differences in modeled electricity savings is usually due to a discovered underestimation or overestimation of energy use in the measurement and verification process.

4.2.1 *Analysis of High Efficiency Technologies*

The technologies, outlined below, and their associated cost benefit analyses clearly demonstrate the feasibility of improving the energy efficiency in tenant spaces under a variety of different space and use conditions. This analysis of high efficiency technologies, discussed in the appendix, provides insight into major energy efficiency opportunities in separate spaces, simple cost-benefit analyses, and links to additional information.[38] This collection of technologies is reflective of the general opportunities and classes of technology that can be used in improving energy efficiency in a separate tenant space, but should not be considered a comprehensive list.

The following technologies are discussed in the appendix:

4.3 Market Opportunities to Improve Energy Efficiency in Tenant Spaces

In addition to technology, there are market-based opportunities to increase energy efficiency through processes, programs, and policies oriented to encourage the uptake of energy efficiency in tenant spaces. This section offers a list of high performance energy efficiency market-based opportunities with the intention of illustrating the variety of approaches available. These energy efficiency approaches are broken out into two categories, processes and programs.

4.3.1 *Processes*

This section discusses the market processes that currently influence the level of energy efficiency within a tenant space, explains how a tenant might navigate these processes, and investigates how these processes might be improved to drive additional energy efficiency across the market.

4.3.1.1 *Analyzing Opportunities*

Within the design and construction process, both tenants and owners have a role in determining the efficiency of the tenant space. As discussed, building owners traditionally control the building shell, shared equipment such as HVAC systems, and any global operational controls. By contrast, tenants

38 The High Impact Technology Catalyst: Technology Deployment Strategies paper prepared by Navigant Consulting for the U.S. DOE is one of the primary additional information resources and provides a list of building technologies with large savings potential.

control the installation of efficient equipment (lighting and plug-loads), and more directly manage energy use behavior.

Depending on the size and characteristics of the space, the tenant may choose to use conventional methods and checklist approaches to determine energy efficiency strategy in the build-out of the space, or employ estimates and energy modeling for a more detailed perspective and to maximize return on investment.

Conventional Methods and Checklist Approaches

Under a conventional fit-out process, driven by a tenant, the tenant may work with architects, engineers, and the owner to outfit the space. This team may rely upon guidelines, rules of thumb, or prior experiences in order to select technologies for meeting their pre-determined energy efficiency goals. Choices can be driven at one extreme by the legal codes and standards (minimum applicable requirements), and at the other by certification standards (ratable standards for design and construction such as LEED and Green Globes). Most fit-outs will fall somewhere in the middle, where decisions to incorporate energy efficiency projects above and beyond minimum applicable requirements are made absent of a coherent efficiency plan.

For many owners and tenants in this middle-ground scenario, checklist approaches may be sufficient to determine their energy efficient technology needs. While checklist approaches may not maximize potential energy savings, these methods may provide easy-to-implement guidance applicable to a variety of space types that align with a clearly defined energy efficiency result. This guidance can be incorporated cost-effectively, particularly in the case of smaller projects.

The industry has taken steps towards providing such guidance checklists. However, the current scope of these checklists falls short in accommodating the industry-wide need for a comprehensive set of guidelines that offer specification language customizable to the variety of tenant spaces that exist (such as a large versus small space or a retail versus office space). Additionally, the industry has not widely publicized these materials, leading to a lack of awareness on their existence and proper usage.

The Saving Energy in Leased Spaces (SELS) training and information website, created by the Consortium for Building Energy Innovation,[39] is one example of an existing online toolkit. The SELS website provides three toolkits focusing on saving energy in: existing leases, new leases, and during tenant improvement projects. Each toolkit provides users with: an online course on energy reduction; tools and checklists to track plug loads and calculate estimated energy savings; and a resource library of reference materials.[40] While the SELS website exhibits some best practices, including specification language for several types of tenant space improvements and options for users in different phases of the leasing cycle, it does not provide customization for different purposes (retail versus office) or sizes (small or large) of leased spaces.

The DOE's Technology & System Specifications represents another example of a collection of best practice guidelines. These specifications are designed to guide building owners and tenants through the process of obtaining quotes for energy efficient purchases.[41] While this collection offers a variety of specifications, users are required to determine which specifications apply to their leased space and to further customize chosen specifications to fit their space's attributes.

The Chartered Institution of Building Services Engineers' "Energy Efficient Refurbishment of Retail

39 The Energy Efficient Buildings Hub (EEBHUB) has been rebranded as the Consortium for Building Energy Innovation, however the SELS website still uses EEBHUB branding.

40 Energy Efficient Buildings Hub. (n.d.). Saving Energy in Leased Spaces (SELS) training and information website. http://savingenergyinleasedspace.com/

41 DOE Better Buildings. (n.d.). Technology & Systems Specifications. https://www4.eere.energy.gov/alliance/activities/specifications

Buildings" document provides guidance specific to retail space fit-outs. However, this document does not include specification language.

RMI is currently developing the Commercial Energy+ Initiative, which aims to rapidly increase the scale of building retrofits by providing a platform to provide accessible and inexpensive energy efficiency solutions for commercial buildings with tenant spaces. RMI reports that this initiative will supply a package of efficiency measures and technologies that can be scaled to specific building attributes and directly increase the efficiency of the space.[42]

Estimates and Energy Models

In scenarios where a tenant chooses to go beyond the minimum code requirements, but not pursue a formal guidance checklist, the tenant or service provider can estimate the value of an energy efficiency measure in a tenant space by calculating upfront costs, lifecycle costs, annual savings, and returns on investment. Tenants can also use energy modeling to help determine the energy efficiency opportunities of a space. With modeling, the tenant can compare different energy efficiency measures and decide which options are most appropriate for the individual space.

One example of such modeling programs is the EnergyPlus energy simulation software, DOE's free and open-source, whole building energy modeling engine that allows users to estimate energy consumption from a variety of sources including: plug and process loads, heating, cooling, and lighting.[43] A companion product is OpenStudio, a free and open-source graphical application for model development, parametric analysis and optimization using EnergyPlus. Commercial, proprietary front ends to EnergyPlus offer additional functionality.

While energy models provide the benefit of assessing energy efficiency measures in detail before their implementation, the effort required to use them has historically prevented such tools from wide-spread market uptake. Energy modeling often requires specialized consultants, and some additional time, both of which can strain project budgets. Modeling guidance for tenant space is also lacking – e.g. there may be confusion over whether central HVAC systems need to be modeled, or how to model adjacent tenant spaces. Clear modeling guidelines for tenant space are needed to ensure consistency and avoid confusion.

Organizations are beginning to develop tools to help translate modeling results to be applicable to tenant spaces. As an example, the ULI Tenant Energy Analysis and Metrics program aims to create a process to assist tenants achieve 30 to 50 percent energy savings with a payback period of 3-5 years through a 10-step process that relies on energy modeling.[44] The program's Excel-based Value Analysis Tool that allows for the comparison of energy efficiency measures grouped into "Good," "Better," and "Best" packages in order for the tenant to decide which options are the most appropriate for their goals and budget – an analysis that can also be useful in traditional non-modeling approaches.

Given the current levels of effort required, energy modeling is most beneficial to large spaces where the return on investment from energy efficiency measures covers the additional upfront costs of modeling. In order to make this process financially feasible for small tenant applications, continued investments in both guidance and turnkey wrappers that make modeling and modeling results more accessible are necessary.[45] Specifically, development of a layman's user interface for comparing simple tenant energy efficiency measures could make robust analysis available to a broad set of tenant spaces.

42 DOE. (n.d.). EnergyPlus Energy Simulation Software. http://energyplus.net/

43 2015-09-30 Comment response to the published RFI: High Performance Tenant Optimization Guide. ID #: EERE-2015-BLDG-0012-0011. http://www.regulations.gov/#!documentDetail;D=EERE-2015-BT-BLDG-0012-0011

44 The popularity of the miles per gallon (MPG) comparison tools at FuelEconomy.gov offers a glimpse of potential for such low-cost software.

45 2015-09-30 Comment response to the published RFI: High Performance Tenant Optimization Guide. ID #: EERE-2015-BLDG-0012-0011. http://www.regulations.gov/#!documentDetail;D=EERE-2015-BT-BLDG-0012-0011

4.3.1.2 *Leasing*

Traditional lease language does not typically directly address the energy efficiency of the tenant space. As discussed in section 4.1 above, a conventional lease might allocate utility expenses to tenants proportionally based on leased area and create a split incentive between tenants and owners with regard to energy efficiency measures. As such, neither owners nor tenants may be financially motivated to reduce energy use. However, in recent years the "green lease" has become an option for owners and tenants to re-align energy efficiency incentives through changes to leasing language.

While there are no formal standards for a "green lease", recent initiatives have articulated best practices and provided templates, including the BOMA Green Lease Guide, and the Green Lease library, maintained by the Institute for Market Transformation (IMT). The requirements for the Green Lease Leader recognition program lend a useful set of criteria for defining a green lease, which should contain:

- **A tenant cost recovery clause** that can be used for energy efficiency-related improvements. Tenant cost recovery clauses, which allow the owner to recover the cost of capital on infrastructure investments through a specified amortization schedule, have been included in most commercial leases for the last 10-15 years. That said, these clauses have not typically been used for energy efficiency improvements. When this clause is used for green leasing, owners are incentivized to invest in energy efficiency improvements as they will be able to recoup their costs.[46]
- **Stipulations for best practices in energy management** that can include: installation of submeters for tenants, minimum standards for tenant energy efficiency improvements (such as equipment specifications or available watts per square foot), payment of services to periodically adjust or calibrate equipment to ensure efficiency, and requirements for tenant disclosure of monthly utility data for building benchmarking purposes.53
- **Guidance on sustainable operations and maintenance** that should cover the restriction of individual tenant space heaters, requests for extensions of normal leasing hours such as weekends, and ensuring janitorial services occur during daytime hours.53

As discussed in Section 4.1.1, energy efficiency remains a relatively minor consideration in larger leasing negotiations. However, even in situations where energy efficiency is a priority, several challenges exist to implementing a green lease:

- **Lease diversity.** Tenants in the same building can have leases that look vastly different from one another as their priorities and negotiating power likely differ.
- **Tenant size.** With smaller or less sophisticated tenants, leasing language is often driven by building ownership. In these cases, owners have greater control over leasing language and may not be responsive to a tenant's requests for modification. With large tenants that have greater purchasing power and mandates for green leasing - such as the General Service Administration, Walmart, Target and others - owners may be more willing to incorporate client-specific mandates within leasing language.

46 Green Lease Library. (n.d.). Program Requirements. http://www.greenleaselibrary.com/program-requirements.html

- **Owner size.** Only owners with significant market power can implement aggressive energy efficiency lease clauses. These large owners may have the ability to retain tenant demand for their buildings despite changes in conventional leasing structures, unlike smaller tenants with less market power. As an example, Pyramid Companies (the largest privately owned developer of shopping centers in the Northeast United States), expanded its Carousel Center retail complex to include a 1.3-million-square-foot LEED Gold certified project for Core & Shell Development in the United States. As part of this development, Pyramid modified its standard lease to require that all 100 tenant spaces achieve LEED for LEED-CI certification.[47]
- **Lack of incentive for brokers to advocate for a green lease.** Real estate brokers are motivated by their commission to close deals quickly and often view green leasing stipulations as an added layer of complexity in a deal.

To continue advancing green leases, which in turn will advance high performance spaces, industry organizations can continue to collect and publish best practices, and create case studies to illustrate the benefits and market opportunity for green leasing strategies. However, providing resources is not enough.

First and foremost, brokers need to become actively motivated to implement green leases. Both owners and tenants can accomplish this by directing their brokers to include key green lease features as their default leasing language in leasing negotiations. Brokers will be driven to accommodate these requests in order to close real estate deals.

Additionally, a broker engagement strategy, which would align incentives so that brokers actively facilitate green leases, would also improve the adoption of green leases. A broker engagement strategy might include the following components:

- Developing a coalition of brokers to encourage and educate existing brokers and brokerage firms about green leasing. NAIOP (the Commercial Real Estate Development Association), SIOR (the Society of Industrial and Office Realtors), National Association of Realtors, or other organizations could play a leadership role.
- Working with the coalition of brokers to develop potential updates to the licensure exam, or additional certifications that could be leveraged as a marketing differentiator. This may require a gradual approach since licensing requirements for commercial real estate brokers often differ depending on the state.
- Basing an ongoing green certification for brokers on the completion of a minimum number of green leases per year (meeting the Green Lease Leader criteria).
- Working with Green Lease Leaders and other programs to communicate the benefits of using an efficiency-certified broker.

Similar steps are currently being taken by industry members. As an example, CBRE developed and launched a training platform for its more than 2,900 U.S. brokerage professionals. The platform includes a broker training video and a resource center that helps brokers understand and communicate the sustainable features of commercial properties helping to connect sustainability conscious tenants with high performing space that meets their needs. This training program does not go as far as a certification, but is a large step towards recognizing and responding to current needs.

By engaging brokers, communicating the value of an "efficiency-certified" broker, and requiring on-going completion of green leases to maintain certification, green leases can be more commonly harnessed to drive efficiency.

47 DOE. (n.d.). Pyramid Companies Implements Green Leasing to Promote Energy Efficiency in Tenant Retail Space. Building Technologies Program. http://apps1.eere.energy.gov/buildings/publications/pdfs/alliances/pyramid_case_study_10-15-12.pdf

4.3.2 *Programs*

Improvements in energy efficiency can also be encouraged through programs that target specific market challenges or opportunities unique to tenant spaces, including: expanding the business case for energy efficiency; rating systems; reporting frameworks; leasing language; voluntary initiatives; regulation; and education, awareness, and behavioral change.

4.3.2.1 *Expanding the business case*

One key reason leading to historic under-emphasis on energy efficiency in the design and construction of tenant spaces are the weak financial incentives to each party (brokers, designers, building owners, and tenants, as discussed in section 4.1). As discussed in section 4.1.2, utility costs are typically small in comparison to rent and other costs associated with the transaction, and often fade from prominence during the negotiation of the lease. However, a growing body of research quantifies the financial benefits of increasing energy efficiency of tenants' spaces to owners, tenants, designers, and brokers alike.

Even in lease structures with a split incentive for energy efficiency, building owners can benefit from increased energy efficiency through market differentiation – and attract higher rents and longer tenures. Research shows that energy efficient buildings rent for an average premium of 2-6%,[48] sell for a premium of as much as 16%,[49] attract high-quality tenants,[50] and have lower default rates for commercial mortgages (Figure 3).[51] According to a 2010 study,[52] lease-up rates for green certified spaces can range from average to 20% above average market rates for conventional spaces. A 2012 study examining the San Diego real estate market showed that the overall vacancy rate for green buildings was 4% lower than for non-green properties and LEED-certified buildings routinely commanded the highest rents, and an increased asset value of their buildings.[53] Significantly, more than 62% of buildings nationally over 500,000 square feet were green certified, representing 76% of all area in those buildings.[54] In such a market, not receiving a green certification actually leads to a competitive disadvantage. Additionally, a recent study found that commercial properties with ENERGY STAR® labels were 20% less likely to default on mortgage loans than those without labels;[52] supporting the conception that buildings with energy efficient features are better financial investments.

48 Eichholtz, P., Kok, N., & Yonder, E. (2012). Portfolio greenness and the financial performance of REITs. Journal of International Money and Finance, 31(7), 1911-1929. http://www.fir-pri-awards.org/wp-content/uploads/Article-Eichhiltz-Kok-Yonder.pdf

49 Eichholtz, P., Kok, N., & Yonder, E. (2010). Doing Well by Doing Good? American Economic Review. http://urbanpolicy.berkeley.edu/pdf/AER_Revised_Proof_101910.pdf

50 Eichholtz, P., Kok, N., & Quigley, J. M. (2009). Why do companies rent green? Real property and corporate social responsibility. Real Property and Corporate Social Responsibility. Program on Housing and Urban Policy Working Paper, (W09-004). http://www.ucei.berkeley.edu/PDF/EPE_024.pdf

51 An, X. & Pivo, G. (2015). Default Risk of Securitized Commercial Mortgages: Do Sustainability Property Features Matter? http://capla.arizona.edu/sites/default/files/faculty_papers/Default%20Risk%20of%20Securitized%20Commercial%20Mortgages%20and%20Sustainability%20Features%2C%202015.pdf

52 Miller, N. (2010). Does Green Still Pay Off? http://www.normmiller.net/wp-content/uploads/2012/08/Does-Green-Still-Pay-Off.docx

53 CBRE Global Research and Consulting (2012). Global Market View - Q2 2012.

54 CBRE. (2015). Green Adoption Index 2015. http://www.cbre.com/~/media/files/corporate%20responsibility/green-building-adoption-index-2015.pdf?la=en

FIGURE 3 – FINANCIAL BENEFITS OF ENERGY EFFICIENCY-CERTIFIED BUILDINGS

Tenants can realize a wide variety of benefits from the implementation of energy efficiency projects in their leased spaces. The most direct benefit of energy efficiency is the decrease in utility costs. However, a number of other benefits can also be attributed to energy efficient spaces such as increased worker productivity,[55 56] attracting and retaining employees,[57] and increasing brand value. Changing social norms, recognition of these benefits, and increased awareness of the "brand" value of green space can drive demand for high performing tenant spaces.

Engineers, architects, and interior designers can also profit from energy efficient tenant spaces. Each of these design professionals wants to remain competitive within their respective industries. Potential clients such as GSA,[58] TD Banknorth, and Capital One now require energy efficiency within their lease terms and will only work with designers who can fulfill such requests.[59]

Broker incentives for energy efficiency remain one of the most challenging open issues holding back energy efficient separate spaces. One recent initiative has been the Green Lease Leader program, which recognizes brokers for successfully implementing green lease language into new or existing leases. As discussed earlier, the broker plays a key role in matching owners and tenants. Providing a powerful incentive for brokers to preferentially consider energy efficient spaces would significantly encourage owners and tenants to implement energy efficiency measures. If brokers adopt practices, language, and processes centered on the leasing of efficient buildings, it could result in a competitive advantage. However, brokers remain unaware or unmotivated to adopt such practices, because the market has not demanded such service.

55 Delmas, M & Pekovic, S. (2012). Environmental standards and labor productivity: Understanding the mechanisms that sustain sustainability. Journal of Organizational Behavior. Pages 34, 230-252. 2012

56 Allen, J., MacNaughton, P., Satish, U., Santanam, S., Vallarino, J., & Spengler, D. (2015). Associations of Cognitive Function Scores with Carbon Dioxide, Ventilation, and Volatile Organic Compound Exposures in Office Workers: A Controlled Exposure Study of Green and Conventional Office Environments. Environmental Health Perspectives. http://ehp.niehs.nih.gov/15-10037/

57 CBRE. (2015). National Green Building Adoption Index, "Houston", CBRE, Page 16.

58 GSA. (n.d.). Green Lease Policies and Procedures. http://www.gsa.gov/portal/category/108551

59 Green Lease Library. (2015). Green Lease Leaders. http://www.greenleaselibrary.com/2015-awardees.html

Efforts to raise awareness of these financial benefits are necessary to increase emphasis on energy efficiency in the design and construction of tenant spaces. Policy makers, owners, and tenants can all participate in these efforts:

- Policy makers can support programs that illustrate and communicate the quantitative link between increased energy efficiency and increased competitiveness to the commercial real estate market can drive change as industry participants become aware of the business benefits of energy efficiency. In a market where high performing tenant spaces are expected, owners would be inclined to implement energy efficiency measures as a way to preserve and increase the value of their investments.
- Owners can advertise the decreased operational costs and increased employee retention, worker productivity, and brand value associated with the energy-efficient aspects of their building to potential tenants.
- Tenants and owners can articulate their demand to brokers for energy efficient buildings and green leasing structures.
- Tenants and owners can implement requirements that push designers to attain certifications and offer services to meet the demand for energy efficient tenant spaces, thus driving energy efficiency through competition.

4.3.2.2 *Rating systems*

By allowing for direct peer-to-peer comparison of buildings based on energy performance, rating systems provide the market with greater insight to evaluate building performance, broadcast the value of energy efficiency measures, and distinguish high-performance buildings from the rest of the market. Simplifying efficiency to an accessible metric gives market participants a "scorecard" to measure higher levels of performance, and often drives activity across the industry as a whole through competitive forces and peer comparison. Whole building rating systems, such as ENERGY STAR® and LEED have histories spanning decades,[60] and have driven energy efficiency demand by providing owners and tenants with broad information about building performance.

However, there are few applicable rating systems in the U.S. that focus on design and operations at the tenant space level. The additional resolution provided by rating systems focused on separate spaces has the potential to provide substantial value if designed in a way that cost-effectively provides the market with unique information about a space.

60 ENERGY STAR®. (n.d.). The value of the ENERGY STAR® certification. http://www.energystar.gov/buildings/facility-owners-and-managers/existing-buildings/learn-benefits/value-energy-star-certification

Whole Building Rating Systems

Three prominent examples of whole building energy rating systems include:

ENERGY STAR®, a voluntary program managed by the Environmental Protection Agency (EPA) and DOE, has encouraged building operators to benchmark energy use, implement energy management practices, cut operational costs, and earn recognition for performance. The ENERGY STAR® ranking system provides a 1-100 score for buildings that directly coincides with performance compared to peer buildings of a similar type. Since 1999, over 27 thousand buildings and plants representing 3.9 billion square feet[61] throughout the United States have earned the ENERGY STAR® certification. The EPA reports that the ENERGY STAR® building initiative saves more than 9 billion dollars and prevents nearly 135 MMT of greenhouse gas emissions each year.[62]

"Designed To Earn ENERGY STAR®" is the ENERGY STAR® design designation through which Architects can help their clients reduce their carbon footprints and energy costs by designing buildings to earn the ENERGY STAR®. These buildings are designed to perform in the top 25% of similar buildings nationwide, and are recognized for their design (and predicted ENERGY STAR® score), rather than operational performance. Many buildings go on to receive the ENERGY STAR® certification.[63]

The U.S. DOE's Building Energy Asset Score is a more recent national standardized tool for assessing the physical and structural energy efficiency of commercial and multifamily residential buildings. The Asset Score generates a simple energy efficiency rating that enables comparison among buildings, and identifies opportunities to invest in energy efficiency upgrades. Unlike an ENERGY STAR® score, which enables the comparison of buildings based on their energy consumption, the Asset Score reflects the energy efficiency of a building based on its design, construction, and energy systems.

The Leadership in Energy and Environmental Design (LEED) rating systems, voluntary frameworks developed by the U.S. Green Building Council (USGBC), guides building owners and operators through the process of achieving green building design, construction, operations, and maintenance solutions. While both LEED and ENERGY STAR® focus on energy efficiency, LEED also incorporates a broader set of performance categories focusing on non-energy related items. Buildings can earn points by demonstrating their ability to address environmental impacts and human benefits through six categories: sustainable sites, water efficiency, energy & atmosphere, materials & resources, indoor environmental quality, and innovation in design. Within the United States alone, more than 25 thousand projects representing about 3.2 billion square feet of building space are LEED-certified.[64]

These LEED and ENERGY STAR® systems have driven market change by demonstrating value to owners, managers, and leaseholders. However, while these systems provide significant value, they don't attribute responsibility to individual actors within a multi-tenant space, with the exception of LEED for Commercial Interiors (LEED-CI) which is discussed below.[65]

61 ENERGY STAR®. (n.d.). Certified Buildings and Plants. https://www.energystar.gov/index.cfm?fuseaction=labeled_buildings.locator

62 ENERGY STAR®. (n.d.). Buildings & Plants: https://www.energystar.gov/buildings?s=mega

63 ENERGY STAR®. (2015). Projects and architects to achieve Designed to Earn the ENERGY STAR®. https://www.energystar.gov/buildings/service-providers/design/step-step-process/apply-designed-earn-energy-star/architects-and-projects

64 USGBC. (2016). Country Market Brief: United States. http://www.usgbc.org/advocacy/country-market-brief

65 LEED has Core and Shell, New Construction, and Existing Building and Maintenance programs, focused on the whole building –the Commercial Interiors program, which does have a tenant component, is discussed in the next section.

Tenant Space Rating Systems

While a tenant space rating system could lead to a significant increase in the energy efficiency of separate spaces, several barriers, discussed in Section 4.1, have hindered emergence of a widely adopted tenant space rating system in the United States:

- Market research hasn't demonstrated strong demand for an additional set of voluntary building rating systems.
- Lack of submetering for energy used in tenant space has prevented measurement of tenant energy use.
- Tenant space rating systems will likely be implemented in buildings that already participate in whole-building rating systems such as LEED or ENERGY STAR®. Therefore, the costs associated with such tenant space rating systems would likely be additive to the costs associated with existing whole-building rating systems.

The most common tenant space rating system in the United States is LEED for Commercial Interiors, a variant of the voluntary LEED system managed by USGBC. However, participation within this LEED rating system and other similar tenant space rating systems in the United States remains small and inconsistent. For example, there are currently 8,000 certified LEED-CI projects representing about 380 thousand square feet of space,[66] these certified spaces equate to less than 0.01% of U.S. commercial real estate floor space.[67] This lack of market uptake and consistency leads to consumer confusion and, as a result, these rating systems have largely not driven significant market change. By contrast, both Australia and Singapore have implemented universal tenant space rating systems that show the potential of a single dominant rating system to propel industry-wide energy efficiency improvements.

LEED for Commercial Interiors

LEED for Commercial Interiors (LEED-CI) addresses the specifics of tenant spaces primarily in office, retail, and institutional buildings. Tenants who lease their space or do not occupy the entire building are eligible. Over 12,000 projects have certified or have declared intent to certify with the LEED-CI.[68]

A primary barrier to LEED-CI is cost, as the program typically involves consultants to guide the project team through the process of certification and documentation. Regardless of the size of the space, all LEED-CI prospects are required to undergo the same process and documentation. This fixed cost is especially challenging for tenants with smaller spaces. Tenants who do use the LEED-CI process tend to be those with a large rental area for which the cost of certification is not prohibitive, or those with corporate guidelines mandating building performance certifications for rental spaces.

LEED-CI is not a universally prevalent scheme in the United States, and thus does not fulfill the full potential of a tenant space-rating scheme to drive energy efficiency. By contrast, the NABERs system in Australia has become prevalent throughout the market, and as a result is used as a common comparison scheme to drive the adoption of energy efficient technologies.

66 USGBC. (2016). Country Market Brief: United States. http://www.usgbc.org/advocacy/country-market-brief

67 EIA. (2003). Commercial Buildings Energy Consumption Survey (CBECS) – 2003 CBECS Survey Data. CBECS website http://www.eia.gov/consumption/commercial/data/2003/

68 Opitz, M. (2008). From Single Commercial Buildings to Portfolios: Streamlining LEED® Documentation for Volume Customers. USGBC. http://aceee.org/files/proceedings/2008/data/papers/4_199.pdf

International Programs: National Australian Built Environment Rating System (Australia and New Zealand)[69]

The National Australian Built Environment Rating System (NABERS) was originally established as in 1998, by the government of the Australian state of New South Wales. At its founding, three building rating systems were developed: whole building, base building (excluding leasable square footage), and tenant spaces. In a critical move, in 2009, the Council of Australian Governments mandated disclosure of energy efficiency of commercial buildings.[70]

In developing its tenancy energy ratings, NABERS has benefited from the fact that, in the Australian states of New South Wales (NSW) and Victoria, the law forbids owners to pass electricity costs through to their tenants. Thus, unlike in the United States, the law has compelled tenant spaces to be individually metered. The typical metering divisions in Australian buildings allocate heating, air conditioning, elevators, and common area HVAC and lighting to the base building meters. The NABERS tenancy rating thus covers the other loads typically on the tenancy distribution board, including lighting within the tenancy, tenant equipment, and supplementary tenant air conditioning.

As a consequence, the NABERs system benefited from two advantages that are not currently available for tenant space ratings in the U.S.

- In Australia, energy data was readily available for tenant spaces.
- The use of the rating system was mandated.

Critical to driving energy efficiency, tenant space ratings are mandated to occur before the point of the real estate transaction. When the owner or manager intends to advertise the space for let, they must engage a NABERS assessor to conduct an assessment, to result in a star rating (1-6) to be used in promotional literature, advertisements, and on the publically posted signage connected to tenant spaces.

Within the NABERS, a rating of 2.5-3 stars is considered market average building performance, 5 stars is considered excellent building performance, and 6 stars is considered to be market-leading building performance. Originally the ratings only went up to five stars, with the sixth star being added four or five years ago after realization that some buildings were achieving five stars and beyond. When NABERS was first being developed, 4 stars was considered "not easily achievable" and 5 stars achievable only through "exceptional design and operation." This held true for some time, as even in 2006, only 5% to 15% of rated buildings achieved 4 stars or higher. However, in more recent years, those ratings have become more prevalent; out of the 1,422 buildings rated using NABERS Energy in 2012/13, the median result was 4 stars with more than 20% achieving 5 stars or higher.[71] A rating is determined by comparing consumption use of the space against spaces of the same type and is valid for one year.

69 Much of the material in this section is drawn from EPA ENERGY STAR® Task Order 306, Technical Direction #1: Memorandum, Case Studies of Government-Sponsored Tenant Energy Performance Programs Based On Measured Energy Data.

70 At present NABERS is administered by an internal government team of 18 full-time staff, drawing on a network of around 600 accredited NABERS assessors who perform the majority of the work required to determine ratings. Most of the funding for the NABERS program (around 80%) comes from fees associated with ratings, including fees for registering a rating with NABERS, as well as accreditation and training fees for assessors. The remaining 20% of funding comes from state and territory representatives that pay a fee to participate in the national steering committee. NABERS is looking to shift to a full cost recovery model, either by increasing fees or streamlining internal costs.

71 The Office of Environmental Heritage. (2014). The Key Principles and Defining Features of NAMBERS Version 1.0. http://www.nabers.gov.au/public/WebPages/DocumentHandler.ashx?docType=3&id=134&attId=0

International Programs: Green Mark for Office Interiors (Singapore)

Singapore's Building and Construction Authority (BCA) launched the voluntary BCA Green Mark Scheme in January 2005. There are several different "schemes," which apply to different space types, including one for office interiors, whose criteria were first developed in May 2009 and revised in November 2012. The criteria for office interiors can be applied to new offices, existing operating offices, as well as existing offices undergoing renovation.

Singapore's regulations require that all new buildings, building additions, or major retrofits to existing buildings of 2000 square meters (21,530 sf) or greater, achieve a sustainability standard equal to Green Mark Certified level. Tenancy ratings for spaces within existing buildings not undergoing build-out or major renovation are voluntary. Certified buildings are required to be re-assessed every three years in order to maintain their Green Mark status.

Unlike a performance based systems, there are specific operational criteria to Singapore's program. As an example, office interiors pursuing Green Mark certification at any level must meet the prerequisite requiring that the office's temperature setting is no lower than 24 degrees Celsius. Those seeking a $Gold^{Plus}$ rating must have an energy efficiency index (EEI) not exceeding 80 $kWh/m^2/year$ (or 7.43 $kWh/ft^2/year$) and a lighting power budget of 11 W/m2 (or 1.02 W/ft^2) or lower.

Additionally, the plan puts forward new awards to recognize buildings that have adopted green leases and achieved certification for at least 50% of their tenant spaces.

Opportunities for a U.S. Tenant Recognition Systems to Drive Energy Efficiency

As seen above, rating systems can help achieve improved efficiency in the design and construction of tenant spaces. As shown by the examples in the U.S., Singapore, and Australia, data availability and a critical focus on simple comprehensive metrics are key to designing an effective, equitable, and widely accepted rating system.

With wide acceptance, energy ratings could make their way into more transactional decisions in real estate. Such programs could include the incorporation of building energy performance data within commonly used real estate platforms, serving to match tenants seeking energy efficient spaces with owners who have available efficient space. In Australia and Singapore, where these ratings are near universal, tenants and owners each have the ability to weigh energy efficiency in their leasing and purchasing decisions. In these markets it is clear:

- When the rating system is universal, the information can be more easily included as part of the transaction, regardless of broker incentives.
- The on-going need to renew ratings can drive competitive energy efficiency improvements.
- If market demand for the voluntary rating system is high, it can cause owners to install the metering equipment necessary to participate.

A Federal Tenant Space Recognition System

The U.S. is exploring a government recognized recognition system. The Energy Efficiency Improvement Act of 2015 mandates the establishment of a voluntary tenant space recognition system in the United States. Administered by the EPA, developing this program will require access to several new data sets, and will also need to confront the same challenges regarding participation and information barriers.

In establishing this system, EPA will have the option of many approaches, each with their own inherent challenges. Options range from gross metrics focused on outcomes like those used by Australia (EUI), to detailed metrics focused on design and operational inputs like Singapore (lighting level, temperature ranges). This paper and other efforts will further assess the market viability, metrics, and structure of a potential system to best accommodate the U.S. market.

4.3.2.3 *Reporting Frameworks*

Investors, owners, tenants, regulators and other stakeholders are increasingly asking for greater levels of transparency with respect to environmental issues. This demand for disclosure on the sustainability performance of property companies and fund managers is broadly driving energy efficiency across portfolios. An increasing number of investors now incorporate such information directly into their investment strategies.[72] Consequently, comprehensive reporting frameworks provide market benchmarks, compare peers, force respondents to monitor and act on energy performance, and encourage improvement through competitive public rankings.

Examples of these reporting frameworks include the following:

- **The Global Real Estate Sustainability Benchmark (GRESB)** is a benchmark used by institutional investors to assess sustainability performance of real estate at the portfolio level. As of 2014, the benchmark included 637 survey participants representing 56,000 assets covered, and $5.5 trillion in institutional capital.[73] Annual survey results are analyzed and turned into portfolio benchmarks and rankings across a number of environmental, social, and governance dimensions.
- **The Carbon Disclosure Project (CDP)** works with public companies to improve their disclosure of environmental impacts and risks. Similar to the use of GRESB survey results, CDP survey respondents can use this information to market their environmental performance and advertise to investors that they comply with voluntary environmental performance disclosure standards. As of 2014, over 5,000 companies respond to the CDP survey each year.[74]

Other reporting frameworks include those organized by the Urban Land Institute's Greenprint Program, the National Council for Real Estate Investment Fiduciaries (NCREIF) collection of sustainability data, and the International Council of Shopping Centers (ICSC) scorecard.

72 GRESB. (2015). 2015 GRESB Report. https://www.gresb.com/results2015/introduction

73 GRESB. (2014). 2014 GRESB Report. http://www.corporate-engagement.com/files/file/2014%20GRESB%20Report.pdf

74 CDP. (2014). Climate Change Program. https://www.cdp.net/respond

These frameworks could be modified and leveraged as a mechanism to encourage owners to implement high performance energy efficiency measures in separate spaces. In particular, frameworks could begin to include tenant specific metrics such as:

- Average tenant space rating (when available).
- Ratio of (sub) meters to leases.
- Cost sharing and how the company handles the split incentive.
- Tenant incentives offered during design and construction or occupancy to encourage energy efficiency.

By expanding these frameworks to recognize those investors who have specifically taken action to significantly improving energy efficiency in commercial buildings through the design and construction of separate spaces, these competitive frameworks can serve as a catalyst to the more rapid adoption of high-performance measures.

4.3.2.4 *Voluntary Initiatives and Professional Certifications*

Voluntary initiatives encourage energy efficiency by fostering peer-to-peer competition and by providing tools and resources to further industry improvement and education. A voluntary initiative specifically focused on tenant spaces would be a powerful mechanism toward driving energy efficiency, by providing a single source for tools, resources, and expertise to drive the market. Voluntary initiatives can range from building-specific, to corporate, to local, to national in scale and they can also take the form of professional certifications.

Better Buildings Initiative and Green Lease Leaders

One successful voluntary initiative, albeit one that focuses on both large institutions and whole-building energy performance, is the DOE's Better Buildings Initiative. As of 2015, more than 250 organizations, representing over 3.5 billion square feet, 650 manufacturing plants, and $5.5 billion in financing investments, have committed to improving their energy efficiency by 20% or more over 10 years[75] through their participation in this voluntary initiative. In addition to an energy savings pledge, organizations also commit to: conduct an energy efficiency assessment of their building portfolio, showcase an energy efficiency project with long-lasting results, and publically report on their progress by sharing their successful methods for energy efficiency.

The Better Buildings Initiative has created: a searchable database for understanding trends in building performance, a dictionary of building characteristics and energy use terms, compiled financing solutions for energy efficiency initiatives, and a building energy asset scoring tool, in addition to a variety of other educational resources. The program has also developed partnerships with large commercial organizations such as Wal-Mart, Best Buy, Macy's, and others, fostering a competition of well-known brands in the public spotlight that will drive further interest and participation in these programs.

Under the Better Building Alliance affiliate program, non-profits, efficiency NGOs, and trade organizations that represent sectors covered by the Alliance, including Commercial Real Estate, Hospitality, Retail, Food Service, Grocery, Healthcare, and Higher Education, are eligible to join the alliance as program affiliates. The affiliates then use their membership resources to advance joint initiatives relating to energy efficiency.

The Green Lease Leaders program provides a number of support pieces that are similar to the Better

75 Better Buildings Solutions Center. (n.d.). About the Better Buildings Challenge. DOE. http://betterbuildingssolutioncenter.energy.gov/about-better-buildings-challenge

Buildings Initiative, including a library of resources, webinars, and a method for contacting an expert. Reflecting the fragmented state of the tenant market, the Green Lease Leaders program does not have the proactive outreach and networking component of the Better Buildings Initiative. The average tenant is seeking turn-key resources when they need to negotiate a lease and fit-out a space, and therefore does not necessarily want to commit to long-term membership in an energy efficiency initiative.

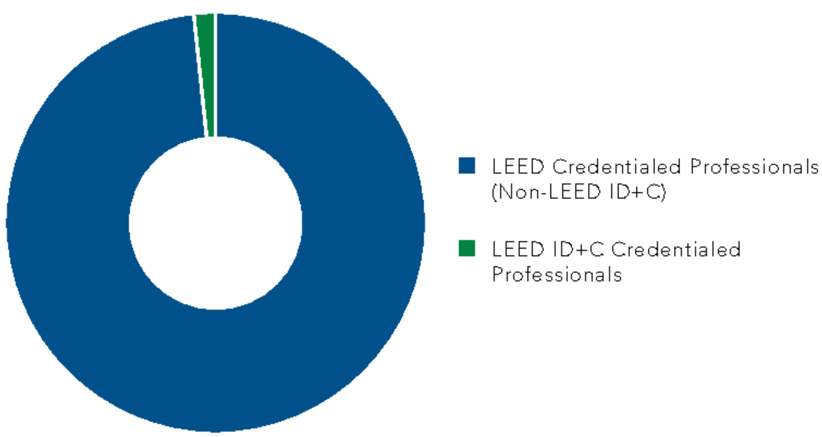
Critically, for many smaller tenants, lease negotiation is an infrequent occurrence, and they only need support at certain discrete points in the business cycle. While the suite of tools and resources produced by the Green Lease Leaders program provides a model to partially replicate for tenant spaces, the on-going support is not necessarily sufficient for the needs of smaller tenants.

Professional Certification Programs

A different tact for creating positive voluntary action is to address personnel, rather than real estate portfolios. While many popular professional certifications exist that relate to energy management, ranging from the certified energy managers (CEM) program to the LEED Accredited Professional (AP), the industry has taken its first steps to extend existing accreditations to explicitly include a curriculum around energy efficient tenant spaces. Ideally, these credentials will begin to improve the ability for designers and other professionals to market their credentials. With such programs, energy-efficiency conscious tenants can begin to choose qualified personnel to assist them in modifying their rental space to fit their needs aesthetically and environmentally.

The USGBC has created such a tenant space certification within their LEED AP Interior Design and Construction (ID+C) specialization. This certification "serves participants in the design, construction and improvement of commercial interiors and tenant spaces that offer a healthy, sustainable and productive work environment."[76] However, LEED ID+C professionals (about 2,500 credential holders) currently represent a small minority, or 1.4%, of LEED credentialed professionals (about 175,000 credential holders) (Figure 4).[77]

FIGURE 4 – LEED ID+C CREDENTIALED PROFESSIONALS AS A PERCENT OF TOTAL LEED CREDENTIALED PROFESSIONALS



76 USGBC. (2016). Distinguish your Expertise. http://www.usgbc.org/credentials#ap

77 USGBC. (2016). County Market Brief: United States. http://www.usgbc.org/advocacy/country-market-brief

Additionally, the Better Buildings Initiative is collaborating with industry practitioners and the National Institute of Building Sciences to maintain voluntary national workforce guidelines that improve the quality and consistency of commercial buildings workforce credentials for energy-related jobs.[78] During 2015, DOE released four Job Task Analyses and Schemes: Energy Manager, Energy Auditor, Building Operator, and Commissioning Professional and announced the corresponding Better Buildings Workforce Guidance (BBWG) recognition program for certification bodies. In late 2015, the Certified Energy Manager certification from the Association of Energy Engineers (AEE) became the first BBWG recognized certification program and others are expected to follow. Building owners and managers can use these guidelines when hiring or procuring services in these four job areas by requesting that individuals hold credentials that are recognized by DOE as aligned with the Better Buildings Workforce Guidelines.

Once these credentials are available, a tenant space focused guideline and certification could be a potential next step in defining and recognizing such skillsets.

While the industry is just beginning to create tenant space professional certification programs, participation and awareness of these programs among energy professionals remains low. As such, there is a market need for the increased support and creation of awareness materials to encourage the further development of, and interest in, such certifications.

4.2.3.5 *Incentives, Policies, and Regulation*

Utility policy, equipment and performance incentives, information disclosure policies, and regulation are additional options to accelerate the adoption of energy efficiency measures in tenant spaces.

Utility Policy and Incentives

The American Council for an Energy-Efficient Economy's State Energy Efficiency Scorecard tracks and evaluates state and local energy efficiency policies, and provides a valuable resource on local utility incentives, as does the DOE's Database of State Incentives for Renewables & Efficiency (DSIRE) program and Energy Incentive Programs listing.[79] [80]

Most states have implemented pre-qualified incentives for existing building energy efficiency initiatives. As an example, under its Existing Facilities Program, the New York State Energy Research and Development Authority (NYSERDA) offers facility owners, management companies, and tenants incentives to help offset the costs of implementing energy efficiency improvements. Applicants can receive up to $30,000 for pre-qualified simple equipment updates including lighting, HVAC, chillers, variable frequency drives, and commercial refrigeration. Larger improvements that save at least 250,000 kWh and/or 2,000 MMBtu per year are eligible for performance-based incentives of up to $500,000.[81]

These types of utility rebates have historically been oriented around pre-qualified (or prescriptive) savings estimates or on engineering studies and modeling estimates to determine the size and nature of the incentive. However, most historical programs have not been designed to tie to measured performance at the meter (kWh reduced below a baseline). Performance based incentives are more complicated to validate, and can be more challenging to implement for applicants who have no guarantee of payment.

78 DOE. (n.d.). Better Buildings. http://energy.gov/eere/better-buildings

79 DOE. (n.d.). Energy Incentive Programs. http://energy.gov/eere/femp/energy-incentive-programs

80 DSIRE. (n.d.). Database of State Incentives for Renewables & Efficiency. http://www.dsireusa.org/

81 Typically, and as a consequence of regulation, utility rebates are awarded for technologies that directly reduce energy usage. As a consequence, rebates are not typically available for submeters. If rebates could be awarded for submeters, this might be a powerful, although expensive, method for increasing the penetration of submeters.

Irrespective of these challenges, the 2015 passage of SB-350 in California "authorize[s] pay for performance programs that link incentives directly to measured energy savings. As part of pay for performance programs authorized by the [State Energy Resources Conservation and Development] commission, customers should be reasonably compensated for developing and implementing an energy efficiency plan, with a portion of their incentive reserved pending post project measurement results." SB 350 later states that "incentive payments shall be based on measured results."

A performance based utility incentive that requires normalized energy consumption to decrease as compared to a baseline could be a technology neutral driver of significant savings. It is notable to mention that this type of incentive can best be captured by tenants if their energy usages are separately metered. Such performance based programs that are explicitly designed for separate spaces and provide concrete energy use data could help to move the market toward greater efficiency. Submetering can be employed to determine accurate energy usage and utility billing of tenant spaces. Clarification of state rules that explicitly allow building owners to submeter tenants would be useful in states where these actions have been in question.

Building Codes and Design Standards

Building codes provide regulated minimum energy efficiency standards at the federal, state, and local level. Most building energy codes are implemented at the local level in the United States.

The American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) and the International Code Council (ICC) are tasked with the development and administration of the two model commercial building energy codes used in the United States: the ASHRAE 90.1 ("Energy Standard for Buildings Except Low-Rise Residential Buildings") and the International Energy Conservation Code (IECC), respectively. Both codes are updated through a revision process that includes submissions of proposed changes, stakeholder participation, public hearing opportunities, and committee review. New editions of the ASHRAE 90.1 and IECC are published every three years and reflect changes gathered through the revision process. States and local jurisdictions can adopt codes through direct legislative action or through specialized regulatory agencies. Upon approval, the building energy code becomes the law within that state or jurisdiction. Unlike federal laws or regulations, energy codes can be changed relatively frequently, and relatively quickly.

Due to the frequent revisions, energy codes can be an effective way to dictate minimum standards for energy efficiency. In fact, the U.S. DOE estimates the ASHRAE 90.1-2010 standard yields 23% energy savings relative to the 2004 edition.[82] Codes adapted to tenant space needs could yield a similar efficiency effect. Adoption can be accomplished by incorporating tenant space measures into existing codes or creating entirely new codes specific to tenant spaces. Specific measures could include prescriptive policies such as: requiring LED lighting, specifying thermostat settings within given ranges, installing automated lighting control technologies; or, efficiency performance specifications such as requiring specific energy use intensity based on the size and function of a tenant space. Tenant space energy codes could serve to set minimum efficiency requirements and impact every tenant improvement project in the state or locality where it is established.

82 DOE. (2014). Saving Energy and Money with Building Energy Codes in the United States. http://energy.gov/sites/prod/files/2014/05/f15/saving_with_building_energy_codes.pdf

Tax Policies

Federal

Federal tax policies can be used as an effective tool to drive energy efficiency. While requiring an act of congress, they can provide a broad financial incentive for increasing efficiency. Previous actions have generally focused on tax incentives for the purchase of equipment meeting energy efficiency standards. Past examples include the American Recovery and reinvestment Act of 2009, which offered tax credits for homeowners purchasing energy efficient equipment for their properties,[83] and the Energy Policy Act of 2005, which established the 179D tax deduction for energy-efficient equipment in commercial buildings.[84]

Any new policies could consider the following options for tenants:

- Offering tax deductions based on achieved energy use intensity.
- Accelerating the depreciation of systems and equipment installed as part of a tenant fit-out.[85]
- Incentivizing the purchasing of energy efficient equipment.
- Removing sales tax on energy efficient equipment.[86]
- Lowering import duties on energy efficient equipment.[87]
- Reducing real estate tax for spaces that have achieved a targeted energy reduction.

Of these ideas, the most common tax incentives are consumer rebates based on equipment installation. However, more recent federal efforts have focused on providing financial incentives to a small amount of manufacturers rather than a large number of consumers.[88]

While any of these incentives could be targeted toward tenant fit-out, focusing on the performance (achieved EUI) offers the most guaranteed benefit, but also requires metering to demonstrate achieved EUI. Incentives not requiring metering would parallel those that have been previously executed – such as offering direct tax credits for energy efficient equipment, or creating a parallel to the 179D deduction and allowing its use for tenant spaces.

83 DOE. (2012). Success of the Recovery Act. http://www.energy.gov/recovery-act

84 Businesses can take a tax deduction for new or renovated buildings by reducing the energy costs associated with three components—lighting system; building envelope; and heating, cooling and water heating equipment. Buildings must meet the ASHRAE 90.1-2001 standard and be placed in service between January 1, 2006 and December 31, 2013 in order to be eligible.

85 Example: The Tax Relief, Unemployment Insurance Reauthorization and Job Creation Act of 2010 provides businesses with 100 percent bonus depreciation for certain capital investments placed in service between September 8, 2010 and December 31, 2011. As an example, outdoor energy efficient LED lighting qualifies for a 100% deduction under the new bonus depreciation rules. http://www.boston.com/business/personalfinance/managingyourmoney/archives/2011/03/tax_opportuniti.html

86 Example: Tax free weekends on ENERGY STAR® equipment are currently offered by Alabama, Florida, Georgia, Louisiana, Maryland, Missouri, Texas and Virginia. http://www.houselogic.com/blog/taxes-incentives/state-sales-tax-holidays/

87 Example: In 2006 the Thai government introduced tax incentives for energy efficiency projects. The tax incentives include: Exemption of the import duties for energy efficiency / renewable energy equipment, exemption of corporate income tax for 8 years for energy efficiency equipment and renewable energy manufacturers and ESCO companies, reduction of the corporate income tax for companies that improve their energy efficiency or develop renewable energy projects. http://iepd.iipnetwork.org/policy/tax-incentives

88 Doris, E., Cochran, J. & Vorum, M. (2009). Energy Efficiency Policy in the United States: Overview of Trends at Different Levels of Government. National Renewable Energy Laboratory Technical Report. http://www.nrel.gov/docs/fy10osti/46532.pdf

Additionally, good tax policy design would ensure that even entities without tax liabilities can still benefit from the tax incentive for an efficiency fit-out. For example if a Real Estate Investment Trust (REIT) that does not receive tax burden, is eligible for an efficiency fit-out tax incentive, they should be allowed to assign (or trade) it to an entity with tax liability (such as the tenant or the engineering firm doing the work).

State and Local

Many states also provide financial incentives to support energy efficiency. [91] [89] One example is found in Oregon, which has offered a Business Energy Tax Credit (BETC) since 1979, which includes a tax credit of 35% towards the purchase of conservation technologies, and includes a Pass-through Option, which allows entities that do not pay a sufficient amount in taxes to receive a lump-sum payment. The options for designing the tax incentive are similar at the state, local, and federal level – however the path to enacting the tax incentive varies by jurisdiction.

4.3.2.6 *Education, Awareness, and Behavioral Change*

The overarching goal of each of the initiatives discussed above, from financial incentives, to rating systems, reporting frameworks, leasing language, voluntary initiatives, and regulation is to drive behavioral change and give people opportunities and incentives to select more energy efficient choices. One additional opportunity is to explicitly educate occupants in order to change the way they interact with the building. Recent scientific studies have drawn a clear link between energy savings education and awareness and behavioral change resulting in reduced energy consumption. For example, a 2013 meta-analysis of 156 energy conservation field studies found that behavioral strategies yielded an average of a 7.4% improvement in energy conservation.[90] [91] Energy conservation behavioral strategies can include:

- Disclosing information such as a building's current energy demand in the lobby or through other tenant communications.
- Adding educational signs that encourage resource conservation and education, such as "turn off the lights when you leave the room."
- Displaying energy efficiency awards (such as LEED certification and ENERGY STAR® plaques) in building common areas to increase awareness.
- Hosting educational training programs or providing tips and fact sheets that train building occupants on energy conservation strategies.
- Encouraging people toward energy-saving behavior through building aesthetics (making stairwells easy to access, pleasant, etc.).
- Energy conservation competitions and recognition of top performers.

89 The same report has a useful chart of all government incentives (non-research and development) that are targeted toward energy efficiency.

90 Although, the same study noted that conservation decreased with relative study rigor.

91 Delmas, M., Fischlein, M. & Asensio, O. (2013). Information Strategies and Energy Conservation Behavior: A Meta-Analysis of Experimental Studies from 1975 to 2012. http://papers.ssrn.com/sol3/papers.cfm?abstract_id=2273850

While most of these initiatives are directly applicable to tenant spaces, there are tools that could be better leveraged to maximize their impact. One option is to maximize the availability of these educational resources through:

- Advertising at public forums that reach general audiences, such as construction trade association meetings, local business associations, chambers of commerce and other events.
- Creating websites with educational toolkits catered specifically to tenants and building owners of separate spaces. ENERGY STAR® "Bring Your Green to Work" is a good example of a current toolkit,[92] as is the Better Buildings Implementation Model for Shorenstein Realty LLC.[93]

One further option is to include such measures as part of the fit-out phase, by incorporating specific requirements (such as educational signs or displays of building energy use). One example might be to install "please shut off the light stickers" next to each switch. Some rating systems, such as LEED, already allocate points within their recognition systems for the inclusion of this type of awareness building.

Stanford University's Precourt Energy Efficiency Center provides several resources on driving energy efficiency through behavioral science. These include a series of foundational readings,[94] as well as a series of tools, such as resources for program design and evaluation, and key behavior and energy questions as identified by sector leaders.

92 ENERGY STAR®. (n.d.). Bring Your Green to Work with ENERGY STAR®. https://www.energystar.gov/buildings/about-us/how-can-we-help-you/communicate/energy-star-communications-toolkit/bring-your-green-work

93 Better Buildings Solutions Center. (n.d.) Implementation Model: "Flip the Switch" Tenant Engagement Program. http://betterbuildingssolutioncenter.energy.gov/implementation-models/%E2%80%9Cflip-switch%E2%80%9D-tenant-engagement-program

94 Precourt Energy Efficiency Center, (n.d.). Stanford University. Foundational Readings. http://peec.stanford.edu/behavior/foundational_readings.php

4.4 Measurement & Verification

4.4.1 *Current Application of Feasibility of M&V in Tenant Spaces*

Measurement and Verification (M&V) is the process for quantifying savings delivered by energy efficiency measures. M&V programs are utilized for a variety of reasons:

- **Tenants and Owners** may have a need to validate a return on their investments. As an example, some tenants and owners invest in efficiency only when they can recover their investment from their reduction in utility costs. In other cases, M&V may be required to demonstrate a return to a rebate issuing third party.
- **Vendors** can use M&V to validate their energy efficiency offerings, and demonstrate the value of their product.
- **Utilities** may require M&V to meet regulatory requirements, to demonstrate savings, or to validate energy rebates.

An M&V platform typically consists of systems to gather, analyze, and manage data. In typical scenarios, an M&V platform can be used to (a) measure actual energy use derived from base consumption and compare it to consumption under energy efficiency measures, and (b) determine whether the implemented measures generate the savings intended in the initial design and construction of the separate spaces.

As M&V platforms differ, decisions can be made as to whether the system will include the whole building or a specific space, incorporate data in real time or at regular intervals, and include shared systems or just local loads. In most cases, data and collection is technically feasible; the main consideration is cost relative to potential return.[95] At the data collection level, there are a number of factors affecting cost:

- While most buildings will have total ("whole-building") utility usage data from a master meter, not all buildings have submeters to isolate separate spaces within a building, nor will all buildings have "smart" meters to support real-time analysis.
- Some M&V projects will require current transformers to apportion energy from shared systems such as cooling towers or shared HVAC.
- In some cases, building management systems can automatically collect energy consumption data via smart meters, data loggers, and network controllers.
- To minimize costs, an M&V system should be designed to work in conjunction with the design of the tenant space, as well as the central systems.

95 In a small space, while feasible, the potential energy savings may not justify significant additional data collection costs. By contrast, in a larger space, M&V can be more easily absorbed in the energy savings.

A major step toward reducing the costs of M&V are the class of technologies considered collectively as, Measurement & Verification (M&V) 2.0. A M&V 2.0 system builds upon energy information technology advancements, such as measurement software, embedded equipment sensors, advanced metering infrastructure and data analytics to calculate energy savings accurately and quickly. Where submetering is in place at the level of a tenant space, these tools can provide a rapid and cost-effective way to track results from energy-saving activities and provide warnings when energy performance begins to degrade.

There are a wide variety of software tools that can be used to construct an M&V program, and which integrate this new technology to varying degrees. These tools track energy usage at greater temporal (daily, hourly, or minute-by-minute) and spatial (space or equipment specific) resolution to match the sub- and smart metering of the building. Based on this data, sophisticated models can be developed to predict and avoid inefficient energy usage.

In addition to tools, guides such as the International Performance Measurement and Verification Protocol, compile best practice techniques for the measurement and verification of energy use data. These resources allow practitioners to use tools consistently and allow for relevant comparisons of energy efficiency data.

The best of the M&V 2.0 tool sets can help eliminate the "night-time walkthrough" or the need to survey the space outside of operating hours to identify equipment that is operating unnecessarily. Instead, the sensors and system can help identify the issues in real time, improve efficiency, and drive down operational costs.

4.4.2 *M&V Gaps & Needs*

Within the M&V 2.0 ecosystem, hardware such as sensors and submeters, analytic software, and the technician time to provide analyses of performance can be expensive.

- While costs are dropping, the most prevalent submetering technologies remain expensive and can be limited in their data collection.
    - A submeter is able to track energy use from plug loads (such as appliances, computers, printers, etc.) but cannot monitor individual use of shared systems such as HVAC units.
    - The installation of submeters and sensors can be complex. If tenants move or reconfigure office space, then submetering systems must be reconfigured accordingly.
- While modern analytic software often simplifies trend analysis, a specialist (consultant) is often required to recommend a course of action.

One major step toward further use of M&V 2.0 is the emerging technology of "smart" devices that can report their own real-time performance to an energy management and information system (EMIS). These devices have the opportunity to transform the M&V process, and are being supported by major industry vendors. Lower costs, easier installation, and high configurability are the keys to future adoption.

5. Acknowledgements

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6. Appendix

6.1 Energy Efficiency Employment Impact Multipliers[96]

The PNNL paper concludes that energy efficiency results in positive economic impacts including overall levels of employment. Greater energy efficiency means households and businesses are able to maintain or increase the levels of service (e.g., comfortable indoor temperatures, illumination, and hot water) from their buildings or equipment while consuming less energy. Over the lifetime of energy efficiency measures, the money saved on energy becomes available to be spent on other goods and services. Typically, the number of jobs required to produce these other goods and services are greater per dollar of output than the number of jobs needed to produce the same dollars' worth of energy. Based on the results of a number of studies, spending money made available by reducing energy expenditures for these alternative goods and services generates a net gain of about 8 jobs per million dollars of consumer bill savings.

Distinct from the effects of bill savings, the PNNL study concludes that initial investments in energy efficiency generate about 11 jobs per million dollars of investment. These activities include the purchasing and installing of measures for retrofit or for new construction and also jobs in other sectors "induced" by this economic activity. This impact occurs in years when these investments occur. Results using this approach are comparable to typical industry-specific estimates of the job creation from spending targeted at specific sectors.

6.1.1 *Modeled Energy Efficiency Scenarios*

PNNL modeled the 2030 employment impacts of a national initiative to accelerate residential and commercial energy efficiency trends under both 15% and 10% electricity savings cases. In the 15% case, efficiency activities save about 15% of Annual Energy Outlook (AEO) Reference Case commercial and residential electricity consumption by 2030.[97] [98]

The analysis of the 15% case indicates that by 2030 nearly 320,000 new jobs likely would result from energy efficiency. To achieve this level of new jobs in 2030 would require an annual average of more than 60,000 jobs in prior years directly supporting the manufacturing, installation, and maintenance of energy efficiency measures and practices.

These are new energy efficiency jobs resulting initially from the investment associated with the construction of more energy-efficient new buildings or the retrofit of existing buildings, and would be sustained for as long as the investment continues. Based on what is known about the current level

96 This text draws heavily from: Anderson, D. M., Belzer, D. B., Livingston, O. V., & Scott, M. J. (2014). Assessing National Employment Impacts of Investment in Residential and Commercial Sector Energy Efficiency: Review and Example Analysis (No. PNNL-23402). PNNL, Richland, WA (US). http://www.pnnl.gov/main/publications/external/technical_reports/PNNL-23402.pdf

97 Significantly, the PNNL study does not consider the impacts of energy efficiency on all fuels, but focuses on electricity. In 2014, electricity generation consumed 40% of the energy in the United States, while residential and commercial fuel consumption accounted approximately another 12%. As the potential energy efficiency gains in separate spaces would likely also reduce fuel consumption, the PNNL paper likely underestimates the total potential employment gains.

98 The 15% case assumed that the additional energy savings in both the residential and commercial sectors due to the scenario begin in 2015 at zero, then increase in an S-shaped market penetration curve, with the level of savings equaling about 7.0 percent of the AEO 2014 U.S. national residential and commercial electricity consumption saved by 2020, 14.8 percent by 2025 and 15 percent by 2030. The 10% case assumes the additional savings due to the scenario begin at zero in 2015, increase to 3.8 percent in 2020, 9.8 percent by 2025 and, 10 percent of the AEO reference case value by 2030.

of building-sector energy efficiency jobs, this would represent an increase of more than 13% from the current estimated level of over 450,000 such jobs. The more significant and longer-lasting effect comes from redirecting energy bill savings to the purchase of other goods and services in the general economy. This example analysis utilized PNNL's ImSET model, a modeling framework that PNNL has used over the past two decades to assess the economic impacts of DOE's energy efficiency programs in the buildings sector.

The PNNL study focuses principally on the economic effects arising from increased levels of energy efficiency in the buildings (both residential and commercial). As the present discussion focuses solely on commercial real estate (and in fact on the office, retail, and industrial subset of the that sector), we can approximate the impacts from an improvement in commercial building energy efficiency by parsing out the electricity consumption in the residential and commercial sectors – the paper attributes approximately 50% of the electricity usage to the commercial sector. As a consequence, perhaps 160,000 net new jobs could be attributed to a 15% reduction in energy consumption in the commercial sector.

6.1.2 *Further Sources*

The employment analysis presented in this paper is largely in line with other similar studies conducted over the past ten years, including papers presented by the American Council for an Energy Efficient Economy (ACEEE),[99] Cambridge Econometrics,[100] the Economic Policy Institute,[101] as well as many of the dozens of peer-reviewed and white papers reviewed in the PNNL paper excerpted above.[102] Investment in energy efficiency has consistently shown a positive multiplier effect – where investments consistently yield increases in employment.

99 American Council for an Energy-Efficient Economy. (n.d). How Does Energy Efficiency Create Jobs? http://aceee.org/files/pdf/fact-sheet/ee-job-creation.pdf.

100 Cambridge Econometrics. (2015). Assessing the Employment and Social Impact of Energy Efficiency. https://ec.europa.eu/energy/sites/ener/files/documents/CE_EE_Jobs_main%2018Nov2015.pdf.

101 Bivens, JoshJ. (2015). A Comprehensive Analysis of the Employment Impacts of the EPA's Proposed Clean Power Plan. http://www.epi.org/publication/employment-analysis-epa-clean-power-plan/./

102 Anderson, D. M., Belzer, D. B., Livingston, O. V., & Scott, M. J. (2014). Assessing National Employment Impacts of Investment in Residential and Commercial Sector Energy Efficiency: Review and Example Analysis (No. PNNL-23402). PNNL, Richland, WA (US). http://www.pnnl.gov/main/publications/external/technical_reports/PNNL-+-23402.pdf.

6.2 Analysis of High Efficiency Technologies Continued

6.2.1 *High Efficiency Lighting*

Lighting accounts for approximately 30-40% of commercial building energy consumption.[103] Installing high efficiency lighting technologies (e.g., LED, high efficiency linear fluorescent, and compact fluorescent lamps) can reduce tenant space lighting energy consumption by up to 30-60%.[104] For example, LED lamps use at least 75% less energy and last 25 times longer than incandescent lighting,[105] which reduces ongoing maintenance and lamp replacement costs. Additionally, high efficiency T8 linear fluorescent lamps, a standard lighting technology in tenant spaces, use 20-35% less energy than standard efficiency linear fluorescent lamps. Finally, LED technologies incorporated in to the most common commercial lighting fixtures, recessed lighting troffers (representing an estimated 50% of commercial lighting fixtures), can provide energy savings up to 60%.[106]

Cost/Benefit analysis for a typical use or uses

High efficiency lighting technologies can reduce tenant space lighting energy consumption by up to 30-60% with a typical payback ranging from 1-3 years.[107] Costs vary considerably with type of upgrade and project size but the average cost is roughly $5/square foot.[108]

More Information

- Interior Lighting Campaign. US DOE Better Buildings. Link.
- LED lighting. US DOE. Link.
- LED Lighting: The New Low-hanging Fruit in a Lighting (R)evolution. CLEAResult. Link.
- Upgrading Troffer Luminaries to LED. US DOE. Link.
- Certified Products. ENERGY STAR®. Link.

6.2.2 *Lighting control technologies*

A variety of cost-effective lighting control technologies can be employed in tenant spaces to reduce lighting energy consumption including vacancy sensors, bi-level switching, timers, and daylight sensors.

- Vacancy sensors require occupants to manually turn the lighting on and then automatically turn the lighting off when motion is not detected for a period of time.
- Bi-level switching enables the control of a lighting system in groups of fixtures or lamps. For example, bi-level switching allows you to turn off half of the lights in a room off when full illumination is not required.

103 Regulations.gov. (2015). This is a Comment on the Energy Efficiency and Renewable Energy Office (EERE) Notice: 2015-07-31 Request for Information (RFI) for High-Performance Energy Efficiency Measures in Separate Spaces. http://www.regulations.gov/#!documentDetail;D=EERE-2015-BT-BLDG-0012-0010.

104 Nelson, DavidD. (2014). Energy Efficient Lighting. Whole Building Design Guide. https://www.wbdg.org/resources/efficientlighting.php.

105 DOE. LED Lighting. DOE Energy Saver. http://energy.gov/energysaver/led-lighting

106 Navigant Consulting for DOE. (2015). High Impact Technology Catalyst: Technology Deployment Strategies. http://energy.gov/sites/prod/files/2015/09/f26/CBI%20HIT%20Deployment%20Strategy.pdf.

107 Nelson, DavidD. (2014). Energy Efficient Lighting. Whole Building Design Guide. https://www.wbdg.org/resources/efficientlighting.php.

108 Benson et al. (2011). Retrofitting Commercial Real Estate: Current Trends and Challenges in Increasing Building Energy Efficiency. http://www.environment.ucla.edu/media/files/Retrofitting-Commercial-Real-Estate-30-mlg.pdf.

- Timers turn lights on or off at pre-determined periods of the day to ensure lighting is activated only when needed.
- Daylight sensors dim lighting when sufficient daylight is available, saving energy and money.[109]

Proper commissioning of such technologies is needed to ensure that sensors and controls are performing as intended.

Cost/Benefit analysis for a typical use or uses

Lighting controls can reduce tenant space lighting energy consumption by 24-38% with a typical payback of less than 3 years.[110] [111] Costs vary considerably with type of strategy and project size but average costs of roughly $2/square foot have been achieved in the industry.[112] Bundling lighting controls with lamp upgrades can maximize the savings opportunity by lowering purchase costs, as it is less expensive to install lighting controls and lamp upgrades at the same time compared to separate installations, and creating higher returns on investment.

More Information

- ENERGY STAR® Building Upgrade Manual. ENERGY STAR®. Link.
- Energy Savings Tips for Small Businesses: Offices- Owners and Tenants. ENERGY STAR®. Link.

6.2.3 *Daylighting*

Daylighting is the controlled introduction of natural light into an interior space to reduce lighting energy consumption. An effective daylighting strategy is integrated with conventional lighting design strategies and appropriately illuminates the tenant space without subjecting occupants to glare or major variations in light levels, which can impact comfort and productivity.[113] Various design strategies can be employed to maximize daylighting in a tenant space, including exterior shades or light shelves that redirect sunlight deep into the space,[114] window films that reduce solar heat gain and improve lighting distribution, light-colored reflective ceiling and wall finishes, window shades on the lower portions of the windows, low wall partitions or translucent panels to allow deep daylight penetration, locating private offices on the interior of the floor to maintain open space along the perimeter walls, and installing daylighting controls to turn off or dim interior lighting when natural lighting is sufficient. Additionally, improving daylighting in a tenant space can lead to increased employee productivity, improved health, and improved mood and reduced absenteeism.[115]

109 ENERGY STAR®. Energy Savings Tips for Small Businesses: Office – Owners and Tenants. http://www.energystar.gov/sites/default/files/tools/Small_Business_Offices_0.pdf.

110 Williams, Alison;A., Atkinson, Barbara;B., Garbesi, Karina;K., & Rubinstein, FrancisF. (2012). Quantifying National Energy Savings Potential of Lighting Controls in Commercial Buildings. Ernest Orlando Lawrence Berkeley National Laboratory. http://eetd.lbl.gov/sites/all/files/quantifying_national_energy_savings_potential_of_lighting_controls_in_commercial_buildings_lbnl-5895e.pdf

111 Kanellos, MichaelM. (2010). Payback for Lighting Controls: Less than Three Years. GreenTechMedia. http://www.greentechmedia.com/articles/read/payback-for-lighting-controls-less-than-three-years

112 Berkeley Lab Energy Technologies Area (ETA). (2013). Lighting Control Testbeds at the General Services Administration Showing Promise for Lighting Energy Reductions. (2013). http://eetd.lbl.gov/news/article/56664/lighting-control-testbeds-at-th.

113 http://www.gsa.gov/portal/mediaId/211239/fileName/Lighting_and_Daylighting_Two_Pager_508_compliant_2-9-15.action GSA. GSA. (n.d.). Saving Energy through Lighting and Daylighting Strategies. http://www.gsa.gov/portal/mediaId/211239/fileName/Lighting_and_Daylighting_Two_Pager_508_compliant_2-9-15.action

114 http://www.wbdg.org/resources/daylighting.php Ander, Gregg DG. (2014). Whole Building Design Guide. Daylighting. http://www.wbdg.org/resources/daylighting.php

115 https://www.portlandoregon.gov/bps/article/285215 City of Portland Bureau of Planning and Sustainability. (n.d.). Creating a High Performance Workplace. https://www.portlandoregon.gov/bps/article/285215

Cost/Benefit analysis for a typical use or uses

An effective daylighting strategy can reduce tenant space lighting energy consumption by 20-80%[116] and has a cost premium of ≤ $5/square foot.[117]

More Information

- Creating a High Performance Workspace. Portland's Green Tenant Improvement Guide. Link.
- Daylighting. Whole Building Design Guide. Link.
- Saving Energy through Lighting and Daylighting Strategies. GSA. Link.

6.2.4 *ENERGY STAR® Certified Appliances and Office Equipment*

ENERGY STAR® certified appliances and office equipment are highly energy efficient and use 10-40% less energy than standard models. They often include higher quality components that can result in fewer mechanical problems, longer equipment life, and extended warranties. Appliances and office equipment with the ENERGY STAR® certification include refrigerators, freezers, dishwashers, vending machines, coffee makers, computers, external displays, printers, and data center storage units.[118]

Cost/Benefit analysis for a typical use or uses

ENERGY STAR® certified appliances and office equipment use 10-40% less energy than standard efficiency models and although there can be a cost premium in the range of $50 - $200; ENERGY STAR®-certified appliances typically provide a payback period of 1-3 years.[119] [120]

More Information

- Certified Products. ENERGY STAR®. Link.

116 http://news.mit.edu/2007/techtalk51-26.pdf MIT. MIT. (2007). Tech Talk. Daylight device lightens electricity cost. http://news.mit.edu/2007/techtalk51-26.pdf

117 http://energy.gov/sites/prod/files/2014/02/f8/BTO_windows_and_envelope_report_3.pdf DOE. DOE. (2014). Windows and Building Envelope Research and Development: Roadmap for Emerging Technologies. http://energy.gov/sites/prod/files/2014/02/f8/BTO_windows_and_envelope_report_3.pdf

118 https://www.energystar.gov/ia/new_homes/features/Appliances_062906.pdf ENERGY STAR®. ENERGY STAR®. (n.d.). ENERGY STAR® Qualified Appliances. https://www.energystar.gov/ia/new_homes/features/Appliances_062906.pdf

119 ENERGY STAR®. (n.d.). Certified Products. https://www.energystar.gov/products

120 Green Building Advisor. (2010). Are Energy-Efficient Appliances Worth it? http://www.greenbuildingadvisor.com/blogs/dept/green-communities/are-energy-efficient-appliances-worth-it

6.2.5 *Plug and Process load (PPL) inventory and reduction strategies*

"Plug and process loads" (PPLs), or the energy consumed by the equipment connected to electrical outlets, account for 30% of the electricity consumption in office buildings.[121] In a commercial building, PPLs include computers, printers, networking equipment, task lighting, kitchen appliances, etc.[122] Performing a plug load inventory and implementing a load reduction strategy can reduce unnecessary tenant space plug loads by up to 20-50%.[123] Effective strategies for tenant spaces include utilizing wireless devices to control specific receptacles, wiring separate electrical zones to enable occupancy sensor or timer control of the PPLs, and end-user dashboard-based feedback technology and smart sub-metering that prompts end-users to power off equipment.

Cost/Benefit analysis for a typical use or uses

A plug load reduction strategy can reduce unnecessary plug load energy use by up to 20-50%.[124] In a National Renewable Energy Laboratory (NREL) study, a $20 electrical outlet timer was installed on an ENERGY STAR® ice maker and saved $150 per year.[125]

More Information

- Assessing and Reducing Plug and Process Loads in Office Buildings. NREL. Link.
- Plug Load Reduction Checklist. GSA. Link.
- Decision Guides for Plug and Process Load Controls. DOE. Link.

High efficiency HVAC units for above-standard operations

Installing high efficiency, ENERGY STAR® certified, supplemental HVAC equipment for tenant spaces with above standard operating hours or heating and cooling needs (e.g., data centers, server rooms, call centers, etc.) can reduce HVAC energy consumption by 5-20%[126] when compared to standard efficiency units. Specifying ENERGY STAR® certified HVAC units with variable speed compressors, fans, and pumps that are appropriately sized for the heating and cooling loads of the space can lead to significant energy saving over less efficient equipment. Where feasible, water-cooled HVAC equipment should be specified that can be tied into the base building condenser water loop. Water-cooled HVAC equipment is typically 10-20% more efficient than air-cooled equipment. Additionally, energy consumption associated with the supplemental HVAC equipment should be submetered.[127]

121 http://www.gsa.gov/portal/mediaId/178935/fileName/PlugLoad_Checklist_Form_Fields_508 GSA. GSA. (n.d). Plug Load Reduction Checklist. http://www.gsa.gov/portal/mediaId/178935/fileName/PlugLoad_Checklist_Form_Fields_508

122 https://www4.eere.energy.gov/alliance/activities/technology-solutions-teams/plug-process-loads Better Buildings, DOE. Better Buildings, DOE. (n.d.). Plug & Process Loads. https://www4.eere.energy.gov/alliance/activities/technology-solutions-teams/plug-process-loads

123 http://www.regulations.gov/#!documentDetail;D=EERE-2015-BT-BLDG-0012-0010 Regulations.gov. Regulations.gov. (2015). 2015-09-30 Comment response to the published Request for Information (RFI). NEMA Comments - DOE RFI on Energy Efficiency in Separate Spaces. http://www.regulations.gov/#!documentDetail;D=EERE-2015-BT-BLDG-0012-0010

124 http://www.regulations.gov/#!documentDetail;D=EERE-2015-BT-BLDG-0012-0010 Regulations.gov. Regulations.gov. (2015). 2015-09-30 Comment response to the published Request for Information (RFI). NEMA Comments - DOE RFI on Energy Efficiency in Separate Spaces. http://www.regulations.gov/#!documentDetail;D=EERE-2015-BT-BLDG-0012-0010

125 Sheppy; Michael,M., Lobato, Chad;C., Pless, Shanti;S., Polese, Luigi;L., & Torcellini, Paul.P. (2013). NREL. Assessing and Reducing Plug and Process Loads in Office Buildings. (2013). http://www.nrel.gov/docs/fy13osti/54175.pdf.

126 https://www.energystar.gov/products/certified-products?s=mega ENERGY STAR®. (n.d.). Certified Products. https://www.energystar.gov/products/certified-products?s=mega

127 https://www.energystar.gov/sites/default/files/buildings/tools/EPA_BUM_Full.pdf ENERGY STAR®. (2008). Building Upgrade Manual. https://www.energystar.gov/sites/default/files/buildings/tools/EPA_BUM_Full.pdf

Cost/Benefit analysis for a typical use or uses

High efficiency, ENERGY STAR® certified, supplemental HVAC equipment is 5-20% more efficient than standard efficiency units and on average have a cost premium of $100 – 180 per ton compared to standard efficiency models.[128] [129]

More Information

- ENERGY STAR® Building Upgrade Manual. ENERGY STAR®. Link.
- Certified Products. ENERGY STAR®. Link.

6.2.6 *Point-of-use domestic water heating*

Electric point-of-use (i.e., tankless) water heaters are typically the most cost-effective domestic water heating technology installed in tenant spaces and can reduce domestic hot water energy consumption by 27-50%. Unlike storage tank water heaters, point-of-use water heaters are installed at each hot water outlet and do not require water distribution piping. They save energy by providing hot water on-demand.[130] Properly maintaining the temperature at the DOE recommended setpoint (120°F) will ensure energy efficiency and safety.[131] [132]

Cost/Benefit analysis for a typical use or uses

Point-of-use water heaters cost on average $200 and can reduce domestic hot water energy consumption by 27-50%, when compared to storage tank water heaters.[133] [134]

More Information

- Tankless of Demand-Type Water Heaters. US DOE. Link.
- Point of Use (POU) Water Heaters. ENERGY STAR®. Link.

128 ENERGY STAR®. (n.d.). Certified Products. https://www.energystar.gov/products/certified-products?s=mega

129 EPA. (n.d.). State and Local Climate and Energy Program. Rules of Thumb. http://www3.epa.gov/statelocalclimate/documents/pdf/table_rules_of_thumb.pdf.

130 http://energy.gov/energysaver/tankless-or-demand-type-water-heaters DOE. DOE. (n.d.). Tankless or Demand-Type Water Heaters. http://energy.gov/energysaver/tankless-or-demand-type-water-heaters

131 https://www.energystar.gov/sites/default/files/buildings/tools/DataTrends_Savings_20121002.pdf http://www.energystar.gov/ia/partners/prod_development/new_specs/downloads/water_heaters/ElectricTanklessCompetitiveAssessment.pdf ENERGY STAR® Portfolio Manager®. (2011). Benchmarking and Energy Savings. https://www.energystar.gov/sites/default/files/buildings/tools/DataTrends_Savings_20121002.pdf

132 R. Milward, R. (2005). EPRI Retail Technology Application Centers. Electric Tankless Water Heating: Competitive Assessment. http://www.energystar.gov/ia/partners/prod_development/new_specs/downloads/water_heaters/ElectricTanklessCompetitiveAssessment.pdf

133 DOE. (n.d.).Estimating Costs and Efficiency of Storage, Demand, and Heat Pump Water Heaters. http://energy.gov/energysaver/estimating-costs-and-efficiency-storage-demand-and-heat-pump-water-heaters.

134 DOE. (n.d.). Tankless or Demand-Type Water Heaters. http://energy.gov/energysaver/tankless-or-demand-type-water-heaters

6.2.7 *Energy management and information systems (EMIS)*

Energy Management and Information Systems (EMIS) comprise a broad family of tools and services to manage commercial building energy use. While EMIS technologies are typically implemented at the building-level, they can be applied to individual tenant spaces to improve energy performance. These technologies include energy information systems (EIS), equipment-specific fault detection and diagnostic systems, benchmarking and utility tracking tools, and building automation systems (BAS).[135] A BAS is a computer-based control system that controls and monitors building mechanical and electrical equipment, including heating and cooling, ventilation, lighting, fire control systems, and security systems. Integrating tenant space HVAC and lighting controls into a well-programmed central BAS can lead to significant energy savings by automatically controlling tenant space operations using advanced control strategies. Benchmarking and monitoring the utility performance of submetered tenant spaces enables the tracking of savings associated with energy conservation measures and the identification of operational anomalies that can improve energy performance when addressed.

Cost/Benefit analysis for a typical use or uses

Benchmarking or closely monitoring tenant space energy consumption can lead to annual energy savings of 2-3%.[136] Integrating the control of tenant space mechanical and electrical systems into a well-programmed BAS can reduce energy consumption by 10-15%.[137] Proper installation and use of EMIS systems can lead up to 16% energy savings and average $0.30/square foot cost with a 1.1 year payback period for existing buildings and 13% energy savings and average $1.16/square foot with a 4.2 year payback in new construction.[138]

More Information

- Energy Management and Information Systems. DOE Better Buildings Alliance. Link.
- Energy Information Systems (EIS): Technology Costs, Benefit, and Best Practice Uses. Lawrence Berkeley National Laboratory. Link.

135 DOE. (n.d.) EMIS Technology Classification Framework. https://www4.eere.energy.gov/alliance/sites/default/files/uploaded-files/emis-technology-classification-framework.pdf

136 Better Buildings Alliance. (n.d.). Energy Management and Information Systems. https://www4.eere.energy.gov/alliance/activities/technology-solutions-teams/energy-management-information-systems

137 Granderson, Jessica;J., Lin, Guanjing;G., & Hult, ErinE. (2013). EMIS: Crash Course. Better Buildings. http://eis.lbl.gov/pubs/emis-crash-course.pdf

138 Mills, Evan. (2009). Building Commissioning A Golden Opportunity for Reducing Energy Costs and Greenhouse Gas Emissions. Report Prepared for: California Energy Commission Public Interest Energy Research (PIER). http://cx.lbl.gov/documents/2009-assessment/lbnl-cx-cost-benefit.pdf

6.2.8 *Optimization of outside air volumes according to tenant occupancy*

Properly ventilated tenant spaces require the HVAC system to deliver adequate amounts of clean, fresh air to building occupants. This fresh air replaces stale air that has become polluted with airborne contaminants from occupant and equipment activities. These airborne pollutants include odors, CO2 (from breathing), equipment emissions (ozone and particulates from copiers and printers), moisture, dirt, dust, mold and various other airborne chemicals.[139] Sensing and control technologies can be employed to deliver fresh air on demand, based on indoor CO2 levels detected by sensors in individual areas within a tenant space. During the design process, the tenant should coordinate with the mechanical designer or building engineering team to ensure that outside air volumes delivered to the tenant space are optimized for the anticipated occupancy. Providing excessive volumes of outside air will increase HVAC system energy consumption, while lower levels of outside air will negatively impact indoor air quality. Additionally, emerging approaches to ventilation systems include scrubbing pollutants directly out of indoor air to reduce the requirement to condition outside air.

Cost/Benefit analysis for a typical use or uses

Optimizing outside air volumes according to tenant occupancy can save $0.05 to over $1.00 per square foot and can range in cost from $300 to $1,000 per HVAC zone.[140] [141] Although it is difficult to apply a specific rule of thumb for savings, studies show that large spaces that have significant variations in occupancy provide the best opportunity to achieve energy savings through optimizing outside air volumes.[142]

More Information

- Creating a High Performance Workspace. Portland's Green Tenant Improvement Guide. Link.

139 https://www.portlandoregon.gov/bps/article/285215 City of Portland Planning and Sustainability. (n.d.). Creating a High Performance Workplace. https://www.portlandoregon.gov/bps/article/285215

140 Oregon Office of Energy. (2003). Northwest Energy Efficiency Alliance. Demand-Controlled Ventilation: A Design Guide. http://www.oregon.gov/energy/cons/bus/dcv/docs/dcvguide.pdf.

141 Sand, James.J. (2004). DOE Federal Energy Management Program. Demand Controlled Ventilation Using CO2 Sensors. (2004). http://infohouse.p2ric.org/ref/43/42844.pdf.

142 Energy Design Resources. (2007). Design Brief: Demand-Controlled Ventilation. https://energydesignresources.com/media/1705/EDR_DesignBriefs_demandcontrolledventilation.pdf?tracked=true.

6.2.9 *Data centers and IT server room best practices*

Data centers and server rooms and are one of the most energy-intensive spaces in commercial buildings, consuming 10 to 50 times the energy per floor area of a typical commercial office building. Collectively, these spaces account for approximately 2% of the total U.S. electricity use, and as use of information technology grows, data center and server energy use is expected to grow too. There are many opportunities to reduce energy use in server closets and data centers,[143] including consolidating servers, decommissioning servers that are not in service, consolidating and organizing stored data to eliminate unnecessary redundancy, installing ENERGY STAR® qualified servers, arranging of server racks and isolating air flows to create hot/cold aisles that prevent the mixing of warm and cool air, adjusting the temperature set points and managing humidity levels, and utilizing air- and water-side economizers when weather conditions permit.[144] Building engineers can play a role in reviewing data center design and providing building-specific recommendations to optimize the performance of the data center.

Cost/Benefit analysis for a typical use or uses

Implementing design and operational strategies to improve energy performance can reduce data centers and server closet energy consumption by up to 80%.[145] A Lawrence Berkeley National Laboratory test on three data centers varying in size, design and energy load showed estimated costs to implement energy efficiency measures from $276,000 - $770,000 with an average payback of approximately 2 years.[146]

More Information

- Top 12 Ways to Decrease the Energy Consumption of your Data Center. ENERGY STAR®. Link.
- Energy Efficiency in Small Server Rooms: Field Surveys and Findings. Lawrence Berkeley National Laboratory. Link.

6.2.10 *Improving Building Envelope Performance*

Improving building envelope performance in tenant spaces is most cost-effective when evaluated during the design phase of new construction projects, as the incremental cost premium for upgrading the building envelope when designing new buildings is significantly lower than when retrofitting existing buildings. Opportunities for improving building envelope performance for new buildings include installing high-efficiency windows and glazing systems, operable windows that provide natural ventilation and increase occupant comfort, exterior shading systems, properly insulating pipes and ducts in perimeter walls, and increasing wall and roof insulation levels. Various strategies can be implemented to improve building envelope performance in existing buildings, which include installing high efficiency window films, interior window shading devices, reducing air infiltration through exterior doors, properly sealing the perimeter walls and openings, and installing a radiant barrier on the

143 http://energy.gov/eere/buildings/data-centers-and-servers DOE. DOE. Data Centers and Services. http://energy.gov/eere/buildings/data-centers-and-servers

144 http://www.energystar.gov/ia/products/power_mgt/downloads/DataCenter-Top12-Brochure-Final.pdf?d63b-c2a9 ENERGY STAR®. ENERGY STAR®. (n.d.). Top 12 Ways to Decrease the Energy Consumption of Your Data Center. http://www.energystar.gov/ia/products/power_mgt/downloads/DataCenter-Top12-Brochure-Final.pdf?d63b-c2a9

145 http://www.energystar.gov/ia/products/power_mgt/ES_Data_Center_Utility_Guide.pdf?ff29-42fa ENERGY STAR®. ENERGY STAR®. (2012). Understanding and Designing Energy-Efficiency Programs for Data Centers. http://www.energystar.gov/ia/products/power_mgt/ES_Data_Center_Utility_Guide.pdf?ff29-42fa

146 Mahdavi, Rod.R. (2014). Prepared for the US DOE's Federal Energy Management Program by the Lawrence Berkeley National Laboratory. Case Study: Opportunities to Improve Energy Efficiency in Three Federal Data Centers. (2014). http://energy.gov/sites/prod/files/2014/06/f16/casestudy_3federaldatacenters_0.pdf.

perimeter walls.[147] For tenant spaces in both new and existing buildings, it is essential to coordinate with the design and building management teams early in the design process to identify opportunities and limitations for improving building envelope performance.[148]

Cost/Benefit analysis for a typical use or uses

Envelope performance can have a wide range of costs and benefits, ranging from the trivial (minor caulking) to transformative (replacement of façade, new windows, comprehensive air sealing). As an example, in multiunit buildings, caulking has been estimated to save 3-12% on energy for conditioning, at a cost of less than $0.31/ft².[149] Additionally, a study of non-residential buildings in Canada found that a 40% to 70% decrease in air infiltration resulted in "a 9% to 15% reduction in overall energy expenditure, with a payback period of less than 2 years."[152] By contrast, replacing the panes on a major office tower can yield significant energy savings with a correspondingly high cost. Envelope improvements at this scale are typically completed as part of a repositioning upgrade and need to be individually evaluated.[150] [151]

More Information

- High-Performance Tenant Build-Out: A Primer for Tenants. Institute for Building Efficiency. Link.
- Tenant Energy Performance in Commercial Office Buildings. Real Estate Roundtable. Link.

147 http://www.institutebe.com/InstituteBE/media/Library/Resources/Existing%20Building%20Retrofits/Primer_Tenant_Build_Outs.pdf Institute for Building Efficiency. (2011). High-Performance Tenant Build-Out: A Primer For Tenants. http://www.institutebe.com/InstituteBE/media/Library/Resources/Existing%20Building%20Retrofits/Primer_Tenant_Build_Outs.pdf

148 http://www.josre.org/wp-content/uploads/2013/02/CMI-PPT-on-Tenant-Energy-Performance.pdf NRDC. NRDC. (2013). Tenant Energy Performance in Commercial Office Buildings. NRDC Center for Market Innovation High Performance Tenant Demonstration Project. http://www.josre.org/wp-content/uploads/2013/02/CMI-PPT-on-Tenant-Energy-Performance.pdf

149 Dentz, J., Conlin, F., Podorson, D. (2012). Case Study of Envelope Sealing in Existing Multiunit Structures. NREL. http://www.nrel.gov/docs/fy13osti/54787.pdf

150 Hampson, R. (2010). Empire State Building goes green, one window at a time. USA Today. http://usatoday30.usatoday.com/news/nation/environment/2010-07-12-empire-state-building-windows-green_N.htm

151 Guevarra, L. (2010). A Tall Order: Serious Materials to Retrofit Empire State Building's Windows. GreenBiz. http://www.greenbiz.com/news/2010/03/03/tall-order-serious-materials-retrofit-empire-state-buildings-windows

6.2.11 *HVAC zoning*

Creating separate HVAC zones to align with hours of operation, occupancy, and unique heating and cooling requirements of tenant spaces will improve the comfort of building occupants and reduce HVAC energy consumption. When a tenant space is properly zoned, heating and cooling is provided based on the temperature requirements of each HVAC zone. For example, a conference room with a high occupant density will require more cooling than an infrequently occupied tenant break room. An effective strategy for HVAC zoning in tenant spaces is organizing the interior layout to create zones with similar needs for heating and/or cooling based on function, level of activity, exposure to the sun or wind, schedules and location in the building. Additionally, utilizing variable air volume (VAV) systems and providing separate thermostats for each zone to precisely control the temperature and volume of the air delivered will further reduce HVAC energy consumption in tenant spaces.

Cost/Benefit analysis for a typical use or uses

Increasing the number of HVAC zones in a space can cost an additional $3/square foot to $6/square foot on top of typical mechanical system costs.[152] Retrofitting a constant volume system to a VAV system can cost between $1/square foot and $4/square foot and can achieve a payback of 10 months to 12.1 years depending on available rebates.[153]

More Information

- Creating a High Performance Workspace. Portland's Green Tenant Improvement Guide. Link.
- Los Alamos National Laboratory Sustainable Design Guide. Chapter 5- Lighting, HVAC, and Plumbing. Link.

152 California Energy Commission. (2003). Advanced Variable Air Volume System Design Guide. http://www.energy.ca.gov/2003publications/CEC-500-2003-082/CEC-500-2003-082-A-11.PDF.

153 ENERGY STAR®. (2008). Building Upgrade Manual: Air Distribution Systems. https://www.energystar.gov/ia/.../EPA_BUM_CH8_AirDistSystems.pdf.

6.2.12 *Window attachments*

Window attachments are a cost-effective means of improving the energy efficiency of a tenant space by reducing solar heat gain and improving light distribution.

Window films:

- High-reflectivity films help reduce solar heat gain and cooling costs during the summer.
- Prismatic films redirect sunlight towards the ceiling to provide more natural light in tenant spaces, reducing lighting energy consumption when daylight sensors are utilized to control electric lighting.[154]
- Window films with a low-e coating provide the benefits of year-round energy savings by improving window insulating performance and helping to keep the heat in during the winter and out during the summer.

Awnings, low-cost shades, and roof overhangs provide a physical barrier from strong midday sunlight while allowing soft light in the early or late hours. The exterior nature of awnings and roof overhangs may be difficult for tenants in high-rise structures, but can prove useful for retail tenants with first floor rental space. In addition to conserving energy, window attachments can reduce glare, improve occupant health and productivity, improve access to daylight and views, and improve thermal comfort.[155]

Cost/Benefit analysis for a typical use or uses

Window films can reduce tenant space energy consumption by 5-17% and typically have a cost premium of ≤ $2/square foot, when compared to standard window systems.[156] [157]

Exterior window attachments, such as awnings, can reduce summertime solar heat gain between 65 and 77%.[158]

More Information

- Energy efficient window treatments. US DOE. Link.
- Windows and Building Envelope Research and Development: Roadmap for Emerging Technologies. US DOE. Link.
- Reducing Supplemental Loads. ENERGY STAR®. Link.

154 Thanachareonkit, Anothai;A., Lee, Elanor;E., & McNeil, AndrewA. (2013). Empirical assessment of a prismatic daylight-redirecting window film in a full-scale office testbed. http://eetd.lbl.gov/daylight/daylight-field-test.pdf

155 Regulations.gov. (2015). 2015-09-23 Comment response to the published Request for Information (RFI). EastmanChemicalCompanyCommentEERE2015BTBLDG0012. http://www.regulations.gov/#!documentDetail;D=EERE-2015-BT-BLDG-0012-0008

156 DOE. (2014). Windows and Building Envelope Research and Development: Roadmap for Emerging Technologies. http://energy.gov/sites/prod/files/2014/02/f8/BTO_windows_and_envelope_report_3.pdf

157 International Window Film Association (IWFA). Enegy Analysis for Window Films Applications in New and Existing Homes and Offices. http://www.iwfa.com/Portals/0/PDFDocs/IWFA%20Energy%20Study%20FINAL.pdf

158 DOE. (n.d.). Energy Efficient Window Treatments. http://energy.gov/energysaver/articles/energy-efficient-window-treatments

6.2.13 *Utility Metering and Submetering*

While submetering provides the opportunity for additional energy savings, it does not, in of itself, save energy. Submetering provides tenants and property management teams an additional level of insight into the energy performance of their space or sub-spaces. Data gathered through a well-designed submetering plan can greatly inform and influence the development of energy management strategies and can highlight the specific impact of energy efficiency projects, providing data-driven evidence of program effectiveness. Submeters also provide more accurate billing for energy usage in a specific tenant space when building operating expenses are normally billed pro rata. Submeters can be applied to measure large (entire building floors) or small scale (circuit-level or outlet-level) energy usage within a tenant space.

As discussed in section 4.1.5, building owners tend to favor less sophisticated meters over utility-grade meters. These meters are less expensive and "get the job done" when it comes to simple and consistent measurement of energy use from a single space. These same meters can be installed with technical options allowing electricity measurements to tie into systems mimicking utility tariff standards. Such sophisticated options are used for heightened accuracy of tenant energy use billback.

Installing permanent submeters is expensive. These costs discourage many owners and tenants from purchasing meters as an energy monitoring tool. While lower-cost wireless meters exist, they currently lack the ability to measure energy use over an extended period of time. Rather, they are most commonly used to temporarily monitor the energy use of a space in order to justify permanent submetering of above-average energy use spaces.

Cost/Benefit analysis for a typical use or uses

Submeters can cost between $700 and $5,000 and less robust models are available at a lower cost.[159] [160]

More Information

- Submetering Business Case: How to calculate cost-effectiveness solutions in the building context. GSA. Link.
- Submetering of Building Energy and Water Usage. National Science and Technology Council Committee on Technology. Link.

159 National Science and Technology Council Committee on Technology. (2011). Submetering of Building Energy and Water Usage. https://www.whitehouse.gov/sites/default/files/microsites/ostp/submetering_of_building_energy_and_water_usage.pdf

160 GSA. (2012). Submetering Business Case: How to calculate cost-effective solutions in the building context. http://www.gsa.gov/portal/mediaId/156791/fileName/Energy_Submetering_Finance_Paper_Knetwork_2012_11_269(508).action

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

TAC: Electrical

Total Mods for **Electrical** in **Pending Review : 16**

Total Mods for report: 16

Sub Code: Energy Conservation

E10088

11

Date Submitted	02/04/2022	**Section**	405.9	**Proponent**	Bryan Holland
Chapter	4	**Affects HVHZ**	No	**Attachments**	No
TAC Recommendation	Pending Review				
Commission Action	Pending Review				

Comments

General Comments Yes **Alternate Language No**

Related Modifications

Summary of Modification

This proposed modification adds requirements for energy monitoring to the code.

Rationale

The investment made for the infrastructure of a building in order to comply with the energy code is significant. The assumption that is currently made upon commissioning a facility is that energy efficiency measures will not degrade, or go out of calibration, over time and their energy consumption will not increase as time passes from the time they were commissioned. Such an assumption is completely inaccurate, and any payback assumed for energy efficient infrastructure investments will be lengthened, thereby reducing the ROI and increasing the payback period. The only means to retain the energy performance of a building is to continuously monitor energy consumption levels of various energy consuming systems and compare them to previous levels. Monitoring sub-systems provides key indications when changes have been made or systems are not operating to specification, which increases energy consumption.

Fiscal Impact Statement

Impact to local entity relative to enforcement of code

This proposed modification will require the local entity to confirm the design and installation of energy monitoring at time of plan review and inspection.

Impact to building and property owners relative to cost of compliance with code

This proposed modification will increase the cost of compliance with the code but will give the building and property owners the ability to monitor their energy consumption as a means of continuous commissioning of the various systems to ensure ROI and promised energy savings.

Impact to industry relative to the cost of compliance with code

This proposed modification will increase the cost of compliance with the code for industry. Energy monitoring software and hardware are readily available in the marketplace, however these systems do require installers and users to receive specialized training.

Impact to small business relative to the cost of compliance with code

Requirements

Has a reasonable and substantial connection with the health, safety, and welfare of the general public

This proposed modification will improve the health and welfare of the general public by improving the effect use of energy and energy conservation.

Strengthens or improves the code, and provides equivalent or better products, methods, or systems of construction

This proposed modification improves the code and meets the mandate outlined in F.S. 553.886 that states; "the Florida Building Code must facilitate and promote the use of cost-effective energy conservation, energy-demand management, and renewable energy technologies in buildings.

Does not discriminate against materials, products, methods, or systems of construction of demonstrated capabilities

This proposed modification does not discriminate against any materials, methods, or systems of constructions.

Does not degrade the effectiveness of the code

This proposed modification improves the effectiveness of the code.

1st Comment Period History

E10088-G1

Proponent	Muthusamy Swami	Submitted	4/17/2022 12:58:48 PM	Attachments	No

Comment:

This proposed code change is going to a new provision for 2023 FBCEC (also new to the 2021 IECC) but the same code exits in ASHRAE 90.1-2019. We have commented in EN1007 (item #1) why we should support this code requirement. FSEC has demonstrated that this proposed code change is cost-effectiveness and determined that the saving to investment ratio (SIR) was 3.44 – 14.01 range. Note that this code change impacts buildings floor size larger than 25,000 square foot. FSEC encourages adoption of this proposed code change.

C405.9 Energy monitoring. New buildings with a gross conditioned floor area of 25,000 square feet (2322 m2) or larger shall be equipped to measure, monitor, record and report energy consumption data in compliance with Sections C405.9.1 through C405.9.5.

Exception: R-2 occupancies and individual tenant spaces are not required to comply with this section provided that the space has its own utility services and meters and has less than 5,000 square feet (464.5 m2) of conditioned floor area.

C405.9.1 Electrical energy metering. For all electrical energy supplied to the building and its associated site, including but not limited to site lighting, parking, recreational facilities and other areas that serve the building and its occupants, meters or other measurement devices shall be provided to collect energy consumption data for each end-use category required by Section C405.9.2.

C405.9.2 End-use metering categories. Meters or other approved measurement devices shall be provided to collect energy use data for each end-use category indicated in Table C405.9.2. Where multiple meters are used to measure any end-use category, the data acquisition system shall total all of the energy used by that category. Not more than 5 percent of the measured load for each of the end-use categories indicated in Table C405.9.2 shall be permitted to be from a load that is not within that category.

Exceptions:

1. HVAC and water heating equipment serving only an individual dwelling unit shall not require end-use metering.

2. End-use metering shall not be required for fire pumps, stairwell pressurization fans or any system that operates only during testing or emergency.

3. End-use metering shall not be required for an individual tenant space having a floor area not greater than 2,500 square feet (232 m2) where a dedicated source meter complying with Section C405.9.3 is provided.

TABLE C405.9.2

ENERGY USE CATEGORIES

LOAD CATEGORY	DESCRIPTION OF ENERGY USE
Total HVAC System	Heating, cooling, and ventilation, including but not limited to fans, pumps, boilers, chillers and water heating. Energy used by 120-volt equipment, or by 208/120-volt equipment that is located in a building where the main service is 480/277-volt power, is permitted to be excluded from the total HVAC system energy use.
Interior lighting	Lighting systems located within the building
Exterior lighting	Lighting systems located on the building site but not within the building.
Plug loads	Devices, appliances, and equipment connected to convenience receptacle outlets.
Process loads	Any single load that is not included in an HVAC, lighting or plug load category and that exceed 5 percent of the peak connected load of the whole building , including but not limited to data centers, manufacturing equipment and commercial kitchens.
Building operations and other miscellaneous loads	The remaining loads not included elsewhere in this table, including but not limited to vertical transportation systems, ornamental fountains, ornamental fireplaces, swimming pools, in-ground spas and snow-melt systems.

C405.9.3 Meters. Meters or other measurement devices required by this section shall be configured to automatically communicate energy consumption data to the data acquisition system required by Section C405.9.4. Source meters shall be allowed to be any digital-type meter. Lighting, HVAC or other building systems that can monitor their energy consumption shall be permitted instead of meters. Current sensors shall be permitted, provided that they have a tested accuracy of ±2 percent. Required metering systems and equipment shall have the capability to provide at least hourly data that is fully integrated into the data acquisition system and graphical energy report in accordance with Sections C405.9.4 and C405.9.5.

C405.9.4 Data acquisition system. A data acquisition system shall have the capability to store the data from the required meters and other sensing devices for a minimum of 36 months. The data acquisition system shall have the capability to store real-time energy consumption data and provide hourly, daily, monthly and yearly logged data for each end-use category required by Section C405.9.2.

C405.9.5 Graphical energy report. A permanent and readily accessible reporting mechanism shall be provided in the building that is accessible by building operation and management personnel. The reporting mechanism shall have the capability to graphically provide the energy consumption for each end-use category required by Section C405.9.2 at least every hour, day, month and year for the previous 36 months.

TAC: Electrical

Total Mods for **Electrical** in **Pending Review : 16**

Total Mods for report: 16

Sub Code: Energy Conservation

12

E10089

Date Submitted	02/04/2022	**Section**	406	**Proponent**	Bryan Holland
Chapter	4	**Affects HVHZ**	No	**Attachments**	No
TAC Recommendation	Pending Review				
Commission Action	Pending Review				

Comments

General Comments Yes **Alternate Language No**

Related Modifications

Summary of Modification

This proposed modification adds two additional efficiency package options and will now require two of the seven options to be selected for compliance.

Rationale

To help improve energy conservation of commercial buildings, this proposal will require a second efficiency package to be selected from the list of options. This essentially doubles the energy efficiency impact of Section C406. Additionally, two new options have been added to allow the installation of energy monitoring and/or FDD in a building not required by C405.9 and C403.2.15, respectfully, to count towards the additional efficiency package requirement. These two options reward the building owner for installation of energy conservation systems not required by the code.

Fiscal Impact Statement

Impact to local entity relative to enforcement of code

This proposed modification will require the local entity to confirm a second efficiency package has been designed and installed at time of plan review and inspection.

Impact to building and property owners relative to cost of compliance with code

This proposed modification will increase the cost of compliance with the code but will result immediate energy savings to the building and property owners.

Impact to industry relative to the cost of compliance with code

This proposed modification will increase the cost of compliance with the code for industry by requiring a second efficiency package to be designed and installed.

Impact to small business relative to the cost of compliance with code

Requirements

Has a reasonable and substantial connection with the health, safety, and welfare of the general public

This proposed modification will improve the health and welfare of the general public by essentially doubling the energy efficiency impact of C406.

Strengthens or improves the code, and provides equivalent or better products, methods, or systems of construction

This proposed modification improves the code and meets the mandate outlined in F.S. 553.886 that states; "the Florida Building Code must facilitate and promote the use of cost-effective energy conservation, energy-demand management, and renewable energy technologies in buildings.

Does not discriminate against materials, products, methods, or systems of construction of demonstrated capabilities

This proposed modification does not discriminate against any materials, methods, or systems of constructions.

Does not degrade the effectiveness of the code

This proposed modification improves the effectiveness of the code.

1st Comment Period History

E10089-G1

Proponent	Muthusamy Swami	Submitted	4/17/2022 1:00:50 PM	Attachments	No

Comment:

The proposed code change provides design flexibility. However, one cannot have these options available unless code change EN9993 (item#2) and EN10088 (item #6) are adopted. FSEC encourages adoption of proposed code changes: EN9993, EN10088, and EN10089.

C406.1 Requirements.

Buildings shall comply with at least ~~one~~ two of the following:

1. More efficient HVAC performance in accordance with Section C406.2.

2. Reduced lighting power density system in accordance with Section C406.3.

3. Enhanced lighting controls in accordance with Section C406.4.

4. On-site supply of renewable energy in accordance with Section C406.5.

5. Provision of a dedicated outdoor air system for certain HVAC equipment in accordance with Section C406.6.

6. High-efficiency service water heating in accordance with Section C406.7.

7. Where not required by Section C405.9, include an energy monitoring system in accordance with Section C405.9.

10. Where not required by Section C403.2.15 include a fault detection and diagnostics (FDD) system in accordance with Section C403.2.15

TAC: Electrical

Total Mods for **Electrical** in **Pending Review : 16**

Total Mods for report: 16

Sub Code: Residential

13

E10138

Date Submitted	02/15/2022	**Section**	3408	**Proponent**	Amanda Hickman
Chapter	34	**Affects HVHZ**	No	**Attachments**	Yes
TAC Recommendation	Pending Review				
Commission Action	Pending Review				

Comments

General Comments No

Alternate Language Yes

Related Modifications

10150

Summary of Modification

GFCI nuisance tripping

Rationale

This modification deletes the problematic new requirement for outdoor GFCI outlets in Section 210.8(F) of the 2020 NEC. AHRI requests that the Florida Building Commission to set this requirement aside until a resolution to nuisance tripping has been developed. This new requirement poses a much greater risk to Floridian's life and health than does the isolated, non-code compliant incident that was used to justify the addition of 210.8 (F) to the 2020 NEC. As of January 1, 2022, the twenty states that have either adopted or in the process of adopting the 2020 NEC have deleted, modified or delayed the implementation.

Fiscal Impact Statement

Impact to local entity relative to enforcement of code

Will improve enforcement of code by setting aside requirement until a resolution is developed.

Impact to building and property owners relative to cost of compliance with code

Reduction to cost of compliance because GFCI are not required.

Impact to industry relative to the cost of compliance with code

Reduction to cost of compliance because GFCI are not required.

Impact to small business relative to the cost of compliance with code

Requirements

Has a reasonable and substantial connection with the health, safety, and welfare of the general public

This modification will protect the health and safety of the general public by deleting this section from the NEC

Strengthens or improves the code, and provides equivalent or better products, methods, or systems of construction

Improves the code by preventing nuisance tripping because the two technologies are not harmonized.

Does not discriminate against materials, products, methods, or systems of construction of demonstrated capabilities

No, simply deletes section. As of January 1, 2022, the twenty states that have either adopted or in the process of adopting the 2020 NEC have deleted, modified or delayed the implementation.

Does not degrade the effectiveness of the code

Improves effectiveness of code by addressing nuisance tripping.

Alternate Language

1st Comment Period History

E10138-A1

Proponent Bryan Holland **Submitted** 3/28/2022 9:07:15 AM **Attachments** Yes

Rationale:

It appears the original proposed modification is referencing an older version of section 210.8(F) that has been updated by TIA 20-13, issued by the NFPA Standards Council on August 26, 2021 and that has addressed the concerns expressed by the proponent. However, the current section has a sunset date of January 1, 2023 that I am proposing be deleted to allow the HVAC equipment employing power conversion equipment to remain exempt under the duration of the 8th edition FBC-B. Approval of this alternative code modification assures GFCI protection remains for outlets where shock and electrocution hazards are present while exempting certain equipment that may not be compatible with GFCI protection, at this time.

Fiscal Impact Statement

Impact to local entity relative to enforcement of code

This proposed alternative modification provides clarity to the AHJ on the enforcement of 210.8(F) with regard to HVAC equipment employing conversion equipment.

Impact to building and property owners relative to cost of compliance with code

This proposed alternative modification will reduce the cost of compliance by exempting certain equipment from the rule.

Impact to industry relative to the cost of compliance with code

This proposed alternative modification will reduce the cost of compliance by exempting certain equipment from the rule.

Impact to small business relative to the cost of compliance with code

Requirements

Has a reasonable and substantial connection with the health, safety, and welfare of the general public

This proposed alternative modification will increase health, safety, and the welfare of the general public by maintaining GFCI protection where it will be most effective while exempting non-compatible equipment.

Strengthens or improves the code, and provides equivalent or better products, methods, or systems of construction

This proposed alternative modification improves the code.

Does not discriminate against materials, products, methods, or systems of construction of demonstrated capabilities

This proposed alternative modification does not discriminate against materials, products, methods, or systems.

Does not degrade the effectiveness of the code

This proposed alternative modification improves the effectiveness of the code.

210.8(F) Outdoor Outlets. All outdoor outlets for dwellings, other than those covered in 210.8(A)(3), Exception to (3) and heating/ventilating/air-conditioning (HVAC) equipment employing power conversion equipment as a means to control compressor speed, that are supplied by single-phase branch circuits rated 150 volts to ground or less, 50 amperes or less, shall have ground-fault circuit-interrupter protection for personnel. ~~This requirement shall become effective on January 1, 2023 for mini-split-type heating/ventilating/air-conditioning (HVAC) equipment and other HVAC units employing power conversion equipment as a means to control compressor speed.~~

Informational Note: Power conversion equipment is the term used to describe the components used in HVAC equipment that is commonly referred to as a variable speed drive. The use of power conversion equipment to control compressor speed differs from multistage compressor speed control.

Exception: Ground-fault circuit-interrupter protection shall not be required on lighting outlets other than those covered in 210.8(C).

SECTION E3408
GFCI PROTECTION

E3408.1 NFPA 70-20: *National Electric Code*, Article 210 (Branch Circuits), Section 210.8, Ground-Fault Circuit-Interrupter Protection for Personnel, is amended to read as follows:

> **210.8 Ground-Fault Circuit-Interrupter Protection for Personnel**. Ground-fault circuit-interrupter protection for personnel shall be provided as required in 210.8(A) through (F). The ground-fault circuit-interrupter shall be installed in a readily accessible location.
>
> … remaining text unchanged
>
> ~~**(F) Outdoor Outlets.** All outdoor outlets for dwellings, other than those covered in 210.8(A)(3), Exception to (3) that are supplied by single-phase branch circuits rated 150 volts to ground or less, 50 amperes or less, shall have ground-fault circuit-interrupter protection for personnel.~~
>
> ~~*Exception: Ground-fault circuit-interrupter protection shall not be required on lighting outlets other than those covered in 210.8(C).*~~

Tentative Interim Amendment

NFPA® 70®

National Electrical Code®

2020 Edition

Reference: 210.8(F)
TIA 20-13
(SC 21-8-29 / TIA Log #1593)

Pursuant to Section 5 of the NFPA *Regulations Governing the Development of NFPA Standards*, the National Fire Protection Association has issued the following Tentative Interim Amendment to NFPA 70®, *National Electrical Code®*, 2020 edition. The TIA was processed by the National Electrical Code Panel 2, and the NEC Correlating Committee, and was issued by the Standards Council on August 26, 2021, with an effective date of September 15, 2021.

1. Revise Section 210.8(F) to read as follows:

210.8 Ground-Fault Circuit-Interrupter Protection for Personnel. …

(F) Outdoor Outlets. All outdoor outlets for dwellings, other than those covered in 210.8 (A)(3), Exception to (3), that are supplied by single-phase branch circuits rated 150 volts to ground or less, 50 amperes or less, shall have ground-fault circuit-interrupter protection for personnel. This requirement shall become effective on January 1, 2023 for mini-split-type heating/ventilating/air-conditioning (HVAC) equipment and other HVAC units employing power conversion equipment as a means to control compressor speed.

Informational Note: *Power conversion equipment* is the term used to describe the components used in HVAC equipment that is commonly referred to as a variable speed drive. The use of power conversion equipment to control compressor speed differs from multistage compressor speed control.

Exception: Ground-fault circuit-interrupter protection shall not be required on lighting outlets other than those covered in 210.8(C).

Issue Date: August 26, 2021

Effective Date: September 15, 2021

(Note: For further information on NFPA Codes and Standards, please see www.nfpa.org/docinfo)

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February 9, 2022

Dear Florida Building Commission,

As of January 1, 2022, 18 of the 20 states that have adopted, or are in processing of adopting, the 2020 National Electrical Code (NEC) have deleted, modified, or delayed the implementation of section 210.8(F), which contains new requirements for ground-fault circuit interrupter (GFCI) protection on outdoor electrical circuits that are supplied by single-phase branch circuits rated 150 volts to ground or less. Specifically, the states that have refused to incorporate the new GFCI requirements in 210.8(F) are OR, WA, CO, TX, ND, SD, MA, IA, UT, GA, OK, SC, OH, MN, ME, NC, NJ and AL.

- Eight states (IA, NC, MA, SD, GA, SC, OK and UT) deleted 210.8(F) in its entirety.
- Four states (OH, ME, OR, and ND) modified 210.8(F).
- Six states (MN, TX, CO, WA, NJ, and AL) delayed the implementation of 210.8(F) until 1/1/2023.
- Two states (RI, DE) have adopted 2020 NEC without addressing 210.8(F).

As Florida considers how to address issues associated with this new 2020 NEC requirement, we refer you to the substantiation used by Massachusetts when they deleted 210.8(F):

> "This addition in the 2020 NEC has not been substantiated. The loss experience supporting this addition to the NEC was based on untrained and unqualified work on an air-conditioning condenser that ended up energized and a thereby caused a boy who jumped a fence and contacted the housing to become electrocuted. GFCI protection saves countless lives and certainly has its place. However, it is a fool's errand to imply to the public that improper work can be rendered essentially safe by waving the GFCI magic wand. For example, contact between two circuit conductors will never trip a GFCI. CMP-2 came within one vote of rejecting this; Massachusetts needs to set it aside and await proper support."

In addition to the above, Minnesota has encountered the same problem of nuisance tripping and issued a tentative interim amendment (TIA) request to the National Fire Protection Association (NFPA) on or about May 14, 2021 (TIA No. 1593). Minnesota's request provided the following rationale:

> "In the state of Minnesota, we began enforcing 210.8(F) on April 5, 2021, and we have already documented many cases of operational tripping occurrences which have been difficult for inspectors and electricians to resolve. The only solution at this time is for the AHJ [Authority Having Jurisdiction] to approve a temporary allowance for the installation of a circuit breaker without GFCI protection so that these HVAC units can operate."

This TIA was approved by the NFPA Code Making Panel 2 (CMP-2) and was issued by the NFPA Standards Council (TIA No. 20-13) in August 2021.

Yet another TIA request was submitted to NFPA on May 14, 2021 by the National Association of Home Builders (NAHB) (TIA No. 1589). The NAHB request notes:

> "The effects of this new requirement in the 2020 edition of the code has come to light over the past 1 to 2 weeks with the first hot/humid weather in Texas. Leading Builders of America (LBA) has collected the following data over the past couple days.
>
>> - Builder A has indicated a 73% failure rate (GFCI breaker tripping) for non-mini-split, non-variable speed systems. In other words, 100% of Builder A's failures are on single-speed conventional cooling systems.
>>
>> - Builder B has 36 homes where the HVAC system is operational. 100% of those homes have experienced a circuit trip. All of Builder B's failures are on single-stage systems. They currently have 10 open warranty tickets for closed (occupied) units where the circuit is tripping consistently, leaving the homeowners with effectively no HVAC."

NAHB goes on to note "In jurisdictions that have adopted 2020 NEC with 210.8(F) intact, there have been numerous instances of field tripping of the GFCI breaker on ductless mini splits, units containing power conversion equipment, and on many single-stage units." This TIA was rejected by NFPA CMP-2 and an appeal to the NFPA Standards Council in August 2021 was rejected.

The Air-Conditioning, Heating, and Refrigeration Institute (AHRI) previously submitted a similar TIA to NFPA (TIA No. 1564) requesting a delay in the effective date of this requirement (as it relates to inverter-driven HVAC equipment) to allow the industry to (1) update certification requirements in UL 943 and UL/CSA 60335-2-40 to address leakage current testing requirements at higher frequencies and (2) to allow manufacturers to make revisions to their equipment (both GFCI breakers and HVAC equipment manufacturers) to comply with new requirements. This TIA request was rejected by NFPA CMP-2, and an appeal was rejected by the NFPA Standards Council in August 2021.

Yet another TIA (No. 1529) was submitted to NFPA in August 2020 by an electrical inspector in Shelby County, Alabama because of the same problem existing in the Birmingham area. This TIA request was approved by CMP-2, for both "Technical Merit" and "Emergency Nature" by a vote of 12-2. However, the Code Correlating Committee unanimously approved the TIA on "correlation" but failed the TIA by a vote of 8-3 (75% required) as to the "emergency nature."

The HVAC industry has experienced many nuisance trips of GFCI breakers operating with inverter-driven HVAC equipment, as well as non-inverter-driven HVAC equipment. 100 percent of all inverter-driven HVAC products that we are aware of, when paired with a GFCI breaker, experience nuisance tripping. As noted in TIA No. 1589, single-stage and two-stage HVAC products also have nuisance tripping when paired with GFCI breakers. The long history of TIA efforts, including three active TIAs, shows that section 210.8(F) is truly problematic.

The NFPA Standards Council (during the AHRI/NAHB Appeals) requested that CMP-2 create a Task Group (including HVAC industry experts, GFCI experts, and other interested parties) to look further into the HVAC/GFCI issue at the urgence of the HVAC industry. The Standards Council expects that the outcome of this Task Group's work will be a new TIA concerning both the 2020 NEC and the 2023 NEC (currently under development).

Technical Justification

HVAC equipment complies with safety standards that have been in use for over 40 years.
Over 90% of HVAC equipment in use today is labeled and listed per UL 1995.[1] Safety standards have ensured that products certified to them are safe. This safety is evidenced by the installation of more than 120 million HVAC units throughout the U.S. in the last twenty years without a documented fatality from equipment that was properly installed by qualified individuals per manufacturer's instructions.[2]

These existing HVAC safety standards focus on the touch current hazard instead of the leakage current in various operating modes and single fault conditions while also ensuring grounding resistance measurements under load.
Specifically:

- UL 1995 clauses 21, 22, 24, 54, 78 and 79 ensure grounding/earthing.
- UL 60335-2-40 (4th ed) sections 13 and 16 cover leakage/electrical strength, while section 27 covers earthing.

Furthermore, GFCI breakers are approved to product safety standard UL 943. This standard specifies leakage current trip requirements only at 60Hz, where a leakage current of 6 mA at 60 Hz must trip the breaker and a leakage current of 4 mA at 60 Hz must not trip the breaker. Leakage current at other frequencies is not addressed by UL 943. As such, there are no test requirements covering additional frequencies used by inverter-driven HVAC equipment.

Air conditioner/heat pumps (AC/HP) are approved to product safety standard UL 1995 which does not specify a maximum for this type of leakage current. UL 1995 is the standard to which all AC/HP have been certified since the early 1990s. There is a new version of standard UL 60335-2-40 (4th edition), earmarked to replace UL 1995, but mandatory compliance with this new standard is not required until January 1, 2024. This new version of the standard UL 60335-2-40 has leakage current requirements but allows up to 10 mA. UL 60335-2-40 4th edition will also contain alternative grounding provisions that continue to ensure safe use and installation without using GFCIs.

The UL Standards Technical Panels (STPs) for both UL 943 and UL 60335-2-40 are addressing the conflict between these two standards, but there is no fixed resolution on the immediate horizon. And

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[1] UL 1995 Heating and Cooling Equipment.

[2] AHRI, Central Air Conditioners and Air-Source Heat Pumps, https://ahrinet.org/resources/statistics/historical-data/central-air-conditioners-and-air-source-heat-pumps (showing the number of central air conditioners installed from 2001 to 2020).

once the standards are modified to resolve the conflict, it will still take time for manufacturers to develop products and get them in the market.

As the committee from Massachusetts noted, the 210.8(F) requirement was added as a result of one incident as a result of "untrained and unqualified work." We note that a CDC report published in 2020 states, "During 2004–2018, an average of 702 heat-related deaths occurred in the United States annually."[3] This CDC report documents 10,527 heat-related deaths in a 15-year period (702/year), and an additional 6,220 deaths where heat was the primary factor (414/year). The CDC report, on pg. 732, further explains that "Past studies have demonstrated a relationship between ambient temperatures and mortality (8). In particular, extreme heat exposure can exacerbate certain chronic medical conditions, including hypertension and heart disease (4,5). In addition, medications that are typically used to treat these chronic medical conditions such as beta-blockers, diuretics, and calcium-channel blockers, can interfere with thermoregulation and result in a reduced ability to respond to heat stress (5)." (*NOTE: The numbers in parenthesis are reference numbers in the CDC document*). It is clear, therefore, that health related concerns associated with heat exposure (lack of cooling) can be significant based on items reported by the CDC.

Recommendation

As such, the HVAC industry recommends that Florida delete 210.8(F) concerning new requirements for ground-fault circuit interrupter (GFCI) protection on outdoor electrical circuits that are supplied by single-phase branch circuits rated 150 volts to ground or less, 50 amperes or less, and to delay incorporating 210.8(F) until a future code cycle when the industry is better prepared to meet these requirements.

Sincerely,

Mary E. Koban

Air-Conditioning, Heating, and Refrigeration Institute
Senior Director Regulatory Affairs
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AHRI
we make life better®

[3] *Heat-Related Deaths – United States, 2004-2018,* Centers For Disease Control and Prevention, Morbidity and Mortality Weekly Report, Vol. 69, No. 24, June 19, 2020, Page 732, available at https://www.cdc.gov/mmwr/volumes/69/wr/pdfs/mm6924a1-H.pdf.

Reference documents:
The following links/summaries document the actions taken by the noted 18 states to delete, modify or delay 210.8(F) in the 2020 NEC.

IA: Section 210.8(F) was deleted in an amendment after adoption
https://dps.iowa.gov/divisions/electrical-examining-board/electrical-code-updates

MA: GFCI protection was removed for outdoor, non-receptacle outlets during the adoption process.
https://www.mass.gov/doc/527-cmr-12-massachusetts-electrical-code-amendments/download

NC (Proposed): Section 210.8(F) is proposed to be deleted when the 2020 edition is adopted later this year.
https://www.ncosfm.gov/media/2068/open - Due to procedural issue – NC remaining on 2017 NEC

ND: An exception is provided for mini-split & A/C units with DC invertors. The installer is required to fill out a form including information describing what the contractor has done to the resolve the issue.
https://www.ndseb.com/

OR: Section 210.8(F) was modified to only apply to outdoor receptacles for other than dwelling units.
https://www.oregon.gov/bcd/codes-stand/Documents/21oesc-table1-E-2021April.pdf

SD: Section 210.8(F) was not adopted with the 2020 NEC.
https://dlr.sd.gov/electrical/documents/adopted_code_2020.pdf

TX: An emergency rule delayed the requirements of Section 210.8(F) effective May 20, 2021.
https://www.sos.state.tx.us/texreg/archive/November122021/Adopted%20Rules/16.ECONOMIC%20REGULATION.html#70
https://www.sos.state.tx.us/texreg/archive/November122021/Adopted%20Rules/16.ECONOMIC%20REGULATION.html#68

UT: Section 210.8(F) is deleted – effective 7/1/2021. Bill SB 0033 signed by Governor 3/16/2021 (see page 29 of link).
https://legiscan.com/UT/text/SB0033/id/2335968/Utah-2021-SB0033-Enrolled.pdf

WA: The state is delaying enforcement of Section 210.8(F) until January 1, 2023.
https://lni.wa.gov/licensing-permits/_docs/Elc2011.pdf

GA: State adopted 2020 NEC effective 1/1/2021. State deleted 210.8(F) due to nuisance tripping issues associated with the expanded GFCI requirements effective 9/1/2021.
https://www.dca.ga.gov/sites/default/files/2021_nec_amendments.pdf

CO: State issued a 1-year temporary Variance to the requirements in 210.8(F) on 6/29/2021.
https://content.govdelivery.com/accounts/CODORA/bulletins/2e613c2

MN: MN adopted TIA 20-13, adding the following statement to 210.8(F) – "This requirement shall become effective on January 1, 2023 for mini-split-type heating/ventilating/air-conditioning (HVAC) equipment and other HVAC units employing power conversion equipment as a means to control compressor speed."

https://www.dli.mn.gov/sites/default/files/pdf/review60fall21.pdf

ME: An exception from these requirements added for heat pumps.
https://up.codes/viewer/maine/nfpa-70-2020/chapter/2/wiring-and-protection#2

DE: Adopted the 2020 NEC at June 2021 meeting and it is effective 9/1/2021.

OK: Deleted 210.8(F) during OUBCC meeting 10/19/2021.
https://www.ok.gov/oubcc/documents/2021%2010%2019%20Meeting%20Minutes.pdf

SC: SC Building Code Council voted to delete 210.8(F) at 10/6/2021 meeting. Amendments to 2020 NEC will be effective 1/1/2023.

NJ: NJ UCC voted to delay the implementation of 210.8(F) until 1/1/2023 unless there is still uncertainty in the practicability of the requirement, in which case the Division can revisit the issue.
https://www.nj.gov/dca/divisions/codes/advisory/pdf_ucc/CAB_minutes_08_13_2021.pdf

OH: Proposal amending 210.8(F) to exempt HVAC units employing power conversion equipment (variable speed drive) as a means to control compressor speed. There is no delay in the proposed amendments so this exclusion would be permanent - not simply delayed until 1/1/2023 per e-mail from OH on 9/2/2021.

AL: Will adopt TIA 20-13 to address concerns over 210.8(F) when completing review/adoption process in 2022.

RI: Effective 2/1/2022, RI adopts the 2020 NEC as the Rhode Island Electrical Code with 210.8(F) intact.
https://rules.sos.ri.gov/Regulations/part/510-00-00-5?reg_id=11323&utm_source=Campaign%3a+Code+Alerts&utm_medium=newsletter&utm_campaign=11+January+2022

NAHB TIA No. 1589 and MN Dept. of Labor and Industry TIA No. 1593
https://www.nfpa.org/codes-and-standards/all-codes-and-standards/list-of-codes-and-standards/detail?code=70

NFPA TIA No. 20-13:
https://www.nfpa.org/codes-and-standards/all-codes-and-standards/list-of-codes-and-standards/detail?code=70

TAC: Electrical

Total Mods for **Electrical** in **Pending Review : 16**

Total Mods for report: 16

Sub Code: Residential

14

E10149

Date Submitted	02/15/2022	**Section**	3408	**Proponent**	Amanda Hickman
Chapter	34	**Affects HVHZ**	No	**Attachments**	Yes
TAC Recommendation	Pending Review				
Commission Action	Pending Review				

Comments

General Comments No **Alternate Language Yes**

Related Modifications

10137

Summary of Modification

GFCI nuisance tripping

Rationale

This modification adds an exception to the current 2020 NEC language regarding the outdoor GFCI requirement [210.8(F)] for listed and labeled HVAC equipment.This proposed exception is urgently needed to prevent nuisance tripping that has and will continue to pose a serious health and safety risk. The sudden and unexpected loss of HVAC cooling in excessive heat due to a tripped GFCI breaker poses a danger to “at risk” populations. This ever-present risk presents a far greater threat to Floridians than does the isolated, non-code compliant incident that was used to justify the addition of 210.8 (F) to the 2020 NEC. The CDC statistics on heat-related deaths shows an annual average of 702 heat-related deaths in the U.S. from 2004 to 2018. LBA strongly encourages the Florida Building Commission to include the proposed HVAC exception or delete the requirement in its entirety to resolve the unintended safety issue caused by the current GFCI requirement.

Fiscal Impact Statement

Impact to local entity relative to enforcement of code

Will improve enforcement of code by resolving the unintended safety issue caused by the current GFCI requirement.

Impact to building and property owners relative to cost of compliance with code

Will reduce cost because GFCI are not required for listed HVAC equipment.

Impact to industry relative to the cost of compliance with code

Will reduce cost because GFCI are not required for listed HVAC equipment.

Impact to small business relative to the cost of compliance with code

Requirements

Has a reasonable and substantial connection with the health, safety, and welfare of the general public

The proposed exception is urgently needed to prevent nuisance tripping that has and will continue to pose a serious health and safety risk.

Strengthens or improves the code, and provides equivalent or better products, methods, or systems of construction

Improves the code because the two technologies are not harmonized.

Does not discriminate against materials, products, methods, or systems of construction of demonstrated capabilities

No, this modification will prevent nuisance tripping and not discriminate against systems of construction.

Does not degrade the effectiveness of the code

Will improve the effectiveness of the code by resolving the unintended safety issue caused by the current GFCI requirement.

Alternate Language

1st Comment Period History

E10149-A1

Proponent Bryan Holland **Submitted** 3/28/2022 9:10:00 AM **Attachments** Yes

Rationale:

It appears the original proposed modification is referencing an older version of section 210.8(F) that has been updated by TIA 20-13, issued by the NFPA Standards Council on August 26, 2021 and that has addressed the concerns expressed by the proponent. However, the current section has a sunset date of January 1, 2023 that I am proposing be deleted to allow the HVAC equipment employing power conversion equipment to remain exempt under the duration of the 8th edition FBC-B. Approval of this alternative code modification assures GFCI protection remains for outlets where shock and electrocution hazards are present while exempting certain equipment that may not be compatible with GFCI protection, at this time.

Fiscal Impact Statement

Impact to local entity relative to enforcement of code

This proposed alternative modification provides clarity to the AHJ on the enforcement of 210.8(F) with regard to HVAC equipment employing conversion equipment.

Impact to building and property owners relative to cost of compliance with code

This proposed alternative modification will reduce the cost of compliance by exempting certain equipment from the rule.

Impact to industry relative to the cost of compliance with code

This proposed alternative modification will reduce the cost of compliance by exempting certain equipment from the rule.

Impact to small business relative to the cost of compliance with code

Requirements

Has a reasonable and substantial connection with the health, safety, and welfare of the general public

This proposed alternative modification will increase health, safety, and the welfare of the general public by maintaining GFCI protection where it will be most effective while exempting non-compatible equipment.

Strengthens or improves the code, and provides equivalent or better products, methods, or systems of construction

This proposed alternative modification improves the code.

Does not discriminate against materials, products, methods, or systems of construction of demonstrated capabilities

This proposed alternative modification does not discriminate against materials, products, methods, or systems.

Does not degrade the effectiveness of the code

This proposed alternative modification improves the effectiveness of the code.

210.8(F) Outdoor Outlets. All outdoor outlets for dwellings, other than those covered in 210.8(A)(3), Exception to (3) and heating/ventilating/air-conditioning (HVAC) equipment employing power conversion equipment as a means to control compressor speed, that are supplied by single-phase branch circuits rated 150 volts to ground or less, 50 amperes or less, shall have ground-fault circuit-interrupter protection for personnel. ~~This requirement shall become effective on January 1, 2023 for mini-split-type heating/ventilating/air-conditioning (HVAC) equipment and other HVAC units employing power conversion equipment as a means to control compressor speed.~~

Informational Note: Power conversion equipment is the term used to describe the components used in HVAC equipment that is commonly referred to as a variable speed drive. The use of power conversion equipment to control compressor speed differs from multistage compressor speed control.

Exception: Ground-fault circuit-interrupter protection shall not be required on lighting outlets other than those covered in 210.8(C).

SECTION E3408
GFCI PROTECTION

E3408.1 NFPA 70-20: *National Electric Code*, Article 210 (Branch Circuits), Section 210.8, Ground-Fault Circuit-Interrupter Protection for Personnel, is amended to read as follows:

210.8 Ground-Fault Circuit-Interrupter Protection for Personnel. Ground-fault circuit-interrupter protection for personnel shall be provided as required in 210.8(A) through (F). The ground-fault circuit-interrupter shall be installed in a readily accessible location.

… remaining text unchanged

(F) Outdoor Outlets. All outdoor outlets for dwellings, other than those covered in 210.8(A)(3), Exception to (3) that are supplied by single-phase branch circuits rated 150 volts to ground or less, 50 amperes or less, shall have ground-fault circuit-interrupter protection for personnel.

Exception No. 1: Ground-fault circuit-interrupter protection shall not be required on lighting outlets other than those covered in 210.8(C).

Exception No. 2: GFCI protection shall not be required for listed and labeled HVAC equipment.

Informational Note: See UL 60335-2-40, Household And Similar Electrical Appliances – Safety – Part 2-40:Particular Requirements for Electrical Heat Pumps, Air-Conditioners and Dehumidifiers or UL 1995, Heating and Cooling Equipment for product safety standards.(1)

Tentative Interim Amendment

NFPA® 70®

National Electrical Code®

2020 Edition

Reference: 210.8(F)
TIA 20-13
(SC 21-8-29 / TIA Log #1593)

Pursuant to Section 5 of the NFPA *Regulations Governing the Development of NFPA Standards*, the National Fire Protection Association has issued the following Tentative Interim Amendment to NFPA 70®, *National Electrical Code*®, 2020 edition. The TIA was processed by the National Electrical Code Panel 2, and the NEC Correlating Committee, and was issued by the Standards Council on August 26, 2021, with an effective date of September 15, 2021.

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Exception: Ground-fault circuit-interrupter protection shall not be required on lighting outlets other than those covered in 210.8(C).

Issue Date: August 26, 2021

Effective Date: September 15, 2021

(Note: For further information on NFPA Codes and Standards, please see www.nfpa.org/docinfo**)**

TAC: Electrical

Total Mods for **Electrical** in **Pending Review : 16**

Total Mods for report: 16

Sub Code: Residential

15

E10244

Date Submitted	02/11/2022	**Section**	3401.5	**Proponent**	John Lovett
Chapter	34	**Affects HVHZ**	No	**Attachments**	Yes
TAC Recommendation	Pending Review				
Commission Action	Pending Review				

Comments

General Comments Yes **Alternate Language No**

Related Modifications

Summary of Modification

drop arc fault (circuit breakers and receptacles) requirment

Rationale

Majority of the trips are nuisance trips. Not constant. Only constant trips I've experienced with arc fault protection are either from an overcurrent or from a direct short. Same protection he would get with a standard trip breaker. No documented proof (that I know of) of arc fault protection actually preventing any fires, but there is very much proof of arc fault protection having nuisance trips. Actually causes a problem and doesn't prevent anything. Causes more problems than was meant to rectify. Documented proof of causing problems and no documented proof of solving problems. "Upgrading" (to AFCI protection), the NEC has downgraded the integrity of any circuit with arc fault protection. Arc fault protection is supposed to detect a spark. Once the spark is already happened it's too late. Like saying, "hello" to somebody after they've walked by you. Michigan and Indiana have completely dropped the requirement. Cost money. Every time nuisance trip being called by homeowner. Creates heat. Causes bus bars to burn over time. A first responder told me that when they cannot find a specific cause of a fire they fill in the blank with “electrical fire”. Have to fill in the blank. Reason there are so many documented electrical fires. Cost money. Every time nuisance trip being called by homeowner. Like taking a medication that causes more side effects than there are symptoms.

Fiscal Impact Statement

Impact to local entity relative to enforcement of code

wouldn't effect either way.

Impact to building and property owners relative to cost of compliance with code

Material would cost less. This would eliminate "nuisance trips" which would save homeowners time, frustration, and money.

Impact to industry relative to the cost of compliance with code

Would eliminate "nuisance trips". Every time the ARC fault breaker trips, the homeowner will be calling the electrician. this could be totally eliminated by this proposal

Impact to small business relative to the cost of compliance with code

Requirements

Has a reasonable and substantial connection with the health, safety, and welfare of the general public

no

Strengthens or improves the code, and provides equivalent or better products, methods, or systems of construction

eliminate "nuisance trips". Every time the ARC fault breaker trips, the homeowner will be calling the electrician. could be eliminated by this proposal. Material would cost less. would eliminate "nuisance trips" .would save homeowners time, frustration, and money.

Does not discriminate against materials, products, methods, or systems of construction of demonstrated capabilities

no

Does not degrade the effectiveness of the code

no

1st Comment Period History

E10244-G1

Proponent	Bryan Holland	Submitted	3/28/2022 8:52:32 AM	Attachments	No

Comment:

NEMA strongly opposes this proposed modification. AFCI protection is a fundamental fire-safety component of a premises wiring system. Deletion of these sections will result in an increased risk of fire as a result of unmitigated arcing-faults in branch circuits, outlets, appliances, and other utilization equipment. The reports of unwanted tripping have not been substantiated by the proponent. Guidance and other AFCI protection related resources have been shared with the proponent to assist him with the proper installation and troubleshooting of AFCI protected branch circuits in new and existing dwellings. NEMA urges the Electrical TAC and Commission reject this proposed modification.

210.12 Arc-Fault circuit-interrupter protection. ~~**Arc-fault circuit-interrupter protection shall be provided as required in 210.12(A), (B), (C), and (D). Arc-fault circuit-interrupter shall be installed in a readily accessible location.**~~

210.12(A) Dwelling units.~~**All 120 volt, single Phase, 15 and 20 ampere branch circuit supplying outlets or devices installed and dwelling unit kitchens, family rooms, dining rooms, living rooms, parlors, libraries, dens, bedrooms, sunrooms, recreation rooms,Closets, hallways, laundry areas, or similar rooms or areas shall be protected by any of the means described in 210.12 (A)(1) through (6)**~~

406.4(4) Arc-Fault circuit interrupter protection. ~~**If a receptacle outlet located in any area specified in 210.12 (A), (B) or (C) is replaced, a replacement receptacle at this outlet she'll be one of the following:(1) a listed outlet branch-circuit type arc-fault circuit-interrupter receptacle(2) A receptacle protected by a listed outlet branch-circuit type arc-fault circuit-interrupter type receptacle(3) A receptacle protected by a listed combination type arc-fault circuit- interrupter type circuit breaker**~~

SILVER STRAND ELECTRIC, INC.
117 POINSETTIA ST.
ATLANTIC BEACH, FL.
32233
LIC.# EC13003769

RE: Arc Fault Protection

2020 NEC

210.12 **Arc-Fault circuit-interrupter protection.** ~~Arc-fault circuit-interrupter protection shall be provided as required in 210.12(A), (B), (C), and (D). Arc-fault circuit-interrupter shall be installed in a readily accessible location.~~

210.12(A) **Dwelling units**. ~~All 120 volt, single Phase, 15 and 20 ampere branch circuit supplying outlets or devices installed and dwelling unit kitchens, family rooms, dining rooms, living rooms, parlors, libraries, dens, bedrooms, sunrooms, recreation rooms,~~
~~Closets, hallways, laundry areas, or similar rooms or areas shall be protected by any of the means described in 210.12 (A)(1) through (6)~~

406.4(4) Arc-Fault circuit interrupter protection. ~~If a receptacle outlet located in any area specified in 210.12 (A), (B) or (C) is replaced, a replacement receptacle at this outlet she'll be one of the following:~~

~~(1) a listed outlet branch-circuit type arc-fault circuit-interrupter receptacle~~

~~(2) A receptacle protected by a listed outlet branch-circuit type arc-fault circuit-interrupter type receptacle~~

~~(3) A receptacle protected by a listed combination type arc-fault circuit- interrupter type circuit breaker~~

E10244Text Modification

Mod_10244_Text_striked arc fault.pdf

Page: 2

SILVER STRAND ELECTRIC, INC.

117 POINSETTIA ST.

ATLANTIC BEACH, FL.

32233

LIC.# EC13003769

Majority of the trips are nuisance trips. Not constant. Only constant trips I've experienced with arc fault protection are either from an overcurrent or from a direct short. Same protection he would get with a standard trip breaker.

No documented proof (that I know of) of arc fault protection actually preventing any fires, but there is very much proof of arc fault protection having nuisance trips. Actually **causes** a problem and doesn't prevent anything.

Causes more problems than was meant to rectify. **Documentedproofof causingproblemsandno documentedproofof solvingproblems.**

"Upgrading" (to AFCI protection), the NEC has **downgraded** the integrity of any circuit with arc fault protection.

Arc fault protection is supposed to detect a spark. Once the spark is already happened it's too late. Like saying, "hello" to somebody after they've walked by you.

Michiganand Indiana have completelydroppedthe requirement.

Cost money. Every time nuisance trip being called by homeowner.

Creates heat. Causes bus bars to burn over time.

A first responder told me that when they cannot find a specific cause of a fire they fill in the blank with “electrical fire”. Have to fill in the blank. Reason there are so many documented electrical fires.

Cost money. Every time nuisance trip being called by homeowner.

Like taking a medication that causes more side effects than there are symptoms.

TAC: Electrical

Total Mods for **Electrical** in **Pending Review : 16**

Total Mods for report: 16

Sub Code: Residential

16

E10437

Date Submitted	02/14/2022	**Section**	4204.2	**Proponent**	Douglas Dorr
Chapter	42	**Affects HVHZ**	No	**Attachments**	Yes
TAC Recommendation	Pending Review				
Commission Action	Pending Review				

Comments

General Comments Yes **Alternate Language No**

Related Modifications

Summary of Modification

The proposed amendment clarifies that a single bare copper wire should only be used for bonding at above ground pools and a wire mesh or grid is necessary for inground pool perimeter surfaces

Rationale

This amendment brings the requirement for equipotential bonding of the perimeter surface of the pool equal to that of the pool shell and is the only safe way to achieve equal voltage potential between the water and the perimeter walking/sitting surfaces. The amendment for the 2020 article 680 leaves the new alternate means (c) as the only alternative to reinforcing steel as a method of providing the required equipotential bonding environment for perimeter pool surfaces for in-ground swimming pools. This method is recommended by IEEE 1695-2016 Guide to Understanding Diagnosing and Mitigating Stray and Contact Voltages. Further, the both the wire mesh and the single wire ring have been extensively studied and tested by three research organizations including EPRI, NEETRAC and Enernex. All three organizations concluded that a single bare copper conductor is inadequate for mitigating shock hazards and fibrillation level currents through a human body. Under tests witnessed by NEC Panel representatives and by IEEE representatives, the copper ring wire bond, described in NEC article 680.26 allowed an 80 mA current to flow through a resistance that approximated the resistance of a human appendage in contact with a concrete walk surface. When the same test was run with the wire bond out of the circuit, and a copper grid as described in NEC 680.26 as alternate means (c) connected, the result was 3 mA current flow. This difference is over an order of magnitude, and the difference between minor discomfort and lethality. It is unusual to have such convincing test results that support a change in the NEC. The ring option would remain for above ground pools, which do not present the same step-off risks.

Fiscal Impact Statement

Impact to local entity relative to enforcement of code

No expected impact to existing inspection and enforcement criteria beyond educational training

Impact to building and property owners relative to cost of compliance with code

If a copper grid is added instead of the copper ring, the amount of wire needed is five to six times the length of the single copper wire. If the cost is 80 dollars per pool the wire grid would be 400 to 480 dollars per pool

Impact to industry relative to the cost of compliance with code

No determinable impact

Impact to small business relative to the cost of compliance with code

Requirements

Has a reasonable and substantial connection with the health, safety, and welfare of the general public

The modification will result in fewer shock a complaints, fewer pools where the deck needs to be removed, and will save lives when GFCIs fail to operate. The voltages will not go away, but the water and the deck surfaces will attain exactly the same potential during the fault conditions

Strengthens or improves the code, and provides equivalent or better products, methods, or systems of construction

The modification strengthens the code to the previous criteria not present since the 2005 version of the NEC

Does not discriminate against materials, products, methods, or systems of construction of demonstrated capabilities

N/A

Does not degrade the effectiveness of the code

N/A

1st Comment Period History

E10437-G1

Proponent	Bryan Holland	Submitted	3/28/2022 9:46:08 AM	Attachments	No

Comment:

NEMA opposes this proposed modification. Several public inputs of this nature were submitted to both the 2020 and 2023 NEC development cycles. In both cases, the limiting of 680.26(B)(2)(b) to above ground pools only was rejected by CMP-17. Here is the statement made by CMp-17 for the 2023 NEC development cycle when addressing this matter: "CMP-17 reaffirms that a copper bonding grid is not justified for perimeter bonding to the exclusion of other alternate means presently permissible. CMP-17 has seen no evidence of incidents resulting in death or injury attributed to use of the alternate bonding means presently permitted. Insufficient technical substantiation has been provided to make the requested change. The supplied report does not appear to provide any new substantive technical information indicating the existing methods are inadequate and have led to injury or death, compared to similar reports that were submitted in previous revision cycles." NEMA agrees with CMP-17 and urges the TAC(s) and Commission to reject this proposed modification.

Amend the forthcoming adoption of the 2020 version of the NEC into the bonding section of with the below prescription of applicability:

680.26(B)(2)(b). Insert an additional paragraph to follow the five-item list and reading as follows:

> "(6) This method using the single bare copper conductor shall only be permitted for above-ground pools."

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EPRI Stray and Contact Voltage Public Safety Bulletin October 2021

Recent measurements at two newly constructed in-ground swimming pools emphasize the safety hazard caused by following the minimum requirements of the 2020 National Electrical Code (NEC) Article 680-26. The liners of the subject in-ground pools were vinyl, and one was "closed to swimming" by the local utility until the owner could eliminate the injury and drowning hazard by installing more robust retrofit equipotential means. Such pool closures are driven by both injury and drowning concerns whereby the pool users could either a) become incapacitated while in the water or b) suffer a startle-and-fall reaction by standing on the wet deck and contacting the bonded metal objects or the pool water. These two concerns are supported more completely in the discussion within the remaining sections of this document.

The unfortunate part of these investigations for the pool owners is that injury and drowning hazards at their new pools could easily have been avoided if the NEC were not deficient in its minimum requirements. Further, the tens of thousands of dollars in costs to remove the surface decking and then install a suitable and code-compliant equipotential wire mesh could have been avoided had the NEC's minimum requirement not been deficient.

Pool Number One: The pool owner's children complained of a severe burning sensation the very first time they swam in their new pool and simultaneously made contact with the deck. Investigators measured up to 10 Vac between the pool water and the walking surfaces, even though the pool was properly constructed and bonded using the minimum criterion in NEC 680.26, which is the "alternate means," a single bare-copper conductor. Similarly, the voltage between a metal deck handrail and the concrete walking surface was up to 10 Vac. This pool was closed until a gridded copper mesh complying with the NEC 680.26 alternate means could be installed. At its Lenox Stray and Contact Voltage Test Laboratory in Massachusetts, EPRI researchers verified the efficacy of a gridded mesh to eliminate the injury hazard for human contact between the handrail and deck and the drowning hazard for swimmer contacts between the water and the deck.

Some notable discussion on this pool investigation includes the following:

1. Before incurring the high costs of removing the concrete deck around the pool perimeter and installing the wire grid, the pool contractor tried other, less costly fixes by installing an additional water bond in the circulating system near the pump and then installing a buried copper ring with ground rods around the perimeter of the pool deck. Neither retrofit eliminated the shock hazard and the danger to swimmers.
2. The negligible voltage measured between the handrail on the deck and the pool water indicated that both were properly bonded together through the buried, solid bare-copper wire allowed by the code. However, each element still measured up to 10 Vac with respect to the surrounding deck and with respect to a remote earth reference point. This clearly points out the deficiency of using a single wire buried in the subgrade to bond the walking surfaces.
3. The key insight here is that there will always be voltages present at properly bonded swimming pools. Therefore, bonding all conductive components ensures that the voltage between the components is always negligible. At the same time, the only way to get the deck walking surface to that same equipotential is with a gridded wire mesh.

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Pool Number Two: The pool owner complained of a shock and burning sensation when standing on the wet earth and touching the metal coping around his new pool during the construction phase. This shock report occurred after the pool's electrical and bonding inspection had been inspected and approved but prior to the builder installing the pool deck. The contractor's electrician subsequently measured up to 5 Vac between the metal portion of the coping and the subgrade walking surfaces. Fortunately, this issue was caught before the deck was finished and the NEC 680.26 alternate means (using a gridded copper mesh) was installed to eliminate the injury hazard for human contact between any bonded handrails and deck and the drowning hazard for swimmer contacts between the water and the deck. Once the gridded wire mesh was installed and the surface regraded, the electrician re-measured, and the voltages between the coping and the subgrade were negligible. Some notable discussion includes the following:

1. Had the pool owner not inadvertently caught the shock concern prior to pool completion, the costs for a retrofit solution would have been significantly greater.
2. Even though just millivolts are now measurable between the bonded coping and the bonded grid, the 5 Vac is still present between all bonded elements and remote earth. Because the elements are properly bonded, negligible voltage difference is measurable between those elements.
3. The measured 5 Vac was just a snapshot in time. This voltage can increase or decrease seasonally and can elevate to over 100 Vac during residential fault conditions.

Why does the NEC still allow the *unsafe* single-wire alternate means for walking surfaces?

This serious flaw in the 2020 National Electrical Code was intentionally enabled by the code-making panel responsible for Article 680.26 (CMP 17). The group initially voted in favor of allowing *only* a metal wire grid for equipotential bonding of walking surfaces. This vote followed supporting presentations by six independent subject-matter experts at the final draft meeting for the 2020 NEC. The following day, after all of the subject-matter experts were no longer present, CMP 17 inexplicably re-added the deficient option for installers to use a single bare-copper conductor for new pool construction *when rebar is not available*. This single bare-wire option is the reason that the pools described in this safety briefing (and thousands of others constructed in this way) are dangerous for swimmers and other pool users.

New Supporting EPRI R&D

One clear conclusion from EPRI's extensive testing on equipotential bonding is that *voltage equipotential between water and pool decking is not possible with a single bare conductor under any circumstance*. To support this conclusion, EPRI validated this finding at its Lenox laboratory in the summer of 2021 by constructing new test areas around a test swimming pool by employing both options described in Article 680.26 (NEC 2020). The testing resulted in three significant takeaways:

- The single bare wire is marginally better than no equipotential bonding wire at all, and pool installers and owners can expect over 100 milliamps of shock current under any residential fault condition.
- The alternate means (grid option) reduces the shock hazard to less than six milliamps of current under any residential fault condition.

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- An enhanced alternate means—with a 6x6-inch wire grid option—performs even better than the 12x12-inch wire grid, and one should expect less than 2 milliamps of shock current with this configuration under any residential fault condition.
- Finally, the closer to the surface the grid is installed, the better it performs (regarding equipotential performance). Therefore, EPRI now recommends a maximum dimension of a 6x6-inch grided mesh for new inground pool construction, either embedded in the concrete pour or placed within the first inch of any subgrade.

To support the data represented in this document, EPRI can supply videos and data from the described measurements upon request to ddorr@epri.com.