# Common Faults and Their Prioritization in Small Commercial Buildings

## February 2017 — December 2017


Janghyun Kim, Jie Cai, and James E. Braun

*Purdue University*
*West Lafayette, Indiana*


NREL Technical Monitor: Stephen Frank


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NATIONAL RENEWABLE ENERGY LABORATORY

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# Nomenclature

| | |
|---|---|
| $\alpha$ | energy usage fraction, dimensionless |
| $\beta$ | fuel fraction, dimensionless |
| AC | air conditioning |
| AEC | annual energy consumption, trillion Btu/yr |
| AEI | annual energy impact of a fault, trillion Btu/yr |
| AFC | annual financial cost, $/yr |
| AFDD | automated fault detection and diagnosis |
| AFI | annual financial impact of a fault, million $/yr |
| Btu | British thermal unit |
| C | equipment cost, $/kWh |
| Cap | capacity, kW |
| CBECS | Commercial Buildings Energy Consumption Survey |
| COP | coefficient of performance, dimensionless |
| EI | energy intensity, thousand Btu/$ft^2$ |
| FC | fuel cost, $/Btu |
| FlrArea | floor area, $ft^2$ |
| Prev | prevalence (frequency), dimensionless |
| HVAC | heating, ventilation, and air conditioning |
| Load | load, kWh |
| r | ratio, dimensionless |
| RTU | rooftop unit |
| SHR | sensible heat ratio, dimensionless |
| t | annual run time, hours |
| VAV | variable air volume |



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**Subscripts**

| | |
|---|---|
| annual | annual |
| base | baseline |
| cap | capacity |
| equip | equipment |
| fault | fault |
| utility | utility |
| LCC | life-cycle cost |
| load | load |
| rated | rated |
| runtime | run time |
| sen | sensible |
| SHR | sensible heat ratio |



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# Executive Summary

Opportunities for saving energy and money with automated fault detection and diagnosis (AFDD) are significant in the small commercial-building sector because small commercial buildings consume almost 20% of all the energy used in commercial buildings in the United States. However, these benefits are difficult to achieve due to the limited availability of cost-effective AFDD tools for small commercial buildings.

To support an ongoing project at the National Renewable Energy Laboratory titled "An Open, Cloud-Based Platform for Whole-Building Fault Detection and Diagnostics" (work breakdown structure number 3.2.6.18 funded by the U.S. Department of Energy's Building Technologies Office), this report documents faults that are commonly found in small commercial buildings (with a floor area of 10,000 $ft^2$ or less) based on a literature review and discussions with building-commissioning experts. It also provides a list of prioritized faults based on an estimation of the prevalence, energy impact, and financial impact of each fault. A total of 47 faults are reviewed in this report and classified by location (building envelope; heating, ventilation, and air conditioning [HVAC]; or lighting system), stage (design or operational), and type (building, equipment, control, or sensor). The technical complexity of detecting each type of fault based on typically available information was evaluated for each fault. Modeling feasibility within EnergyPlus™ and OpenStudio® and model validation feasibility were also evaluated.

The annual energy impact (AEI) and annual financial impact (AFI) of each fault were estimated based on available information. Both AEI and AFI represent nationwide annual impacts for all small commercial buildings. AEI was calculated by estimating the amount of excess energy (site energy) that is consumed due to faulted operation, and AFI was calculated by including the increased energy cost and equipment life-cycle cost due to faulted operation. Best estimations were made from available literature for parameters such as prevalence of fault, efficiency degradation, capacity degradation, sensible heat ratio (SHR) degradation, load increase, equipment unit cost, equipment efficiency, equipment life span, and equipment operating hours for AEI and AFI estimations. Based on these estimations, 20 top-priority faults that apply to packaged units, control systems, sensor devices, lighting systems, or building envelopes were identified as shown in Table ES 1, rank-ordered by AEI value.



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**Table ES 1. Prioritized List of 20 Top-Priority Faults**

| Fault | AEI, trillion Btu/yr | AFI, million $/yr |
|---|---|---|
| Excessive infiltration through the building envelope | 47.00 | 1,127 |
| Air-duct leakage | 40.92 | 1,047 |
| Incorrect HVAC on/off modes | 22.50 | 920 |
| Nonstandard refrigerant charging | 14.56 | 587 |
| Inappropriate lighting schedules | 13.16 | 393 |
| Inappropriate set points/schedule for thermostats | 12.04 | 492 |
| Condenser fouling | 5.35 | 274 |
| Insufficient evaporator airflow | 5.19 | 914 |
| Inappropriate electric line voltage | 3.82 | 355 |
| Oversized equipment at design | 3.27 | 90 |
| Improper time-delay setting in occupancy sensors | 2.91 | 87 |
| Biased zone temperature sensor | 1.90 | 60 |
| Compressor flow fault | 1.87 | 244 |
| Economizer damper stuck at certain position | 1.75 | 53 |
| Fan motor degradation | 1.25 | 128 |
| Refrigerant liquid line restriction | 1.12 | 133 |
| Presence of non-condensable in refrigerant | 0.98 | 29 |
| Condenser fan degradation | 0.43 | 91 |
| Biased economizer sensor | 0.18 | 56 |
| Occupancy-sensor malfunction | 0.05 | 1 |

Excessive infiltration through the building envelope has the greatest impact with the highest prevalence, AEI, and AFI. Air-duct leakage has the second-largest energy impact, and this fault is very common in rooftop units, causing higher energy use for both heating and cooling. Three other building operation faults—incorrect HVAC on/off modes, inappropriate set points/thermostat schedules, and zone temperature sensor bias—are also among the 20 top faults in terms of energy and financial impact. In addition, inappropriate lighting schedules/controls are top-priority faults with substantial energy and financial impacts. Seven out of the 20 top-priority faults occur in vapor-compression systems such as air-conditioning, heat-pump, and refrigeration equipment. Nonstandard charging, condenser, and evaporator fouling are the most prominent faults in this type of equipment, which is most likely the reason that AFDD for vapor-compression systems has been studied extensively.

Relatively comprehensive information is available in the literature for faults in space heating and cooling equipment, so their national energy and financial impact estimations should be reasonably accurate. However, there are several weak points that cannot be improved due to the



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lack of high-quality data in the literature. The project team will address these shortfalls during the course of this project if pertinent information becomes available.

- In the refrigeration fault analysis, this study used the same prevalence and energy-impact values as the respective faults in rooftop units or split systems. It is believed to be the best estimate without any solid data from the literature. However, the actual fault prevalence could be significantly different between a refrigeration unit and an air-conditioning system, or even between a freezer and refrigerator. For example, the possibility or prevalence of condenser fouling may be much lower for many refrigeration units when the condenser is placed in a clean, controlled environment, whereas an air-conditioning system always has its condenser outdoors, leading to a better chance of condenser fouling.
- Chiller faults have been studied considerably in the past, and relatively complete information is available for calculating the national energy impact. However, chillers are rarely used in small commercial buildings, leading to almost zero national energy impact for all chiller faults.
- This report covers a number of faults in direct-expansion vapor-compression system-based equipment; however, only a few faults associated with other space cooling or heating equipment are included.
- Although material, installation, and maintenance costs are the main factors for estimating the equipment's life cycle cost increase due to each fault, only material and installation costs were included. Maintenance cost was not included in the financial-impact estimation.
- Parameters such as prevalence, efficiency degradation, capacity degradation, SHR degradation, load increase, equipment life span, and equipment operating hours were estimated using the information available, and best estimates were made for faults when data for these parameters were unavailable.



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# 1 Introduction

Small commercial buildings with a floor area of 10,000 $ft^2$ or less are responsible for almost 20% of total commercial-building energy consumption in the United States (CBECS 2017). There are significant energy and economic savings opportunities in the small commercial-building sector associated with automated fault detection and diagnosis (AFDD). Although there are reports that focus on the benefits of AFDD for the entire commercial-building sector (Roth et al. 2004, 2005), AFDD benefits for the small commercial -building sector are more difficult to achieve because of the limited availability of cost-effective AFDD tools specifically tailored to small commercial buildings (Frank et al. 2018). However, the approaches that were used in these previous reports are useful for analyzing the impacts of faults for the small commercial-building sector. Roth et al. (2004, 2005) quantified the national energy impact of 13 different faults in buildings, and their impact varied between 4% and 18% of the commercial buildings' heating, ventilation, and air-conditioning (HVAC); lighting; and refrigeration energy consumption. "Lights or HVAC left on when space unoccupied" and "duct leakage" were identified as major faults contributing significantly to the entire commercial-building sector's energy consumption.

Using a similar approach, faults that are commonly seen in small commercial buildings were surveyed based on a literature review and discussions with building-commissioning experts. This report documents the faults and prioritizes them based on an analysis of prevalence, energy impact, financial impact, technical complexity, and modeling feasibility within EnergyPlus™ and OpenStudio®, the U.S. Department of Energy's flagship energy-simulation software tools. To support the development of model-based AFDD tools as well as the standardized assessment of fault impacts, the team will study and model a subset of the top-priority faults identified in this document using OpenStudio; these models will be validated using laboratory tests or field data. More broadly, the current project aims to develop a model-based AFDD platform that leverages whole-building, physics-based energy models to provide AFDD with fewer sensors than traditional and rule-based methods require. Use of physics-based modeling within an AFDD tool is more precise when accurate and consistent physical models for common building faults are available.



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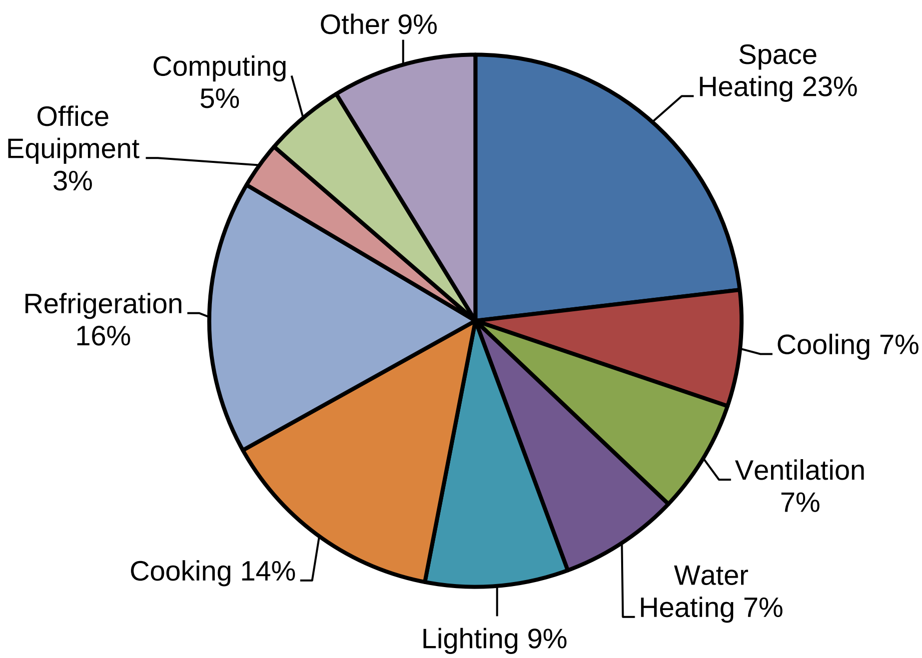
# 2 Overview of Small Commercial Buildings

The current project focuses on small commercial buildings with a floor area of 10,000 $ft^2$ or less. Small commercial buildings in the United States consume 1.37 quadrillion Btu (quads) of site energy each year (about 3 quads of primary energy consumption), which is close to 20% of the total energy use in the commercial building sector (Table A1 in Appendix A) (CBECS 2012a). The total floor space for small commercial buildings under consideration here is 16.9 billion $ft^2$—about 19.5% of the total commercial-building floor space (Table A2 [CBECS 2012b] and Table A3 [CBECS 2012c] in Appendix A). Figure 1 shows energy consumption in small commercial buildings by end use; the detailed breakdowns are provided in Table A1 in Appendix A. Space heating (0.31 quads) and refrigeration (0.22 quads) are the two largest end uses in this building sector. Although cooking consumes significant energy (0.19 quads), literature related to cooking-equipment faults was not available, and it is not included in the scope of this study. End-use energy for lighting (0.12 quads), space cooling (0.1 quads), and ventilation (0.09 quads) have similar magnitudes. The HVAC equipment together consumes 37% of total energy for small commercial buildings; therefore, HVAC-related faults are extensively studied in this project. Lighting and refrigeration faults are also considered.




Source: CBECS 2012a

**Figure 1. Energy consumption in small commercial buildings by end use**



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# 3 Common Faults in Small Commercial Buildings

Through literature review and discussions with building-commissioning experts, a list of faults commonly found in small commercial buildings was obtained. This section provides a high-level introduction to the major faults by category.

Table B1 in Appendix B includes detailed information for all considered faults. “Location” in the first column of Table B1 categorizes faults based on where the fault occurs in the building system (e.g., envelope, general HVAC, rooftop unit [RTU], split system, lighting, refrigeration). Chiller faults are not included in this report because the portion of small commercial buildings that use central chillers is negligible. “Fault stage” in the second column of Table B1 categorizes faults based on the stage when the fault occurs. A design-stage fault is one that occurs before the equipment is installed, such as undersizing of equipment or inadequate sealing of the building for infiltration. An operation-stage fault occurs after the equipment is installed. “Fault type” in the third column of Table B1 categorizes faults based on the type of device in which the fault occurs (building, equipment, control, or sensor). The last three columns are references for equipment-type classification in the Commercial Buildings Energy Consumption Survey (CBECS) according to different energy usages such as heating, cooling, ventilation, lighting, and refrigeration. These references were used to estimate the annual energy consumption (AEC) of equipment related to each fault, as described in Section 4.1.

## 3.1 Building-Envelope Faults

### *3.1.1 Design-Stage Fault*

#### *3.1.1.1 (Building Fault) Excessive Infiltration through the Building Envelope*

Excessive infiltration through the building envelope occurs through the unintentional introduction of outside air into a building, typically through cracks in the building envelope and through doors and operable or leaky windows. Infiltration is driven by pressure differences between the outdoors and the building interior caused by wind and by air-buoyancy forces commonly known as the stack effect (ASHRAE 2005). Excessive infiltration can affect thermal comfort, indoor air quality, and heating and cooling demand. It can also cause moisture damage in building-envelope components (Emmerich, McDowell, and Anis 2005).

## 3.2 General HVAC Faults

### *3.2.1 Design-Stage Fault*

#### *3.2.1.1 (Sensor Fault) Misplaced Thermostats or Temperature-Control Input Error*

A thermostat in an occupied space in a building controls the space conditioning system to maintain a comfortable local temperature. The location of the thermostat can impact the heating and cooling energy demand, as well as occupant thermal comfort. A poorly positioned thermostat can misrepresent the overall condition in the space, which leads to high total energy consumption through overcooling or overheating of the space. This can also occur when multiple thermostats are connected to conditioning equipment that does not serve the zones where the thermostats are located.



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### 3.2.2 Operation-Stage Faults

#### 3.2.2.1 (Control Fault) Incorrect HVAC On/Off Modes and Inappropriate Set Points/Schedules for Thermostats

Thermostat schedules are employed to change the thermostat set point for comfort during occupied hours and for energy savings during unoccupied hours, to switch fan operation from being continuously on during occupied times to being coupled to cooling or heating demands at other times, and to closing ventilation dampers during unoccupied periods. Faults can occur due to malfunctioning, unprogrammed, or incorrectly programmed or scheduled thermostats that lead to increased energy consumption and/or compromised comfort and air quality.

#### 3.2.2.2 (Sensor Fault) Biased Zone Temperature Sensor

Drift of the thermostat temperature sensor over time can lead to increased energy use and/or reduced occupant comfort.

## 3.3 Rooftop Unit and Split-System Faults

This subsection describes faults considered in this report that occur in either packaged RTUs or in split systems. Because these two systems both employ vapor-compression cycles, they have many faults in common. However, an RTU system delivers conditioned air from a packaged outdoor unit to indoor spaces, whereas in a split system, air conditioning (AC) or heating (in heat-pump mode) occurs in an indoor air-handling unit that is connected to an outdoor unit with refrigerant piping. Therefore, some faults primarily affect RTUs and have relatively small fault impacts for split systems. For example, air-duct leakage has a relatively small impact for split systems when air ducts are located entirely within the building, as is common in the commercial sector. A portion of the RTU air-distribution system is located outdoors, however, and air-duct leakage can have a significant impact on energy usage. There are studies in the literature for both systems, so the energy impacts of the RTU and split systems are expressed separately in Appendix B. In this study, split systems include heat pumps and residential-type air conditioners.

### 3.3.1 Design-Stage Fault

#### 3.3.1.1 (Equipment Fault) Oversized Equipment at Design

Oversizing heating and cooling equipment is a commonly accepted practice in real-world applications. In a previous study (Felts and Bailey 2000), more than 40% of the units surveyed were oversized by more than 25%, whereas 10% were oversized by more than 50%. System oversizing can ensure that the highest heating and cooling demands are met. Excessive oversizing of units can also lead to increased equipment cycling that results in increased energy use due to efficiency losses.

### 3.3.2 Operation-Stage Faults

#### 3.3.2.1 (Equipment Fault) Air-Duct Leakages

Leakage of air into (out of) the supply (return) air duct can be caused by torn or missing external duct wrap, poor workmanship around duct takeoffs and fittings, disconnected ducts, improperly installed duct mastic, and temperature and pressure cycling (Roth et al. 2004). Conditioned air leaking into an unconditioned space in buildings increases the equipment heating or cooling demand and can increase fan power for variable air volume (VAV) systems.



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#### 3.3.2.2 (Equipment Fault) Air-Handling Unit Fan Motor Degradation

Fan motor degradation decreases motor efficiency, which increases overall fan power consumption.

#### 3.3.2.3 (Equipment Fault) Compressor Flow Fault

A compressor flow fault is a reduction in the volumetric flow of the compressor typically caused by internal leakage from high- to low-pressure regions within a compressor. This leakage can occur across suction or discharge valves for compressors that employ valves (e.g., reciprocating) or between high- and low-pressure pockets within rotary, scroll, or screw compressors. This fault causes degradation in cooling capacity and efficiency that is not typically detected until comfort is compromised.

#### 3.3.2.4 (Equipment Fault) Condenser Fan Motor Degradation

Motor efficiency degrades when a motor suffers from a bearing or a stator winding fault. These faults cause the motor to draw higher current from the electricity supply without changing the fluid flow. In other words, they reduce the motor efficiency for converting electricity into mechanical energy without affecting the volumetric flow rate of the fan or pump driven by the motor.

#### 3.3.2.5 (Equipment Fault) Condenser Fouling

Condenser fouling occurs when litter, dirt, or dust accumulates on or between the fins of a condenser of an air conditioner located in the outdoor environment. The blockage reduces the airflow across the condenser and increases the condensing temperature in the refrigerant circuit. The elevated temperature increases the pressure difference across the compressor and reduces the equipment efficiency.

#### 3.3.2.6 (Equipment Fault) Economizer Opening Stuck at Certain Position

Stuck dampers associated with economizers can be caused by seized/inoperable actuators, broken linkages, economizer control system failures, or the failure of sensors that are used to determine damper position (Roth et al. 2004). In extreme cases, dampers stuck at either 100% open or closed can have a serious impact on system energy consumption or occupant comfort in the space.

#### 3.3.2.7 (Equipment Fault) Inappropriate Electric Line Voltage

Inappropriate electric line voltage is a fault that can increase fan and compressor power consumption and/or reduce equipment life.

#### 3.3.2.8 (Equipment Fault) Insufficient Evaporator Airflow

Insufficient evaporator airflow can occur when the filter upstream of a cooling/evaporator coil is fouled, the duct is improperly designed (leading to high static pressure loss that the fan cannot overcome), or the blower speed is too low (e.g., belt slipping or control problem). This fault decreases the evaporator saturation temperature, which decreases overall cooling capacity, sensible heat ratio (SHR), and the coefficient of performance (COP). The lower SHR leads to increased latent capacity to meet a particular sensible load.



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#### 3.3.2.9 (Equipment Fault) Refrigerant Liquid-Line Restriction

A liquid-line restriction fault occurs when particles accumulate within the refrigerant filter located between the condenser and the expansion valve in the refrigerant circuit of a vapor-compression cycle. The accumulation increases the flow resistance of the refrigerant circuit and the pressure difference across the compressor. It also reduces the evaporating temperature and leads to lower cooling capacity, efficiency, and SHR. The lower SHR leads to increased latent capacity to meet a particular sensible load.

#### 3.3.2.10 (Equipment Fault) Nonstandard Refrigerant Charging

Nonstandard charging occurs when the refrigerant is undercharged or overcharged within the refrigerant circuit of an AC, heat pumping, or refrigeration system. Without sufficient refrigerant running in the system, the average refrigerant density, the evaporating temperature, and the refrigerant mass flow rate from the compressor drop, leading to reduced capacity, increased operating time, and increased energy consumption. The overcharged refrigerant causes the condenser pressure to rise due to decreased heat exchanger area associated with two-phase heat transfer. The increased pressure increases the compressor power and lowers the cycle efficiency. Nonstandard refrigerant charge can be due to leakage or improper charging during service.

#### 3.3.2.11 (Equipment Fault) Presence of Noncondensable in Refrigerant

When an AC, heat pump, or refrigeration unit is not properly evacuated prior to being charged with refrigerant, the unit runs with a mixture of air and refrigerant. Because it is non-condensable, the air inside the refrigerant circuit typically is trapped in the high-pressure vapor downstream of the compressor, and the pressure difference across the compressor and the compressor power consumption exceeds the normal level.

#### 3.3.2.12 (Sensor Fault) Biased Economizer or Supply-Air Temperature Sensors

When temperature and humidity sensors for outdoor air, return air, or supply air drift and are not regularly calibrated, sensor bias occurs. Sensor readings often drift from their calibration with age, causing equipment control algorithms to produce outputs that deviate from their intended function. This can lead to increased energy use, reduced comfort, and insufficient ventilation.

## 3.4 Lighting Faults

### 3.4.1 Operation-Stage Faults

#### 3.4.1.1 (Control Fault) Improper Time-Delay Setting in Occupancy Sensors

Guo et al. (2010) reviewed occupancy-based lighting-control technology and showed that improper time-delay settings in an occupancy sensor could lead to significant increase in lighting energy. For example, the lighting energy consumption with a 15-minute delay time was 10% higher than the case with an 8-minute delay setting. However, lower time-delay settings might cause frequent false shutoffs and would be less acceptable for occupants.

#### 3.4.1.2 (Control Fault) Inappropriate Lighting Schedules

Lighting should be turned off or at least reduced during off hours, but some commissioning studies have found noticeable lighting energy use at night, either because lighting schedules are improperly configured or occupants forget to turn off lights when leaving a building (Haasl, Stum, and Arney 1996; Kahn, Potter, and Haasl 2002). In particular, Kahn et al. (2002) reported



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non-reduced lighting at night in 10 unoccupied spaces (within a 43,000 $ft^2$ long-term care facility building) during a retrocommissioning procedure. They estimated a 2.5% savings relative to the total building energy consumption if the lighting control could be improved. A similar savings potential was observed in another nursing facility. The reported savings was about 10% relative to the lighting energy use. Note that this fault should not occur in building spaces employing occupancy sensors. Based on CBECS data, only 10% of the floor space in small commercial buildings has occupancy sensors. By assuming identical lighting energy intensities for different sizes of buildings, this fault, which only happens in buildings without occupancy sensors, has an impact on 90% of the total lighting energy use. This assumption was also used to calculate the annual lighting energy consumption of buildings with and without occupancy sensors in a later section.

#### *3.4.1.3 (Sensor Fault) Occupancy-Sensor Malfunction*

Occupancy sensors are used in more than 43% of the total floor space in commercial buildings, although their use in small commercial buildings is not that common. Only 10% of the floor space in small commercial buildings has occupancy sensors (see Table A6 in Appendix A). Malfunctioning occupancy sensors could incorrectly trigger lights to turn on or off, causing higher energy consumption or occupancy dissatisfaction. Floyd, Parker, and Sherwin (1996) showed that three out of 23 occupancy sensors were malfunctioning, leading to false triggering of lights during unoccupied periods and a 3% lighting energy increase.

## 3.5 Refrigeration Faults

Refrigeration energy use accounts for 16% of the total energy consumption in the small commercial-building sector. Refrigeration equipment commonly used in small commercial buildings includes residential-type[1] compact units, cases or cabinets, walk-in units, commercial ice makers, and vending machines. These types of equipment employ a vapor-compression cycle such that many of the faults are similar to those discussed in Section 3.3. However, the impacts of refrigeration unit faults can be significantly different because they typically operate with greater temperature/pressure lifts and within different environments than AC systems.

Numerous papers can be found in the literature for AC system faults, but only a few studies are available describing faults and their impacts for refrigeration systems, all of which were based on laboratory tests. For example, Wichman and Braun (2008) artificially introduced faults in a small commercial walk-in cooler typically used in restaurants and a small walk-in freezer. The investigated faults include a reciprocating-compressor valve leak, liquid-line restriction, condenser fouling, evaporator fouling, and refrigerant overcharge/undercharge. Laboratory testing with different fault levels resulted in up to 55% cooling capacity loss as a result of a compressor valve leak in the walk-in cooler and 8% loss in the walk-in freezer. Condenser and evaporator fouling caused up to 8% capacity loss in the walk-in cooler and 9% loss in the walk-in freezer. Liquid-line restriction caused up to 50% capacity loss in the walk-in cooler and freezer. Nonstandard charging caused up to 25% capacity loss in the walk-in cooler and freezer.

[1] Based on CBECS definition, "Residential-Type Refrigeration Unit: The type of refrigerator, freezer, or combination refrigerator and freezer such as would be found in a home kitchen. This category also includes half-size units such as might be found in a dormitory, office, or hotel."



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Qureshi and Zubair (2011) developed a detailed refrigeration system model and performed a simulation study to investigate overall performance degradation caused by condenser fouling. A follow-on study validated the findings via a laboratory test and demonstrated a 40% efficiency reduction with a 90% condenser face-area blockage (Qureshi and Zubair 2014).

There is little to no literature covering the prevalence and levels of faults for refrigeration systems in the field. As a result, this report estimates the national energy impact for a number of refrigeration faults based on prevalence and energy impact identified for the same fault in RTUs or split systems. The evaluated faults are excessive cooling in refrigerated cases, ice buildup on case doors, evaporator fouling or frost accumulation, presence of non-condensable gases, condenser fan degradation, condenser fouling, liquid-line restriction, compressor flow fault, and nonstandard charging. Detailed categorization of these faults can be found in Table B1 in Appendix B.



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# 4 Fault Prioritization

This section describes a methodology used to estimate the national energy and financial impacts of each fault and a brief summary of the fault prioritization result. The energy-impact estimations are based on site energy analysis that heavily relies on data from CBECS (CBECS 2017). Rather than approximating the primary energy consumption by using the averaged conversion factor, which varies every year, this report estimates the energy impact based on site energy analysis. The terminologies of equipment used in the current report follow the same definitions defined in CBECS. CBECS provides nationwide end-use energy-consumption data in the commercial-buildings sector classified in various ways, such as building floor space, energy sources, heating equipment type, cooling equipment type, lighting equipment type, refrigeration equipment type, and more. The financial impact of each fault is estimated to reflect the utility cost increase (including price differences between energy-source types such as electricity, gas, and fuel oil) and the incremental cost of operating the equipment due to the fault.

## 4.1 National Annual Energy Consumption Estimation of Each Equipment Type

National AEC estimates for different types of equipment ($AEC_{equip}$) are needed to assess the national energy impact of a fault. This requires estimation of detailed equipment end uses because a fault will typically affect some types of equipment, but not all. For example, an air-duct leakage fault causes higher heating energy use in equipment relying on air ducts for heat distribution such as packaged heating units. It does not, however, affect energy use for boilers or individual space heaters. Publicly available national end-use data at this granularity were not identified as part of this project. Westphalen and Koszalinski (2001) developed a rigorous bottom-up approach to estimate national primary-equipment energy consumption. However, the results presented in the report were generated for the whole commercial-building sector and are not directly usable in the current project because the types of equipment used in small commercial buildings are significantly different than those in medium- to large-sized commercial buildings. Furthermore, there were not enough resources to replicate the modeling approach developed by Westphalen and Koszalinski (2001). In this study, equipment site energy uses were estimated with a simpler approach to provide a first-order estimate of the fault impacts.

Table 1 shows the total floor areas served by different heating and cooling equipment in small commercial buildings in the United States. The presented results are based on CBECS data (CBECS 2017). Detailed floor-space data are given in Table A2 and Table A3 in Appendix A. Table 1 shows that packaged units provide space heating to 59% of the total heated floor space in small commercial buildings. Individual space heaters are the second most widely used heating equipment. For space cooling, packaged AC units and residential-type central AC units each serve about 40% of the total cooled floor space for the small commercial sector.

National average cooling and heating energy intensities were also extracted for all relevant equipment from the CBECS data (see Table A4 and Table A5 in Appendix A for detailed data). Then, equipment-specific energy end uses were estimated with:

$$AEC_{equip,i} = FlrArea_{equip,i} \cdot EI_{equip,i}\ , \qquad (1)$$



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where $FlrArea_{equip,i}$ is the floor area served by the $i^{th}$ cooling or heating equipment and $EI_{equip,i}$ is the cooling or heating energy intensity for the corresponding floor space. The estimated annual energy end uses by equipment are shown in Table 1. The cooling-equipment energy uses add up to 116 trillion Btu, which is higher than the national cooling energy use of 95 trillion Btu (in Appendix A). This difference is seen because the equipment categorizations in CBECS are not mutually exclusive (e.g., a packaged heat pump fits into two categories—heat pumps and packaged units); however, the difference is relatively small and does not affect the overall analysis presented in this report. Literature related to refrigeration or lighting faults in terms of providing accurate estimates of their national energy impacts were not available. In the refrigeration-fault evaluations, the same prevalence and energy impact were assumed for all types of refrigeration equipment. The same assumption was used for lighting-fault assessments.

**Table 1. Annual Energy Consumption for Each Energy and Equipment Type in Small Commercial Buildings**

| **Category** | Type | Floor Area million $ft^2$ | $AEC_{equip}$, trillion Btu/yr |
|---|---|---|---|
| **Heating** | All | 14,289 | 312 |
| | Furnaces | 2,507 | 53.4 |
| | Packaged Heating Units | 8,431 | 160.2 |
| | Boilers | 1,134 | 37.8 |
| | District Heat | 0 | 0 |
| | Heat Pumps | 1,906 | 23.1 |
| | Individual Space Heaters | 3,772 | 86.8 |
| | Other | 0 | 0 |
| **Cooling** | All | 13,428 | 95 |
| | Residential-Type Central Air Conditioners | 5,318 | 33.5 |
| | Packaged AC Units | 5,236 | 46.6 |
| | Central Chillers | 0 | 0 |
| | District Chilled Water | 0 | 0 |
| | Heat Pumps | 2,176 | 20.0 |
| | Individual Air Conditioners | 1,999 | 15.8 |
| | Other | 0 | 0 |
| **Other** | Ventilation | - | 93 |
| | Lighting w/ Occupancy Sensor | - | 11.7 |
| | Lighting w/o Occupancy Sensor | - | 105.3 |
| | Refrigeration | - | 224 |



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## 4.2 National Annual Energy Impact of Each Fault

From literature review results and conversations with building-commissioning experts, the national energy impact of each fault was evaluated. The impact estimation method was based on Roth et al. (2005). For each fault, the annual energy impact (AEI) is estimated using:

$$AEI_{fault} = \left(\sum_{i}^{equip} AEC_i\right) \cdot Prev_{fault} \cdot r_{degrad,fault} \, , \qquad (2)$$

where *AEI* is the fault annual energy impact, *AEC* is the national annual energy consumption of the equipment impacted by the fault, $Prev_{fault}$ is the prevalence (or probability) that a fault occurs causing an appreciable efficiency degradation, and $r_{degrad,fault}$ is the average degradation ratio (decreased efficiency or increased load) caused by the fault. Figure 2 shows an example of how *AEI* is calculated for excessive infiltration through the building envelope. Although the excessive infiltration fault is not affected by the type of HVAC equipment, it causes increased heating and cooling demand, which will affect heating, cooling, and ventilating energy in buildings. Thus, the AEC for excessive infiltration is calculated by adding AEC values of “All” heating (312 trillion Btu/yr), “All” cooling (95 trillion Btu/yr), and ventilation (93 trillion Btu/yr) categorized in Table 1. Other faults such as lighting-related faults primarily affect lighting-equipment energy usage, and these differences in the energy classifications affected by each fault are summarized in the last three columns in Table B1. For example, the air-duct leakages fault affects the energy consumption values (or AEC) classified under “packaged heating units” in heating, “packaged AC units” in cooling, and “ventilation” in others category in Table B1. Based on the values of $Prev_{fault}$ and $r_{degrad,fault}$, the *AEI* for excessive infiltration is calculated as 47 trillion Btu/yr as shown in Figure 2. Representative values for $Prev_{fault}$ and $r_{degrad,fault}$ were identified based on literature review results, and the national energy uses for different types of equipment are estimated in Section 4.1. Note that most of the available literature does not provide values for both $Prev_{fault}$ and $r_{degrad,fault}$. In addition, information to estimate the fault energy impact is lacking for some faults. In such cases, best estimates were made based on available information from similar faults for other types of equipment.

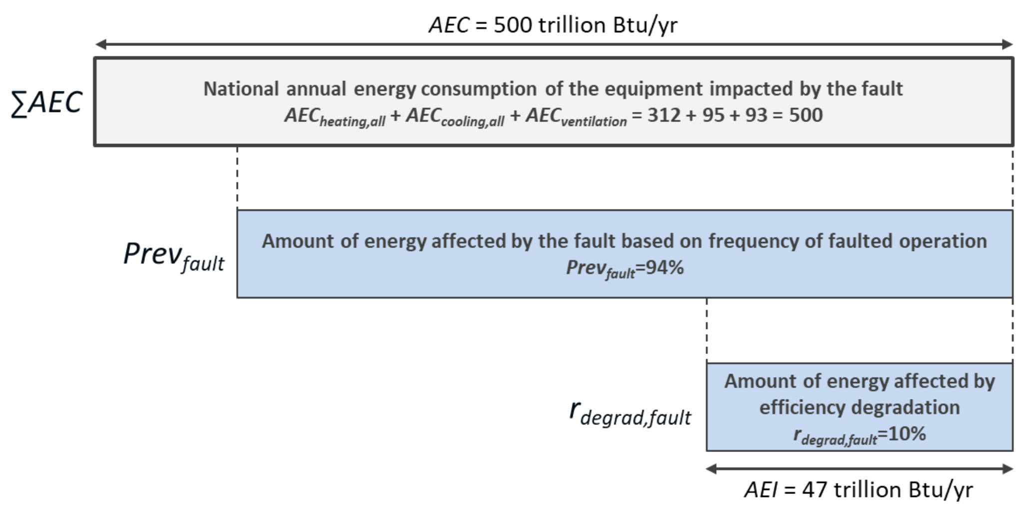


**Figure 2. Example of annual energy-impact estimation (excessive infiltration through the building envelope)**



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## 4.3 National Annual Financial Impact of Each Fault

A financial impact of each fault was calculated by considering both utility cost increase and equipment life-cycle cost increase due to faulted operation. The annual financial impact (AFI) is calculated as shown in the equation below:

$$AFI_{fault} = AFI_{utility,fault} + AFI_{LCC,fault} \text{ ,} \quad (3)$$

where $AFI_{fault}$ is the fault's annual financial impact, which is the sum of the increased utility cost ($AFI_{utility,fault}$) and the increased equipment life-cycle cost ($AFI_{LCC,fault}$).

### 4.3.1 Annual Financial Impact of Faults on Utility Cost

$AFI_{utility,fault}$ is estimated by converting excess energy usage of $AEI_{fault}$ to a cost value according to

$$AFI_{utility,fault} = \sum_{j}^{energy}\left(\sum_{i}^{fuel} \alpha_j \cdot \beta_i \cdot FC_i \cdot AEI_{fault}\right) . \quad (4)$$

$\alpha_j$ is the fraction of different energy usages in category *j* where *j* is an index representing one of the uses—heating, cooling, ventilation, lighting, or refrigeration—that corresponds to each fault's equipment type. $\beta_i$ is the different fuel fractions in category *i* where *i* is an index representing electricity, natural gas, or fuel oil for each energy-usage type (other types of fuels were not considered because these three represent most consumption in small commercial buildings based on CBECS data). For each fault, the sum of all $\alpha_j$ and the sum of all $\beta_i$ becomes one, independently. *FC* is the unit cost of each fuel. $\alpha_j$ and $\beta_i$ values are not directly available in CBECS data.

To approximate the average values of $\alpha_j$ and $\beta_i$ for the small commercial-building sector, *AEC* values in Table 1 and CBECS microdata were used. CBECS microdata includes 6,702 records of individual buildings that represent the average trend of buildings around the nation. To approximate $\beta_i$ values, 2,614 data points—representing small commercial buildings (floor space less than 10,000 $ft^2$)—out of the 6,702 records were used. Figure 3 shows an example of $AFI_{utility,fault}$ estimation for the excessive infiltration fault. Because excessive infiltration affects heating, cooling, and ventilation energy in buildings, $\alpha_j$ values for this fault were estimated using AEC values of heating (312), cooling (95), and ventilation (93) corresponding to the equipment type in Table B1 in Appendix B.

$\beta_i$ values were estimated from the CBECS microdata to calculate the amount of energy used by each fuel. Figure 4 shows the summary of $\beta_i$ values estimated from the CBECS microdata for the small commercial-building sector. Among the entire 2,614 data points, necessary data points with relevant data were narrowed down for calculating portions of each fuel related to each equipment type. As shown in the figure, electricity is mostly used for cooling and other (ventilation, lighting, and refrigeration) equipment. Although natural gas is used in a significant portion of heating equipment, more than 50% of that portion is accounted for by electricity for heat pumps and district heating (district steam or piped hot water). More specifically, for heat pumps, 10 out of the 278 individual buildings in the CBECS results were equipped with a heat-pump system and a "natural/bottled gas backup (dual fuel)" unit. This resulted in a finding that natural gas provided 33% of the energy for heating among all small commercial buildings that



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have heat pumps. These different percentages between different fuels ($\beta_i$) shown in the figure are only used for calculating $AFI_{utility,fault}$.

The costs of fuels were used to calculate the $AFI_{utility,fault}$. Costs of electricity ($0.102/kWh), natural gas ($11.07/thousand-cubic-feet), and fuel oil ($1.595/gal) were adapted from various reports representing nationwide average prices (EIA 2017a; EIA 2017b; EIA 2017c; Engineering ToolBox 2015a, 2015b).

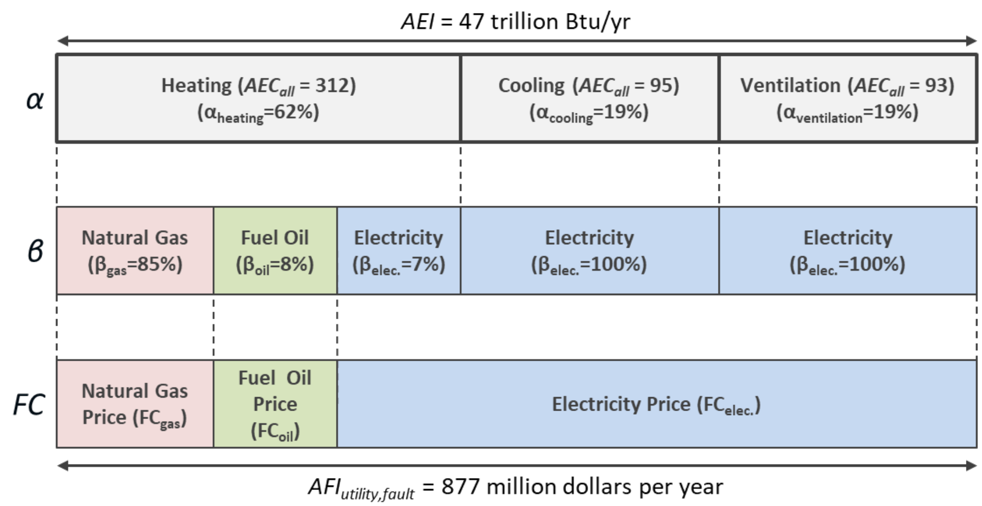


**Figure 3. Example of $AFI_{utility,fault}$ estimation (excessive infiltration through the building envelope)**

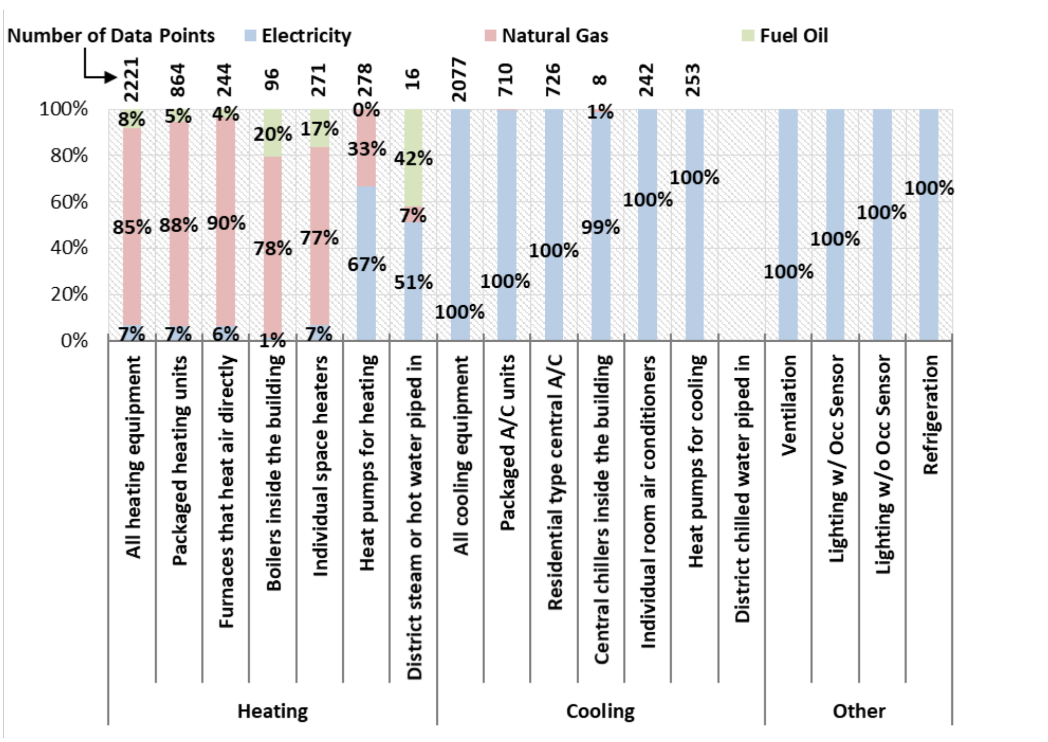


**Figure 4. Portion of major fuels used in small commercial buildings that contain various types of HVAC equipment**



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### 4.3.1 Annual Financial Impact of Faults Due to Increased Life-Cycle Cost

Certain faults degrade HVAC cooling/heating capacities and require longer run times to meet building loads. Prolonged run time could lead to reduced unit life span and incur additional equipment and maintenance costs. Previous studies have shown that the equipment cost is similar to or even higher than the electricity cost per unit of run time (Li and Braun 2007). Thus, the incremental equipment cost (or the annual financial impact due to the equipment's life-cycle cost increase, $AFI_{LCC,fault}$) should be accounted for in the overall economic analysis. This study uses a modified approach from Li and Braun (2007) as shown below:

$$AFI_{LCC,fault} = AFC_{fault} - AFC_{base} = AFC_{base} \cdot \left(\frac{AFC_{fault}}{AFC_{base}} - 1\right). \qquad (5)$$

This equation calculates increased financial cost due to a fault in a system by subtracting baseline annual financial cost (AFC) without fault from the total AFC of the faulted system. To calculate Eq. (5), i$^{th}$ equipment's annual financial cost ($AFC_i$) is first defined as follows:

$$AFC_i = C_i \cdot t_{runtime,i} \cdot Cap_{rated,i} \,, \qquad (6)$$

where $C_i$ ($/kWh) is i$^{th}$ equipment's average hourly cost per unit of cooling capacity determined by dividing the total equipment cost per kW of capacity (including costs associated with unit purchase and installation) by the unit life span. $t_{runtime,i}$ is the i$^{th}$ equipment's annual run time. $Cap_{rated,i}$ is the total rated capacity for the i$^{th}$ equipment. Equipment annual run time is calculated as

$$t_{runtime,i} = \frac{Load_{sen,annual}}{Cap_i \cdot SHR_i}, \qquad (7)$$

where $Load_{sen,annual}$ is the annual building sensible load (kWh) and $SHR_i$ and $Cap_i$ are the average sensible heat ratio and capacity for the i$^{th}$ equipment during the operation. $Load_{sen,annual}$ can be estimated as

$$Load_{sen,annual} = AEC_i \cdot COP_i \cdot SHR_i \,, \qquad (8)$$

where $COP_i$ is the typical COP and $SHR_i$ is the typical SHR for a specific type of equipment. Applying Eqs. (7) and (8) into Eq. (6) gives $AFC_i$ as shown below:

$$AFC_i = C_i \cdot AEC_i \cdot COP_i \,. \qquad (9)$$

$AFC_{base}$ in Eq. (5) can be derived by using Eq. (9) and including different types of equipment associated with each fault.

$$AFC_{base} = \sum_{i}^{equip} C_i \cdot AEC_i \cdot COP_i \qquad (10)$$



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The term $AFC_{fault}/AFC_{base}$ in Eq. (5) can also be expressed in the following form by using Eq. (6) and (7).

$$\frac{AFC_{fault}}{AFC_{base}} = \frac{\sum_i^{equip}\left(C_i \cdot t_{runtime,i} \cdot Cap_{rated,i}\right)_{fault}}{\sum_i^{equip}\left(C_i \cdot t_{runtime,i} \cdot Cap_{rated,i}\right)_{base}}$$

$$= \frac{\sum_i^{equip}\left(C_i \cdot \frac{Load_{sen,annual}}{Cap_i \cdot SHR_i} \cdot Cap_{rated,i}\right)_{fault}}{\sum_i^{equip}\left(C_i \cdot \frac{Load_{sen,annual}}{Cap_i \cdot SHR_i} \cdot Cap_{rated,i}\right)_{base}} \tag{11}$$

$$= \sum_i^{equip}\left(\frac{Load_{sen,annual,fault}}{Load_{sen,annual,base}} \cdot \frac{Cap_{base,i}}{Cap_{fault,i}} \cdot \frac{SHR_{base,i}}{SHR_{fault,i}}\right)$$

Equation (11) is simplified to its last form by canceling the cost ($C_i$) and rated capacity ($Cap_{rated,i}$) terms in denominator and numerator on the assumption that they are the same for both faulted operation and baseline operation without fault. Equation (11) is simplified again to adopt parameters that are found from the literature by defining the relative impacts ($r$) of a fault on the building's sensible load, equipment capacity, and SHR as shown below:

$$r_{load} = \sum_i^{equip} \frac{Load_{sen,annual,fault} - Load_{sen,annual,base}}{Load_{sen,annual,base}} \tag{12}$$

$$r_{cap} = \sum_i^{equip} \frac{Cap_{i,base} - Cap_{i,fault}}{Cap_{i,base}} \tag{13}$$

$$r_{SHR} = \sum_i^{equip} \frac{SHR_{i,base} - SHR_{i,fault}}{SHR_{i,base}}. \tag{14}$$

With these definitions, the $AFI_{LCC,fault}$ due to a fault can be expressed as

$$AFI_{LCC,fault} = AFC_{base} \cdot \left\{\frac{1 + r_{load}}{\left(1 - r_{cap}\right)\left(1 - r_{SHR}\right)} - 1\right\}$$

$$= \left(\sum_i^{equip} C_i \cdot AEC_i \cdot COP_i\right)\left\{\frac{1 + r_{load}}{\left(1 - r_{cap}\right)\left(1 - r_{SHR}\right)} - 1\right\}. \tag{15}$$

Table 2 shows average material[2] and installation costs for each equipment type collected from RSMeans data found in Gordian (RSMeans 2017). Although the equipment's life-cycle cost estimation requires material, installation, and maintenance costs, maintenance costs for each equipment type were not available and were not included in the financial-impact estimation. To derive $C_{equip}$ from the cost information available from RSMeans data, annual operating hours of all HVAC equipment in commercial buildings were assumed to be 1,200 hours per year (Li and

[2] Defined as "The material or materials required to complete the installation as described" in RSMeans (2017)



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Braun 2007) and annual operating hours of lighting systems were assumed to be 4,088 hours per year (DOE 2012). Cooling equipment COP values were assumed to be 2.82 and heating equipment efficiency was assumed to be 97%. Heat-pump equipment costs and COPs for heating and cooling were assumed to be the same. Although the equation for $AFI_{LCC,fault}$ estimation is originally intended for faults related to HVAC cooling equipment, this equation was also used for faults that are not specific to HVAC cooling equipment in this report. For example, an inappropriate lighting-schedule fault that increases the annual lighting operating hours can increase the light-bulb replacement cost (or the equipment life-cycle cost) during the building life span. Faults that are not related to the HVAC cooling equipment as in the example, $r_{cap}$ and $r_{SHR}$, were assumed to be zero, and $r_{load}$ was assumed to be the percentage of increased energy use due to faulted operation. Refrigeration-system equipment costs were only available in terms of equipment size in cubic feet instead of rated capacity; thus, faults related to the refrigeration system were not considered for life-cycle cost impact estimation. $C_{equip}$ for "All" type equipment for heating were calculated using a weighted average of other heating equipment costs in terms of their energy impact (AEC). This was also applied for "All" type equipment for cooling. Based on these assumptions, estimates of $C_{equip}$ for each equipment type are given in the last column in Table 2.

**Table 2. Material and Installation Costs per kW of Capacity for Each Type of Equipment**

| Category | Equipment Type | AEC, trillion Btu/yr | Cost | Efficiency, COP, or % | Equipment Life, yrs | Operating Hours, hrs/yr | $C_{equip}$, $/kWh |
|---|---|---|---|---|---|---|---|
| Cooling | All | 95.0 | Used with weighted average | | | | 0.0266 |
| Cooling | Packaged AC units | 46.6 | 260 $/kW | 2.82 | 10 | 1,200 | 0.0217 |
| Cooling | Residential-type central AC units | 33.5 | 299 $/kW | 2.82 | 10 | 1,200 | 0.0249 |
| Cooling | Heat pumps | 20.0 | 351 $/kW | 2.82 | 10 | 1,200 | 0.0293 |
| Cooling | Individual AC units | 15.8 | 501 $/kW | 2.82 | 10 | 1,200 | 0.0417 |
| Heating | All | 312.0 | Used with weighted average | | | | 1.890E-03 |
| Heating | Furnaces | 53.4 | 0.057 $/kW | 0.97 | 10 | 1,200 | 4.738E-06 |
| Heating | Packaged heating units | 160.2 | 0.434 $/kW | 0.97 | 10 | 1,200 | 3.615E-05 |
| Heating | Boilers | 37.8 | 0.148 $/kW | 0.97 | 10 | 1,200 | 1.229E-05 |
| Heating | Heat pumps | 23.1 | 351 $/kW | 2.82 | 10 | 1,200 | 0.0293 |
| Heating | Individual space heaters | 86.8 | 0.074 $/kW | 0.97 | 10 | 1,200 | 6.190E-06 |
| Others | Ventilation | 93.0 | 120 $/kW | 0.9 | 10 | 1,200 | 0.01 |
| Others | Refrigeration | 224.0 | n/a | | | | |
| Others | Lighting | 117.0 | 0.0056 $/kW | 1 | 1.3 | 4,088 | 1.043E-06 |



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## 4.4 Fault Prioritization Procedure

The result of the national annual energy and financial impact estimations are included in Table C1 in Appendix C, in which faults are ranked based on higher AEI values and the remaining faults without AEI values are included at the bottom of the table. Detailed information for each fault—such as AEC, prevalence (*Prev*), degradation ratio ($r_{degrad,fault}$), capacity loss ($r_{cap}$), load increase ($r_{load}$), *SHR* degradation ($r_{SHR}$), and the calculated annual energy and financial impacts (AEI and AFI)—can also be found. In addition to AEI and AFI, technical complexity and modeling (and validation) feasibility are included as separate columns in the table. Technical complexity is defined as a level (low-medium-high) of difficulty in detecting each particular type of fault based on the information typically available. Modeling (and validation) feasibility is defined as a level of difficulty (easy-moderate-difficult) in modeling and validating each particular type of fault and is also based on the available information. A total of 47 faults were identified from the literature; however, national AEI and AFI estimation was only possible for 33 of the faults. The remaining faults have insufficient information to determine prevalence or energy impact, or both. Multiple values of prevalence and energy impact can be found in the literature for certain faults and average values were used in such cases. The AEC only accounts for energy end uses potentially impacted by the fault. For example, all faults associated with vapor-compression cycles affect the cooling energy use in RTUs, whereas RTU heating primarily relies on gas or electrical heaters, which are not impacted by vapor-compression faults. Short descriptions and evidence of how the values were obtained for each fault are included in the comments column of Table C1.



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# 5 Top-Priority Faults

The top-priority faults were determined in this work based on estimated prevalence, AEI, AFI, and ease of implementation in EnergyPlus and OpenStudio. Two different types of lists are included in this section. First are the lists of faults (Figure 5, Figure 6, and Figure 7) depending on the equipment type. In these lists, the same types of faults are differentiated for different types of equipment. For example, these lists show the different AEI, AFI, and prevalence values of the nonstandard charging fault for RTUs, split systems, and refrigeration systems, respectively. The second list (Table 3) shows overall values of AEI, AFI, and prevalence values independent of the equipment type. This list can be considered as the final list of prioritized faults because it focuses on the type of the fault regardless of the equipment type. This is based on the assumption that the modeling of a certain fault can be similarly applied to different types of equipment. Models will be developed for these faults in the first year of the project period. The fault models are expected to be validated with laboratory test data or field measurements and will be implemented in the EnergyPlus and OpenStudio ecosystem.

Figure 5, Figure 6, and Figure 7 show the 20 top-priority faults depending on the equipment type and their AEI, AFI, and prevalence values rank-ordered in terms of AEI, AFI, and prevalence, respectively. Excessive infiltration through the building envelope has the highest impact in all three figures, as this fault has high prevalence, AEI, and AFI causing higher energy uses for both heating and cooling equipment. Air-duct leakage has the second-largest energy impact, and this was also identified as one of the major faults in the entire commercial-building sector (Roth et al. 2004, 2005). This fault is very common in RTUs, causing higher energy uses in heating and cooling equipment and blowers.

Three other building-operation faults—incorrect HVAC on/off modes, inappropriate set points/thermostat schedules, and zone temperature sensor bias—are also among the 20 top faults in terms of energy impact. In addition, inappropriate lighting schedules/controls are top-priority faults with high energy and financial impacts. Although the utility cost increase ($AFI_{utility,fault}$ = $ 3.93E+08/yr) due to inappropriate lighting schedules/controls is relatively high compared to other faults, the life-cycle equipment cost increase ($AFI_{LCC,fault}$ = $ 8,040/yr) is almost negligible because the cost of purchasing and installing lights is small.

Ten out of the 20 top-priority faults in Figure 5 occur in vapor-compression systems such as AC, heat-pump, and refrigeration equipment. Nonstandard charging and condenser and evaporator fouling are the most prominent faults in this type of equipment, which is most likely the reason AFDD for vapor-compression systems has been studied extensively. As shown in Figure 6, the financial impacts of faults for cooling equipment are more influenced by energy impacts than by equipment-life degradation. Utility cost increase ($AFI_{utility,fault}$) due to the faulted operation is mostly high for faults with a high AEI. The equipment life-cycle cost increase ($AFI_{LCC,fault}$) is greater when the percentage of load increase, capacity degradation, and SHR degradation due to the fault become severe as shown in the result of insufficient evaporator airflow ($AFI_{LCC,fault}$ = $ 7.01E+08/yr). The fault of improper time-delay setting in occupancy sensors has a relatively high prevalence (*Prev* = 80%) but less energy and financial impact compared to other faults with lower prevalence, because the amount of energy affected by this fault (*AEC* = 11.7 trillion Btu/yr) is small.



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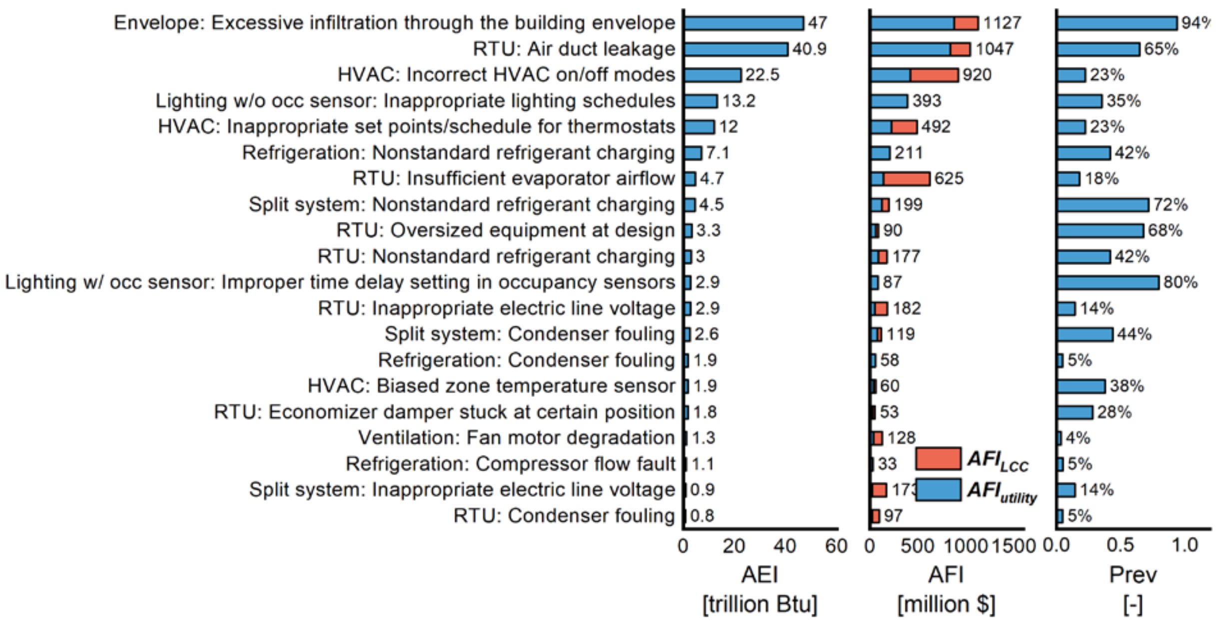


**Figure 5. Estimated 20 top-priority faults, rank-order sorted using energy impact**

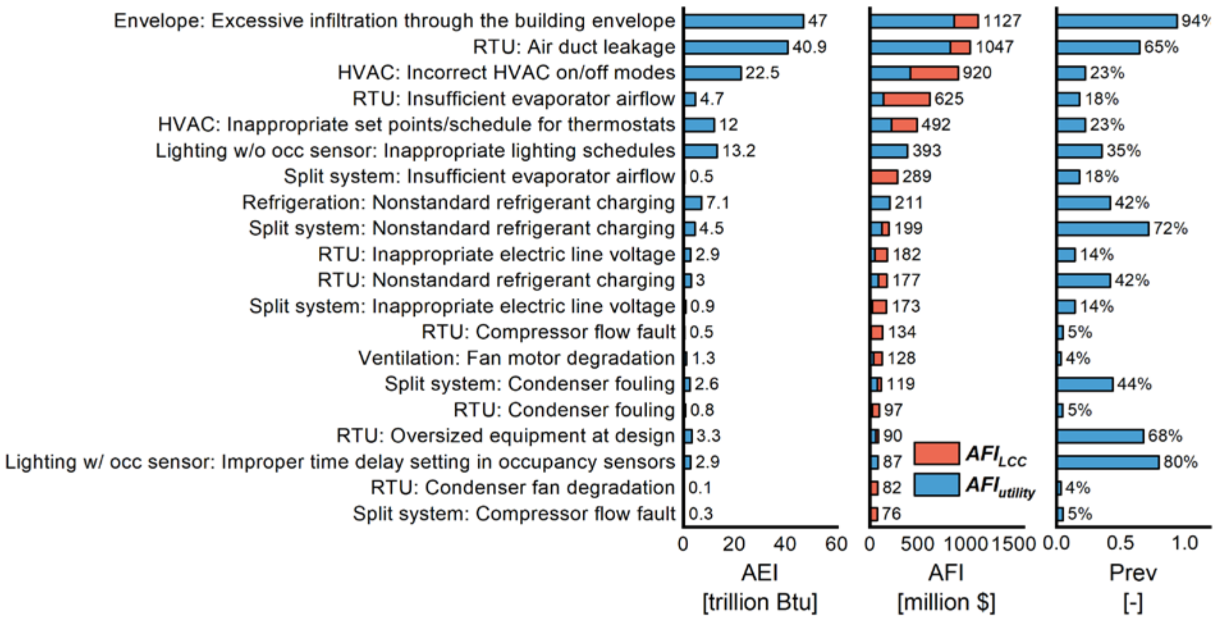


**Figure 6. Estimated 20 top-priority faults rank-order sorted using financial impact**



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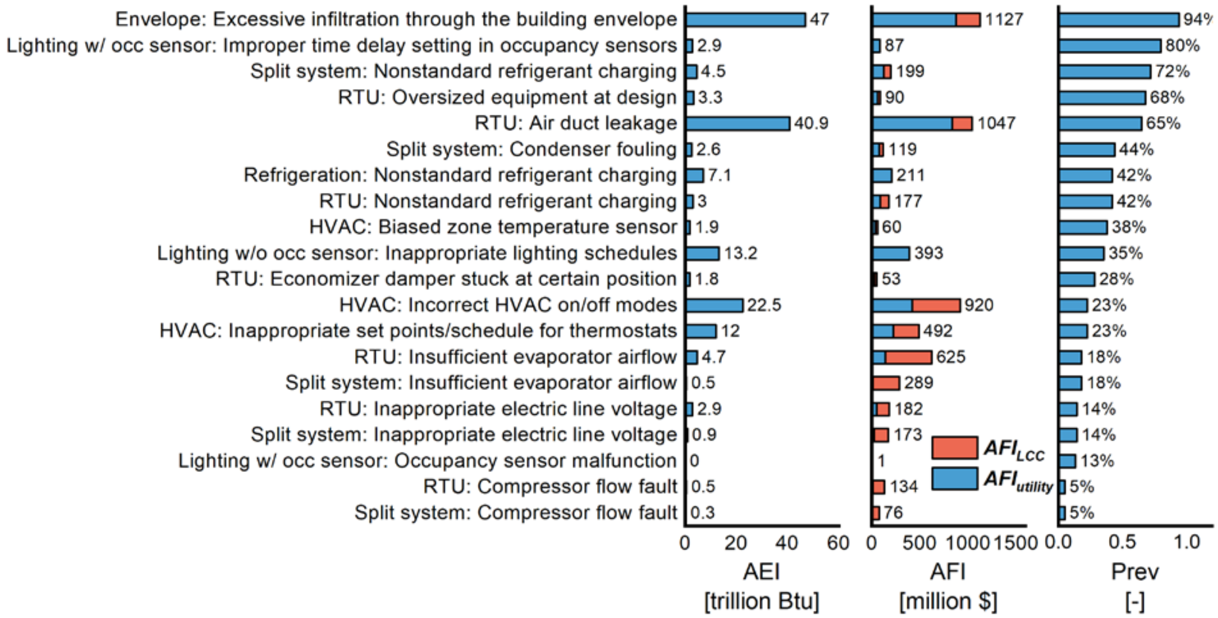


**Figure 7. Estimated 20 top-priority faults rank-order sorted using prevalence (*$Prev_{fault}$*)**

Table 3 summarizes the 20 top-priority faults independent of equipment type and rank-ordered with higher AEI. Values of AEI and AFI of faults such as nonstandard refrigerant charging and condenser fouling, which were classified separately in Figure 5, Figure 6, and Figure 7 depending on the type of equipment (RTU, split system, and refrigeration system), are now added together to approximate the overall impact of each specific type of fault. The total impact of the 20 top-priority faults is 180 trillion Btu/yr in energy and $7 billion every year in cost. Nine out of the top 20 faults in the list occur in the vapor-compression system, and the sum of the impact becomes 30 trillion Btu/yr in energy and $1.8 billion per year in cost. The total impact of control faults is 51 trillion Btu/yr and $1.9 billion per year.

It is straightforward to implement most of the top-priority faults shown in Table 3 in EnergyPlus and OpenStudio. Building-operation faults, such as incorrect HVAC on/off modes, inappropriate lighting schedules, and inappropriate set points/thermostat schedules, can be directly modeled by altering schedules or set points in the corresponding thermal zones. Sensor bias faults can be considered by adding an artificial bias to the control/measurement point. Correlation models are widely used in EnergyPlus to simulate AC, heat pump, and refrigeration equipment due to the low computational burden. It will be difficult to capture fault impact directly in the correlation models. In this project, detailed physics-based models will be developed for the various vapor-compression systems, and the top-priority faults will be incorporated in the developed models to simulate the faulty behaviors. The detailed fault models will then be used on existing models within EnergyPlus to simulate the fault impacts.



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**Table 3. Prioritized List of 20 Top-Priority Faults**

| Fault | *AEI*, trillion Btu/yr | *AFI*, million $/yr |
|---|---|---|
| Excessive infiltration through the building envelope | 47.00 | 1127 |
| Air duct leakages | 40.92 | 1047 |
| Incorrect HVAC on/off modes | 22.50 | 920 |
| Nonstandard refrigerant charging | 14.56 | 587 |
| Inappropriate lighting schedules | 13.16 | 393 |
| Inappropriate set points/schedule for thermostats | 12.04 | 492 |
| Condenser fouling | 5.35 | 274 |
| Insufficient evaporator airflow | 5.19 | 914 |
| Inappropriate electric line voltage | 3.82 | 355 |
| Oversized equipment at design | 3.27 | 90 |
| Improper time delay setting in occupancy sensors | 2.91 | 87 |
| Biased zone temperature sensor | 1.90 | 60 |
| Compressor flow fault | 1.87 | 244 |
| Economizer opening stuck at certain position | 1.75 | 53 |
| Fan motor degradation | 1.25 | 128 |
| Refrigerant liquid line restriction | 1.12 | 133 |
| Presence of non-condensable in refrigerant | 0.98 | 29 |
| Condenser fan degradation | 0.43 | 91 |
| Biased economizer sensor | 0.18 | 56 |
| Occupancy sensor malfunction | 0.05 | 1 |



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# 6 Conclusions

An extensive literature review was performed to identify common faults in small commercial buildings. Various aspects of the identified faults were considered to analyze the fault priority, including site energy-use impacts, fault prevalence, and financial impacts. The acquired information was used within a simple quantification method to estimate the fault's national energy and financial impacts. Based on those impacts, along with technical complexity and modeling feasibility in EnergyPlus and OpenStudio, the identified faults were prioritized and a reduced list consisting of the top priority faults was developed. The identified top-priority faults will be the main focus for model development in EnergyPlus and OpenStudio.

Relatively comprehensive information is available in the literature for faults in AC and space-heating equipment, so their national energy and financial impact estimations should be reasonably accurate. However, there are several weak points that cannot be improved due to the lack of high-quality source data, which have not yet been identified. These shortfalls will be updated during the course of this project if pertinent information becomes available.

- In the refrigeration fault analysis, this study used the same values of prevalence and energy impact as the respective faults in RTUs or split systems. It is believed to be the best estimate without any solid data from the literature. However, the actual fault prevalence could be significantly different between a refrigeration unit and an AC system, or even between a freezer and refrigerator. For example, the possibility or prevalence of condenser fouling may be much lower for many refrigeration units because the condenser is located in a clean, controlled environment. On the other hand, an AC system always has its condenser outdoors, leading to a higher chance of air-side condenser fouling.
- Chiller faults have been studied extensively, and relatively complete information is available for calculating their national energy impact. However, chillers are rarely used in small commercial buildings, leading to almost zero national energy impact for all chiller faults.
- This report covers a number of faults in vapor-compression-system-based equipment; however, only a few faults associated with other space cooling or heating equipment are included.
- Material, installation, and maintenance costs are the main factors for estimating the equipment's life-cycle cost increase due to each fault. But only material and installation costs were included here, and maintenance cost was not included in the financial impact estimation.
- Parameters such as prevalence, efficiency degradation, capacity degradation, SHR degradation, load increase, equipment life span, and equipment operating hours were estimated with available literature, and best estimates were made for faults in the absence of available literature for these parameters.



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# References

ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers). 2005. *ASHRAE Handbook—Fundamentals*. www.ashrae.org.

Breuker, Mark S., and James E. Braun. 1998a. "Common Faults and Their Impacts for Rooftop Air Conditioners." *HVAC&R Research* 4:303–318. doi:10.1080/10789669.1998.10391406. www.researchgate.net/publication/232859081_Common_Faults_and_Their_Impacts_for_Rooftop_Air_Conditioners.

Breuker, Mark S., and James E. Braun. 1998b. "Evaluating the Performance of a Fault Detection and Diagnostic System for Vapor Compression Equipment." *HVAC&R Research* 4:401–425. doi:10.1080/10789669.1998.10391412. www.researchgate.net/publication/233473780_Evaluating_the_Performance_of_a_Fault_Detection_and_Diagnostic_System_for_Vapor_Compression_Equipment.

CBECS (Commercial Buildings Energy Consumption Survey). 2012a. Table E1. *Major fuel consumption (Btu) by end use*. www.eia.gov/consumption/commercial/data/2012/c&e/pdf/e1-e11.pdf.

CBECS. 2012b. Table B39. *Heating equipment, floorspace*. www.eia.gov/consumption/commercial/data/2012/bc/pdf/b39.pdf.

CBECS. 2012c. Table B41. *Cooling equipment, floorspace*. www.eia.gov/consumption/commercial/data/2012/bc/pdf/b41.pdf.

CBECS. 2012d. *Table E2. Major fuel consumption intensities (Btu) by end use*. www.eia.gov/consumption/commercial/data/2012/c&e/pdf/e2.pdf.

CBECS. 2012e. Table B7. *Building size, floorspace*. www.eia.gov/consumption/commercial/data/2012/bc/pdf/b7.pdf.

CBECS. 2017. U.S. Energy Information Administration. Accessed 3.16.17. www.eia.gov/consumption/commercial/.

Cheung, Howard, and James E. Braun. 2015. *Development of Fault Models for Hybrid Fault Detection and Diagnostics Algorithm*. NREL/SR-5500-65030. National Renewable Energy Laboratory. www.nrel.gov/docs/fy16osti/65030.pdf.

Cho, Jin Min, Jaehyeok Heo, W. Vance Payne, and Piotr A. Domanski. 2014. "Normalized performance parameters for a residential heat pump in the cooling mode with single faults imposed." *Applied Thermal Engineering* 67:1–15. doi:10.1016/j.applthermaleng.2014.03.010. www.researchgate.net/publication/261104882_Normalized_performance_parameters_for_a_residential_heat_pump_in_the_cooling_mode_with_single_faults_imposed.

Djunaedy, Ery, Kevin van den Wymelenberg, Brad Acker, and Harshana Thimmana. 2011. "Oversizing of HVAC system: Signatures and penalties." *Energy and Buildings* 43:468–475. doi:10.1016/j.enbuild.2010.10.011.



This report is available at no cost from the National Renewable Energy Laboratory (NREL) at www.nrel.gov/publications.

www.researchgate.net/publication/232397419_Oversizing_of_HVAC_system_Signatures_and_penalties.

DOE (U.S. Department of Energy). 2012. *U.S. Lighting Market Characterization*. Office of Energy Efficiency and Renewable Energy, Building Technologies Program. www1.eere.energy.gov/buildings/publications/pdfs/ssl/2010-lmc-final-jan-2012.pdf.

Domanski, Piotr A., Hugh I. Henderson, and W. Vance Payne. 2014. *Sensitivity Analysis of Installation Faults on Heat Pump Performance*. NIST Technical Note 1848. National Institute of Standards and Technology. http://nvlpubs.nist.gov/nistpubs/TechnicalNotes/NIST.TN.1848.pdf.

Downey, Tom, and John Proctor. 2002. "What Can 13,000 Air Conditioners Tell Us?" ACEEE Summer Study on Energy Efficiency in Buildings. Panel 1, Residential Buildings: Technologies,

Design, Performance Analysis, and Building Industry Trends. http://aceee.org/files/proceedings/2002/data/papers/SS02_Panel1_Paper05.pdf.

EIA (U.S. Energy Information Administration). 2017a. "Table 5.6.A. Average Price of Electricity to Ultimate Customers by End-Use Sector." *Electric Power Monthly*. Accessed 6.8.17. www.eia.gov/electricity/monthly/epm_table_grapher.cfm?t=epmt_5_6_a.

EIA. 2017b. *Heating Oil and Propane Update*. Accessed 6.8.17. www.eia.gov/petroleum/heatingoilpropane/ - itn-tabs-2.

EIA. 2017c. *Natural Gas Prices*. Accessed 6.8.17. www.eia.gov/dnav/ng/ng_pri_sum_dcu_nus_m.htm.

Emmerich, Steven J., Timothy P. McDowell, and Wagdy Anis. 2005. *Investigation of the Impact of Commercial Building Envelope Air Tightness on HVAC Energy Use*. Text No. NISTIR 7238. National Institute of Standards and Technology. https://www.nist.gov/publications/investigation-impact-commercial-building-envelope-airtightness-hvac-energy-use-0.

Engineering ToolBox. 2005a. *Fuel Gases Heating Values*. Accessed 6.8.17. www.engineeringtoolbox.com/heating-values-fuel-gases-d_823.html.

Engineering ToolBox. 2005b. *Fuel Oil Combustion Values*. Accessed 6.8.17. www.engineeringtoolbox.com/fuel-oil-combustion-values-d_509.html.

Felts, Don R., and Patrick Bailey. 2000. "The State of Affairs—Packaged Cooling Equipment in California." European Council for an Energy-Efficient Economy. ACEEE Summer Study on Energy Efficiency in Buildings. American Council for an Energy Efficient Economy. https://www.eceee.org/library/conference_proceedings/ACEEE_buildings/2000/Panel_3/p3_11/.

Floyd, David B., Danny S. Parker, and John R. Sherwin. 1996. *Measured Field Performance and Energy Savings of Occupancy Sensors: Three Case Studies*. FSEC-PF-309-96. Florida Solar Energy Center. https://pdfs.semanticscholar.org/19ae/d4cb72bc6da27524cb6e67dc95aaaf84947e.pdf.



This report is available at no cost from the National Renewable Energy Laboratory (NREL) at www.nrel.gov/publications.

Frank, Stephen, Xin Jin, Daniel Studer, and Amanda Farthing. 2018. "Automated Fault and Diagnosis Technology for Small Commercial Buildings: An Overview." Draft to be submitted.

Guo, Xin, Dale K. Tiller, Gregor P. Henze, and Clarence E. Waters. 2010. "The performance of occupancy-based lighting control systems: A review." *Lighting Research & Technology* 42:415–431. doi:10.1177/1477153510376225. www.researchgate.net/publication/245385617_The_performance_of_occupancy-based_lighting_control_systems_A_review.

Haasl, Tudi, Karl Stum, and Mark Arney. 1996. "Better Buildings Through Improved O&M—A Five Building Case Study." *Proceedings of the Fourth National Conference on Building Commissioning*.

Han, Hua, Zhikun Cao, Bo Gu, and Neng Ren. 2010. "PCA-SVM-Based Automated Fault Detection and Diagnosis (AFDD) for Vapor-Compression Refrigeration Systems." *HVAC&R Research* 16:295–313. doi:10.1080/10789669.2010.10390906. www.researchgate.net/publication/232964533_PCA-SVM-Based_Automated_Fault_Detection_and_Diagnosis_AFDD_for_Vapor-Compression_Refrigeration_Systems.

House, John M., Won Yong Lee, and Don Ryul Shin. 1999. "Classification Techniques for Fault Detection and Diagnosis of an Air-Handling Unit." *ASHRAE Transactions: Symposia* Atlanta 105:1087–1097. https://www.nist.gov/publications/classification-techniques-fault-detection-and-diagnosis-air-handling-unit.

Jacobs, Pete, Vernon Smith, Cathy Higgins, and Matt Brost. 2003. "Small Commercial Rooftops: Field Problems, Solutions and the Role of Manufacturers." *Proceedings of the Eleventh National Conference on Building Commissioning* May 20–22. www.performancealliance.org/Portals/4/Documents/Committees/NonResQM/2003_Jacobs_CEC%20Rooftop%20Unit%20study.pdf.

Kahn, Aleisha, Amanda Potter, and Tudi Haasl. 2002. "Retrocommissioning of Two Long-Term Care Facilities in California." *Proceedings of the ACEEE Summer Study on Energy Efficiency in Buildings* 3.169–3.180. American Council for an Energy Efficient Economy. http://aceee.org/files/proceedings/2002/data/papers/SS02_Panel3_Paper14.pdf.

Khan, Yasin, Vaibhav Rai Khare, Jyotirmay Mathur, and Mahabir Bhandari. 2015. "Performance evaluation of radiant cooling system integrated with air system under different operational strategies." *Energy and Buildings* 97:118–128. doi:10.1016/j.enbuild.2015.03.030. www.osti.gov/biblio/1185702-performance-evaluation-radiant-cooling-system-integrated-air-system-under-different-operational-strategies.

Lee, Sang Hoon, and Francis W.H. Yik. 2010. "A study on the energy penalty of various air-side system faults in buildings." *Energy and Buildings* International Conference on Building Energy and Environment (COBEE 2008) 42:2–10. doi:10.1016/j.enbuild.2009.07.004. www.researchgate.net/publication/257226594_A_study_on_the_energy_penalty_of_various_air-side_system_faults_in_buildings.



This report is available at no cost from the National Renewable Energy Laboratory (NREL) at www.nrel.gov/publications.

Li, Haorong, and James E. Braun. 2007. "An overall performance index for characterizing the economic impact of faults in direct expansion cooling equipment." *International Journal of Refrigeration* 30:299–310. doi:10.1016/j.ijrefrig.2006.07.026. www.researchgate.net/publication/223475988_An_overall_performance_index_for_characterizing_the_economic_impact_of_faults_in_direct_expansion_cooling_equipment.

Mowris, Robert J., Anne Blankenship, and Ean Jones. 2004. "Field Measurements of Air Conditioners with and without TXVs." *Proceedings of the ACEEE Summer Study on Energy Efficiency in Buildings* 1-212–1-227. American Council for an Energy Efficient Economy. https://aceee.org/files/proceedings/2004/data/papers/SS04_Panel1_Paper19.pdf.

Neme, Chris, John Proctor, and Steve Nadel. 1999. *Energy Savings Potential from Addressing Residential Air Conditioner and Heat Pump Installation Problems*. Text No. Report Number A992. American Council for an Energy Efficient Economy. http://aceee.org/research-report/a992.

Oleskowicz-Popiel, Czeslaw, and Marta Sobczak. 2014. "Effect of the roller blinds on heat losses through a double-glazing window during heating season in Central Europe." *Energy and Buildings* 73:48–58. doi:10.1016/j.enbuild.2013.12.032. www.researchgate.net/publication/260111484_Effect_of_the_roller_blinds_on_heat_losses_through_a_double-glazing_window_during_heating_season_in_Central_Europe.

Palani, Manivannan, Dennis O'Neal, and Jeff Haberl. 1992. "The Effect of Reduced Evaporator Air Flow on the Performance of a Residential Central Air Conditioner." *Proceedings of the Eighth Symposium on Improving Building Systems in Hot and Humid Climates* 20–26. Energy Systems Laboratory. https://oaktrust.library.tamu.edu/bitstream/handle/1969.1/92896/ESL-HH-92-05-04.pdf?sequence=1&isAllowed=y.

Parekh, Anil. 1992. "Power Demand and Energy Savings Through Air Leakage Control in High-Rise Residential Buildings in Cold Climates." *Proceedings of the Thermal Performance of the Exterior Envelopes of Whole Buildings V International Conference* 632–642. http://web.ornl.gov/sci/buildings/conf-archive/1992%20B5%20papers/084.pdf.

Proctor, John. 2004. "Residential and Small Commercial Central Air Conditioning; Rated Efficiency isn't Automatic." Presentation at the Public Session, ASHRAE Winter Meeting, Anaheim, California.

Qin, Jianying, and Shengwei Wang. 2005. "A fault detection and diagnosis strategy of VAV air-conditioning systems for improved energy and control performances." *Energy and Buildings* 37:1035–1048. doi:10.1016/j.enbuild.2004.12.011. www.researchgate.net/publication/223929832_A_fault_detection_and_diagnosis_strategy_of_VAV_air-conditioning_systems_for_improved_energy_and_control_performances.

Qureshi, Bilal A., and Syed M. Zubair. 2011. "Performance degradation of a vapor compression refrigeration system under fouled conditions." *International Journal of Refrigeration* 34: 1016–1027. doi:10.1016/j.ijrefrig.2011.02.012. www.researchgate.net/publication/251508604_Performance_degradation_of_a_vapor_compression_refrigeration_system_under_fouled_conditions.



This report is available at no cost from the National Renewable Energy Laboratory (NREL) at www.nrel.gov/publications.

Qureshi, Bilal A., and Syed M. Zubair. 2014. "The impact of fouling on the condenser of a vapor compression refrigeration system: An experimental observation." *International Journal of Refrigeration* 38: 260–266. doi:10.1016/j.ijrefrig.2013.08.012. www.researchgate.net/publication/267452242_The_impact_of_fouling_on_the_condenser_of_a_vapor_compression_refrigeration_system_An_experimental_observation.

Roth, Kurt, Detlef Westphalen, Patricia Llana, and Michael Feng. 2004. "The Energy Impact of Faults in U.S. Commercial Buildings." International Refrigeration and Air Conditioning Conference. July 12–15. http://docs.lib.purdue.edu/iracc/665.

Roth, Kurt W., Detlef Westphalen, Michael Y. Feng, Patricia Llana, and Louis Quartararo. 2005. *Energy Impact of Commercial Building Controls and Performance Diagnostics: Market Characterization, Energy Impact of Building Faults and Energy Savings Potential*. TIAX reference no. D0180. U.S. Department of Energy Building Technologies Program. http://s3.amazonaws.com/zanran_storage/www.tiaxllc.com/ContentPages/42428345.pdf.

RSMeans. 2017. Data from Gordian. Accessed 6.26.17. www.gordian.com/products/rsmeans-data-services.

Rubinstein, Francis M., Mahmut Karayel, 1984. "The Measured Energy Savings from Two Lighting Control Strategies." *IEEE Transactions on Industry Applications* IA-20, 1189–1197. doi:10.1109/TIA.1984.4504582. www.researchgate.net/publication/3174620_The_Measured_Energy_Savings_from_Two_Lighting_Control_Strategies.

Schein, Jeffrey, and John M. House. 2003. "Application of Control Charts for Detecting Faults in Variable-Air-Volume Boxes." *ASHRAE Transactions.* Atlanta 109. https://ws680.nist.gov/publication/get_pdf.cfm?pub_id=101206.

Shaw, Chia-Yu, and James T. Reardon. 1995. "Changes in Airtightness Levels of Six Office Buildings." *Airflow Performance of Building Envelopes, Components, and Systems* Mark P. Modera and Andrew K. Persily (eds.). ASTM International, 100 Barr Harbor Drive, P.O. Box C700, West Conshohocken, Pennsylvania 19428-2959, 47:47–57. doi:10.1520/STP14688S. www.astm.org/DIGITAL_LIBRARY/STP/PAGES/STP14688S.htm.

Srinivasan, Shravan, Arunchandar Vasan, Venkatesh Sarangan, and Anand Sivasubramaniam. 2015. "Bugs in the Freezer: Detecting Faults in Supermarket Refrigeration Systems Using Energy Signals." *Proceedings of the 2015 ACM Sixth International Conference on Future Energy Systems, E-Energy '15* Bangalore, India, July 14–17. Association for Computing Machinery. New York, NY, USA. 101–110. doi:10.1145/2768510.2768536. https://dl.acm.org/citation.cfm?doid=2768510.2768536.

Von Neida, Bill, Dorene Manicria, and Allan Tweed. 2013. "An Analysis of the Energy and Cost Savings Potential of Occupancy Sensors for Commercial Lighting Systems." *Journal of the Illuminating Engineering Society* 30:111–125. doi:10.1080/00994480.2001.10748357. www.researchgate.net/publication/261684584_An_Analysis_of_the_Energy_and_Cost_Savings_Potential_of_Occupancy_Sensors_for_Commercial_Lighting_Systems.



This report is available at no cost from the National Renewable Energy Laboratory (NREL) at www.nrel.gov/publications.

Westphalen, Detlef, and Scott Koszalinski. 2001. *Energy Consumption Characteristics of Commercial Building HVAC Systems Volume I: Chillers, Refrigerant Compressors, and Heating Systems*. Contract No. DE-AC01-96CE23798. Final Report to the U.S. Department of Energy. www1.eere.energy.gov/buildings/publications/pdfs/commercial_initiative/hvac_volume1_final_report.pdf.

Wichman, Adam, and James E. Braun. 2008. "Fault Detection and Diagnostics for Commercial Coolers and Freezers." *International Refrigeration and Air Conditioning Conference*. http://docs.lib.purdue.edu/cgi/viewcontent.cgi?article=1918&context=iracc.

Xiao, Fu, Yang Zhao, Jin Wen, and Shengwei Wang. 2013. "Bayesian network based FDD strategy for variable air volume terminals." *Automation in Construction* 41:106–118. doi:10.1016/j.autcon.2013.10.019. www.researchgate.net/publication/259136248_Bayesian_network_based_FDD_strategy_for_variable_air_volume_terminals.



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# Appendix A. Commercial Building Characteristics

**Table A1. Major Fuel Consumption in Small Commercial Buildings by End Use**

(Source: CBECS 2012a, Table E1)

| | Total Major Fuel Consumption (trillion Btu) | | | |
|---|---|---|---|---|
| | ***All Buildings*** | **Small Commercial Buildings** | | **Medium and Large Commercial Buildings, >10,000 ft$^2$** |
| | | **<5,000 ft$^2$** | **>5,000 ft$^2$ and <10,000 ft$^2$** | |
| *Total* | *6,963* | *723* | *646* | *5,594* |
| Space heating | *1,756* | 155 | 157 | 1,444 |
| Cooling | *656* | 50 | 45 | 561 |
| Ventilation | *668* | 45 | 48 | 575 |
| Water heating | *507* | 56 | 42 | 409 |
| Lighting | *724* | 59 | 58 | 607 |
| Cooking | *517* | 105 | 82 | 330 |
| Refrigeration | *670* | 131 | 93 | 446 |
| Office equipment | *172* | 21 | 17 | 134 |
| Computing | *405* | 33 | 33 | 339 |
| Others | *857* | 56 | 62 | 739 |



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**Table A2. Total Floor Space Served by Different Heating Equipment**

(Source: CBECS 2012b, Table B39)

| | Total Floor Space (million ft²) | | | |
|---|---|---|---|---|
| | ***All Buildings*** | **Small Commercial Buildings** | | **Medium and Large Commercial Buildings, >10,000 ft²** |
| | | **<5,000 ft²** | **>5,000 ft² and <10,000 ft²** | |
| *All buildings* | *87,093* | *8,041* | *8,900* | *70,152* |
| *Buildings with space heating* | *80,078* | 6,699 | 7,590 | 65,789 |
| Heat pumps | *11,846* | 868 | 1,038 | 9940 |
| Furnaces | *8,654* | 1,091 | 1,416 | 6,147 |
| Individual space heaters | *20,766* | 1,747 | 2,025 | 16,994 |
| District heat | *5,925* | Q | Q | Q |
| Boilers | *22,443* | 400 | 734 | 21,309 |
| Packaged heating units | *49,188* | 3,809 | 4,622 | 40,757 |
| Other | *1,574* | Q | Q | Q |

Q = Data withheld either because the relative standard error was greater than 50% or fewer than 20 buildings were sampled.



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**Table A3. Total Floor Space Served by Different Cooling Equipment**

(Source: CBECS 2012c, Table B41)

| | Total Floor Space (million ft²) | | | |
|---|---|---|---|---|
| | *All Buildings* | Small Commercial Buildings: <5,000 ft² | Small Commercial Buildings: >5,000 ft² and <10,000 ft² | Medium and Large Commercial Buildings, >10,000 ft² |
| *All buildings* | *87,093* | *8,041* | *8,900* | *70,152* |
| *Buildings with cooling* | *79,294* | 6,124 | 7,304 | 65,866 |
| Residential-type central AC systems | *14,765* | 2,350 | 2,968 | 9,447 |
| Heat pumps | *12,538* | 983 | 1,193 | 10,362 |
| Individual AC units | *12,420* | 1,027 | 972 | 10,421 |
| District chilled water | *4,608* | Q | Q | Q |
| Central chillers | *17,041* | Q | Q | Q |
| Packaged AC units | *45,153* | 2,154 | 3,082 | 39,917 |
| Swamp coolers | *1,918* | 155 | Q | Q |
| Other | *328* | Q | N | Q |

*Q = Data withheld either because the relative standard error was greater than 50% or fewer than 20 buildings were sampled.*

*N = No cases in reporting sample.*

**Table A4. Major Fuel Energy Intensity for Space Heating by Equipment Type**

(Source: CBECS 2012d, Table E2)

| | Major Fuel Energy Intensity (thousand Btu/ft²) | | | | |
|---|---|---|---|---|---|
| | Heat Pumps | Furnaces | Individual Space Heaters | Boilers | Packaged Heating Units |
| Major fuel energy intensity for space heating (thousand Btu/ft²) | 12.1 | 21.3 | 23 | 33.3 | 19 |



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**Table A5. Major Fuel Energy Intensity for Space Cooling by Equipment Type**

(Source: CBECS 2012d, Table E2)

| | Major Fuel Energy Intensity (thousand Btu/ft$^2$) | | | |
|---|---|---|---|---|
| | **Heat Pumps** | **Residential-Type AC Units** | **Individual AC Units** | **Packaged AC Units** |
| Major fuel energy intensity for space cooling (thousand Btu/ft$^2$) | 9.2 | 6.3 | 7.9 | 8.9 |

**Table A6. Lighting Operation Features**

(Source: CBECS 2012e, Table B7)

| | Total Floor Space (million ft$^2$) | | | |
|---|---|---|---|---|
| | | Small Commercial Buildings | | |
| | ***All Buildings*** | **<5,000 ft$^2$** | **>5,000 ft$^2$ & <10,000 ft$^2$** | **Medium and Large Commercial Buildings, >10,000 ft$^2$** |
| *All buildings* | *87,093* | *8,041* | *8,900* | *70,152* |
| *Buildings never open/ electricity not used* | *3,603* | *807* | *727* | *2,069* |
| **Percent lit during off hours** | | | | |
| Zero | *24,746* | 4,000 | 4,256 | 16,490 |
| 1 to 50 | *50,753* | 3,068 | 3,798 | 43,887 |
| 51 to 100 | 6,926 | 280 | 319 | 6,327 |
| Building always open with no off hours | 2,443 | 144 | Q | Q |
| Lighting scheduling | *30,263* | 984 | 1,417 | 27,862 |
| Occupancy sensors | *35,871* | 527 | 1171 | 34,173 |



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# Appendix B. Fault Categorization

**Table B1. Definitions of Fault Measures**

| Location | Fault Stage | Fault Type | Faults | CBECS Classification | | |
|---|---|---|---|---|---|---|
| | | | | Heating | Cooling | Others |
| Envelope | Operation | Building | Excessive infiltration through the building envelope | All | All | Ventilation |
| RTU | Operation | Equipment | Air duct leakages | Packaged heating units | Packaged AC units | Ventilation |
| HVAC | Operation | Control | Incorrect HVAC on/off modes | All | All | Ventilation |
| Lighting w/o occ sensor | Operation | Control | Inappropriate lighting schedules | | | Lighting w/o occ sensor |
| HVAC | Operation | Control | Inappropriate set points/schedule for thermostats | All | All | Ventilation |
| Refrigeration | Operation | Equipment | Nonstandard charging | | | Refrigeration |
| RTU | Operation | Equipment | Insufficient evaporator airflow | | Packaged AC units, Individual AC units, Residential type central AC units | |
| Split system | Operation | Equipment | Nonstandard charging | Heat pumps | Heat pumps, Residential type central AC units | |
| RTU | Design | Equipment | Oversized equipment at design | Packaged heating units | Packaged AC units, Residential type central AC units | |
| RTU | Operation | Equipment | Nonstandard charging | | Packaged AC units, Individual AC units, Residential type central AC units | |
| Lighting w/ occ sensor | Operation | Control | Improper time delay setting in occupancy sensors | | | Lighting w/ occ sensor |
| RTU | Operation | Equipment | Inappropriate electric line voltage | Packaged heating units | Packaged AC units, Residential type central AC units | |
| Split system | Operation | Equipment | Condenser fouling | | Heat pumps, Residential type central AC units | |
| Refrigeration | Operation | Equipment | Condenser fouling | | | Refrigeration |
| HVAC | Operation | Sensor | Biased zone temperature sensor | All | All | Ventilation |



This report is available at no cost from the National Renewable Energy Laboratory (NREL) at www.nrel.gov/publications.

| Location | Fault Stage | Fault Type | Faults | CBECS Classification | | |
|---|---|---|---|---|---|---|
| | | | | Heating | Cooling | Others |
| RTU | Operation | Equipment | Economizer opening stuck at certain position | Packaged heating units | Packaged AC Units | |
| Ventilation | Operation | Equipment | Fan motor degradation | | | Ventilation |
| Refrigeration | Operation | Equipment | Compressor flow fault | | | Refrigeration |
| Split system | Operation | Equipment | Inappropriate electric line voltage | Heat pumps | Heat pumps, Residential type central AC units | |
| RTU | Operation | Equipment | Condenser fouling | | Packaged AC units, Individual AC units, Residential type central AC units | |
| Refrigeration | Operation | Equipment | Refrigerant liquid line restriction | | | Refrigeration |
| Refrigeration | Operation | Equipment | Presence of non-condensable in refrigerant | | | Refrigeration |
| Split system | Operation | Equipment | Insufficient evaporator airflow | | Heat pumps, Residential type central AC units | |
| RTU | Operation | Equipment | Compressor flow fault | | Packaged AC units, Individual AC units, Residential type central AC units | |
| RTU | Operation | Equipment | Refrigerant liquid line restriction | | Packaged AC units, Individual AC units, Residential type central AC units | |
| Refrigeration | Operation | Equipment | Condenser fan degradation | | | Refrigeration |
| Split system | Operation | Equipment | Compressor flow fault | | Heat pumps, Residential type central AC units | |
| RTU | Operation | Equipment | Presence of non-condensable in refrigerant | | Packaged AC units, Individual AC units, Residential type central AC units | |
| RTU | Operation | Sensor | Biased economizer sensor | Packaged heating units | Packaged AC units | |
| RTU | Operation | Equipment | Condenser fan degradation | | Packaged AC units, Individual AC units, Residential type central AC units | |
| Split system | Operation | Equipment | Presence of non-condensable in refrigerant | Heat pumps | Heat pumps, Residential type central AC units | |



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| Location | Fault Stage | Fault Type | Faults | CBECS Classification | | |
|---|---|---|---|---|---|---|
| | | | | Heating | Cooling | Others |
| Lighting w/ occ sensor | Operation | Sensor | Occupancy sensor malfunction | | | Lighting w/ occ sensor |
| Split system | Operation | Equipment | Refrigerant liquid line restriction | | Heat pumps, Residential type central AC units | |
| RTU | Operation | Sensor | Biased supply air temperature sensor | Packaged heating units | Packaged AC units, Residential type central AC units | |
| Refrigeration | Operation | Equipment | Evaporator fouling or frost accumulation | | | Refrigeration |
| Refrigeration | Operation | Control | Excessive cooling in refrigerated cases | | | Refrigeration |
| VAV box | Operation | Sensor | Fan control input error | | | |
| VAV box | Operation | Sensor | Flow sensor reading biased | | | |
| VAV box | Operation | Sensor | Flow sensor reading frozen | | | |
| Refrigeration | Operation | Control | Ice buildup on case door | | | Refrigeration |
| Shading | Operation | Control | Inappropriate shade control | | | |
| HVAC | Design | Sensor | Misplaced thermostats | All | All | Ventilation |
| VAV box | Operation | Equipment | Reheat coil fouling | | | |
| VAV box | Operation | Equipment | Reheat control valve stuck | | | |
| HVAC | Operation | Sensor | Temperature control input error | All | All | Ventilation |
| VAV box | Operation | Equipment | VAV box damper stuck | | | |
| VAV box | Design | Equipment | VAV terminal undersized | | | |



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# Appendix C. Fault Characterization in Small Commercial Buildings

**Table C1. Prioritization of Faults in Small Commercial Buildings Based on National Energy Impact**

| Location | Faults | *AEC*, trillion Btu/yr | *Prev* | $r_{degrad}$ | *AEI*, trillion Btu/yr | $r_{cap}$ | $r_{load}$ | $r_{SHR}$ | $AFI_{utility}$, $/yr | $AFI_{LCC}$, $/yr | $AFI_{fault}$, $/yr | Technical Complexity | Modeling & Validation Feasibility | Comments |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Envelope | Excessive infiltration through the building envelope | 500 | 94.0% | 10.0% | 47.00 | 0.0% | 10.0% | 0.0% | $ 8.77E+08 | $ 2.50E+08 | $ 1.13E+09 | high | Easy | Emmerich, McDowell, and Anis (2005) reported that only 6% of the tested buildings listed would meet the target airtightness level. Cheung and Braun (2015) reported 30% excessive infiltration resulting in 0.7% more total power consumption and 13.3% more total gas consumption. Parekh (1992) described the air leakage reduced by an average of 35%, resulted in heating energy consumption -9%. Shaw and Reardon (1995) reported an -11% heating energy consumption after a 43% improvement in measured airtightness. |
| RTU | Air-duct leakages | 300 | 65.0% | 21.0% | 40.92 | 0.0% | 19.5% | 0.0% | $ 8.38E+08 | $ 2.11E+08 | $ 1.05E+09 | high | Easy | Roth et al. (2004, 2005) estimated the occurrence of the duct leakage fault is between 50%–80% and reported heating and cooling energy increases of 13%–26%. Domanski, Henderson, and Payne (2014) reported 10% duct leakage can increase the annual power consumption by up to 12%. Neme, Proctor, and Nadel (1999) reported maximum efficiency improvement of 26% for eliminated duct leakage (21% efficiency degradation). |
| HVAC | Incorrect HVAC on/off modes | 500 | 22.5% | 20.0% | 22.50 | 0.0% | 20.0% | 0.0% | $ 4.20E+08 | $ 5.00E+08 | $ 9.20E+08 | low | Easy | Roth et al. (2004, 2005) reported the occurrence percentage is between 15%–30%. Roth et al. estimated the average increase in energy consumption is 10%–30%. |



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| Location | Faults | *AEC*, trillion Btu/yr | *Prev* | $r_{degrad}$ | *AEI*, trillion Btu/yr | $r_{cap}$ | $r_{load}$ | $r_{SHR}$ | $AFI_{utility}$, $/yr | $AFI_{LCC}$, $/yr | $AFI_{fault}$, $/yr | Technical Complexity | Modeling & Validation Feasibility | Comments |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Lighting w/o occ sensor | Inappropriate lighting schedules | 105 | 35.4% | 35.4% | 13.16 | 0.0% | 25.0% | 0.0% | $ 3.93E+08 | $ 8.04E+03 | $ 3.93E+08 | low | Easy | Khan et al. (2015) estimated an approximate savings of 10% with better lighting control. Rubinstein et al. (1984) reported savings in office building applications between 10% and 40%. So prevalence*energy impact = 12.5% |
| HVAC | Inappropriate set points/schedule for thermostats | 500 | 22.5% | 10.7% | 12.04 | 0.0% | 10.7% | 0.0% | $ 2.25E+08 | $ 2.68E+08 | $ 4.92E+08 | low | Easy | Prevalence assumed as the same as incorrect on/off percentage (15%–30%). Domanski, Henderson, and Payne (2014) reported 1.1K lower set point lead to 32% annual power consumption increase. Cheung and Braun (2015) 4K reported reduction of cooling thermostat set point when outside temperature is higher than 30°C resulting in 0.7% more power consumption. 4K increase of heating thermostat set point when outside temperature is lower than 5°C resulting in 31.3% more gas consumption. No overnight setback resulting in 0.1% more power consumption and 1.6% more gas consumption. |
| Refrigeration | Nonstandard refrigerant charging | 224 | 42.0% | 7.5% | 7.06 | 10.0% | 0.0% | -5.0% | $ 2.11E+08 | $ 0.00E+00 | $ 2.11E+08 | medium | Moderate | Prevalence and energy impact values for the RTU and split system faults were used (no data available in literature, but there are references mentioning). (Han et al. 2010; Wichman and Braun 2008) |
| RTU | Insufficient evaporator airflow | 96 | 18.0% | 27.3% | 4.71 | 10.0% | 0.0% | 10.0% | $ 1.41E+08 | $ 4.84E+08 | $ 6.25E+08 | medium | Easy | Breuker and Braun (1998a, 1998b) reported 6% of major faults of RTUs is a result of evaporator fouling. Roth et al. (2004, 2005) estimated the possibility of the insufficient evaporator airflow between 20%–40%. Breuker and Braun reported 17% drop of COP when the airflow rate to the evaporator of a |



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| Location | Faults | *AEC*, trillion Btu/yr | *Prev* | $r_{degrad}$ | *AEI*, trillion Btu/yr | $r_{cap}$ | $r_{load}$ | $r_{SHR}$ | $AFI_{utility}$, $/yr | $AFI_{LCC}$, $/yr | $AFI_{fault}$, $/yr | Technical Complexity | Modeling & Validation Feasibility | Comments |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | | | | 3-ton rooftop unit is reduced by 36%. Palani et al. (1992) reported EER drop from 4.2% at 25% reduction in evaporator airflow to 71% at 90% reduction in evaporator airflow. Roth et al. (2004, 2005) estimated energy impact of fault 4%–13%. |
| Split system | Nonstandard refrigerant charging | 77 | 72.0% | 8.1% | 4.48 | 5.0% | 0.0% | -1.0% | $ 1.09E+08 | $ 7.30E+07 | $ 1.82E+08 | medium | Moderate | Mowris, Blankenship, and Jones (2004) reported 72% of the tested units had improper refrigerant charge. Domanski, Henderson, and Payne (2014) reported -30% charge resulting in -15% (-5%) COP, -13% (-10%) capacity, +2% SHR, and -2.5% (-5%) power for cooling (heating). Domanski, Henderson, and Payne (2014) reported +30% charge resulting in -2.5% (-10%) COP, +2% (+1%) capacity, 0% SHR, and +5% (+12%) power for cooling (heating). |
| RTU | Oversized equipment at design | 240 | 68.0% | 2.0% | 3.27 | 0.0% | 2.0% | 0.0% | $ 5.93E+07 | $ 3.04E+07 | $ 8.97E+07 | low | Easy | Djunaedy et al. (2011) reported 51% use manufacturers' software for sizing and 17% rely on rules-of-thumb, which are an indication of oversizing. Domanski, Henderson, and Payne (2014) estimated 50% oversizing resulting in -2% COP, 0% capacity, and 0% SHR. |
| RTU | Nonstandard refrigerant charging | 96 | 42.0% | 7.5% | 3.02 | 5.0% | 0.0% | -1.0% | $ 9.02E+07 | $ 8.71E+07 | $ 1.77E+08 | medium | Moderate | Breuker and Braun (1998a, 1998b) reported 21% of RTU's fault is caused by refrigerant leaks. Downey and Proctor (2002) reported improper refrigerant charge was found in 57% of all systems. Proctor (2004) reported 60% of commercial air conditioners had incorrect refrigerant charge. Roth et al. (2004, 2005) estimated 40%–80% as occurrence percentage. Cheung and Braun (2015) |



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| Location | Faults | *AEC*, trillion Btu/yr | *Prev* | $r_{degrad}$ | *AEI*, trillion Btu/yr | $r_{cap}$ | $r_{load}$ | $r_{SHR}$ | $AFI_{utility}$, $/yr | $AFI_{LCC}$, $/yr | $AFI_{fault}$, $/yr | Technical Complexity | Modeling & Validation Feasibility | Comments |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | | | | estimated 30% undercharge, resulting in 0.7% increased total building energy. Roth et al. estimated energy impact of fault 5%–15%. Remaining values were adopted from split system fault. |
| Lighting w/ occ sensor | Improper time delay setting in occupancy sensors | 12 | 80.0% | 31.0% | 2.91 | 0.0% | 31.0% | 0.0% | $ 8.69E+07 | $ 1.11E+03 | $ 8.69E+07 | low | Easy | An estimate of 0.8 was assumed for prevalence: 0.8 since most delay settings in occupancy sensors are above 20 mins. Von Neida, Manicria, and Tweed et al. (2012) reported for 5–20 min delay, energy savings were estimated for Classroom 37%–45%, Private Office 22%–32%, Conference Room 32%–43%, Break Room 10%–22%, Restroom 26%–41%. |
| RTU | Inappropriate electric line voltage | 240 | 14.2% | 8.5% | 2.90 | 0.0% | 8.5% | 0.0% | $ 5.26E+07 | $ 1.29E+08 | $ 1.82E+08 | medium | Hard | Energy impact is assumed the same as the split system's percentage. Breuker and Braun (1998a, 1998b) reported 14.2% of major faults of RTUs is a result of electrical faults only including inappropriate electric line voltage fault. Energy impact is assumed as the same as the split system's percentage. |
| Split system | Condenser fouling | 54 | 44.0% | 11.0% | 2.59 | 8.0% | 0.0% | -5.0% | $ 7.74E+07 | $ 4.12E+07 | $ 1.19E+08 | medium | Easy | Mowris, Blankenship, and Jones (2004) reported 44% of entire units had improper airflow through the condenser. Cho et al. (2014) estimated -11% COP, -8% capacity, +5% SHR, and +5% power when blocked area increases 30%. Split air conditioners with condenser fouling at 50% resulting in elec consumption +1.1% (Cheung and Braun 2015). |



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| Location | Faults | *AEC*, trillion Btu/yr | *Prev* | $r_{degrad}$ | *AEI*, trillion Btu/yr | $r_{cap}$ | $r_{load}$ | $r_{SHR}$ | $AFI_{utility}$, $/yr | $AFI_{LCC}$, $/yr | $AFI_{fault}$, $/yr | Technical Complexity | Modeling & Validation Feasibility | Comments |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Refrigeration | Condenser fouling | 224 | 4.8% | 18.0% | 1.94 | 8.0% | 0.0% | -5.0% | $ 5.79E+07 | $ 0.00E+00 | $ 5.79E+07 | medium | Easy | Prevalence and energy impact values for the RTU and split systems were used (no data available in literature, but there are references mentioning). (Han et al. 2010; Qureshi and Zubair 2014, 2011; Wichman and Braun 2008). |
| HVAC | Biased zone temperature sensor | 500 | 38.0% | 1.0% | 1.90 | 0.0% | 1.0% | 0.0% | $ 3.55E+07 | $ 2.50E+07 | $ 6.05E+07 | low | Easy | Prevalence is assumed as 38%, which is the percentage of the zone thermostat malfunctioning measured by Jacobs et al. (2003). Lee and Yik (2010) reported positive offset of 4◦C results in 19% less cooling energy and negative offset of 4◦C results in 21% increased cooling energy. |
| RTU | Economizer opening stuck at certain position | 207 | 28.3% | 3.0% | 1.75 | 0.0% | 3.0% | 0.0% | $ 2.85E+07 | $ 2.50E+07 | $ 5.35E+07 | low | Easy | Jacobs et al. (2003) reported 30% of economizers in the field did not move. Roth et al. (2004, 2005) estimated 25%–40% as occurrence percentage. Lee and Yik (2010) reported outdoor damper stuck closed results in 12% decreased HVAC energy (ventilation requirement violated) and outdoor air damper stuck open results in 3% more HVAC energy. |
| Ventilation | Fan motor degradation | 93 | 3.6% | 37.0% | 1.25 | 0.0% | 37.0% | 0.0% | $ 3.74E+07 | $ 9.08E+07 | $ 1.28E+08 | medium | Easy | Breuker and Braun (1998a, 1998b) reported 3.6% of major faults of RTUs is a result of air handling faults only including fan motor degradation fault. Cheung and Braun (2015) estimated 25% motor efficiency degradation resulting in 1.2% whole building energy (approximately 37% blower energy use). |



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| Location | Faults | *AEC*, trillion Btu/yr | *Prev* | $r_{degrad}$ | *AEI*, trillion Btu/yr | $r_{cap}$ | $r_{load}$ | $r_{SHR}$ | $AFI_{utility}$, $/yr | $AFI_{LCC}$, $/yr | $AFI_{fault}$, $/yr | Technical Complexity | Modeling & Validation Feasibility | Comments |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Refrigeration | Compressor flow fault | 224 | 5.0% | 10.0% | 1.12 | 10.0% | 0.0% | -5.0% | $ 3.35E+07 | $ 0.00E+00 | $ 3.35E+07 | high | Hard | Prevalence and energy impact values for the split system cases were used (no data available in literature, but there are references mentioning). (Han et al. 2010; Wichman and Braun 2008). |
| Split system | Inappropriate electric line voltage | 77 | 14.2% | 8.5% | 0.92 | 0.0% | 8.5% | 0.0% | $ 2.25E+07 | $ 1.47E+08 | $ 1.69E+08 | medium | Hard | Prevalence is assumed as the same as the RTU's percentage. Cho et al. (2014) and Domanski, Henderson, and Payne (2014) reported +20% line voltage resulting in -10% COP, -1% capacity, 0% SHR, and +7% power (cooling). Domanski, Henderson, and Payne (2014) reported -7% COP, +1% capacity and +9% power (heating). |
| RTU | Condenser fouling | 96 | 4.8% | 18.0% | 0.83 | 8.0% | 0.0% | -5.0% | $ 2.47E+07 | $ 7.26E+07 | $ 9.74E+07 | medium | Easy | Breuker and Braun (1998a, 1998b) showed 2.1% of major faults of RTUs is a result of condenser fouling. Roth et al. estimated 5%–10% as occurrence percentage. Cheung and Braun (2015) reported condenser fouling with 50% blockage can result in 1.4% increased whole building energy (18% cooling energy increase). Remaining values were adopted from split system fault. |
| Refrigeration | Refrigerant liquid-line restriction | 224 | 2.0% | 17.0% | 0.76 | -2.0% | 0.0% | 2.0% | $ 2.28E+07 | $ 0.00E+00 | $ 2.28E+07 | high | Hard | Prevalence and energy impact values for the RTU cases were used (no data available in literature, but there are references mentioning). (Han et al. 2010; Wichman and Braun 2008). |
| Refrigeration | Presence of non-condensable in refrigerant | 224 | 3.0% | 9.0% | 0.60 | -0.5% | 0.0% | -1.0% | $ 1.81E+07 | $ 0.00E+00 | $ 1.81E+07 | high | Hard | Prevalence value for the chiller cases were used (no data available in literature). Energy impact value for the RTU and split system faults were used (no data available in literature). |



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| Location | Faults | *AEC*, trillion Btu/yr | *Prev* | $r_{degrad}$ | *AEI*, trillion Btu/yr | $r_{cap}$ | $r_{load}$ | $r_{SHR}$ | $AFI_{utility}$, $/yr | $AFI_{LCC}$, $/yr | $AFI_{fault}$, $/yr | Technical Complexity | Modeling & Validation Feasibility | Comments |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Split system | Insufficient evaporator airflow | 54 | 18.0% | 5.0% | 0.48 | 10.0% | 0.0% | 10.0% | $ 1.44E+07 | $ 2.75E+08 | $ 2.89E+08 | medium | Easy | Prevalence of this fault is assumed as the same as the RTU's percentage and energy impact. Cho et al. (2014) reported -30% insufficient airflow resulting in -5% COP, -10% capacity, -10% SHR, and -3% power (cooling). |
| RTU | Compressor flow fault | 96 | 5.0% | 10.0% | 0.48 | 10.0% | 0.0% | -5.0% | $ 1.43E+07 | $ 1.20E+08 | $ 1.34E+08 | high | Hard | Breuker and Braun (1998a, 1998b) reported 5% of major faults of RTUs is a result of compressor fault. Energy impact is assumed as the same as split system. |
| RTU | Refrigerant liquid-line restriction | 96 | 2.0% | 17.0% | 0.33 | 2.0% | 0.0% | 1.0% | $ 9.73E+06 | $ 6.34E+07 | $ 7.31E+07 | high | Hard | Breuker and Braun (1998a, 1998b) reported 2% of major faults of RTUs is a result of expansion device fault. Cheung and Braun (2015) estimated 30% more liquid line restriction resulting in 1.3% increased whole building energy (approximately 17% cooling energy increase). Remaining values were adopted from split system fault. |
| Refrigeration | Condenser fan degradation | 224 | 3.5% | 3.8% | 0.30 | 0.0% | 0.3% | 0.0% | $ 8.91E+06 | $ 0.00E+00 | $ 8.91E+06 | medium | Hard | Prevalence and energy impact values for the RTU cases were used (no data available in literature). Not enough reference for AEI estimation. But there are references mentioning (Srinivasan et al. 2015). |
| Split system | Compressor flow fault | 54 | 5.0% | 10.0% | 0.27 | 10.0% | 0.0% | -5.0% | $ 8.00E+06 | $ 6.82E+07 | $ 7.62E+07 | medium | Hard | Prevalence is assumed as the same as RTU's percentage. Cho et al. (2014) reported -10% COP, -10% capacity, +5% SHR, and -5% energy consumption when flow drops 12%. |



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| Location | Faults | *AEC*, trillion Btu/yr | *Prev* | $r_{degrad}$ | *AEI*, trillion Btu/yr | $r_{cap}$ | $r_{load}$ | $r_{SHR}$ | $AFI_{utility}$, $/yr | $AFI_{LCC}$, $/yr | $AFI_{fault}$, $/yr | Technical Complexity | Modeling & Validation Feasibility | Comments |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| RTU | Presence of non-condensable in refrigerant | 96 | 3.0% | 9.0% | 0.26 | -0.5% | 0.0% | -1.0% | $ 7.73E+06 | $ 0.00E+00 | $ 7.73E+06 | high | Hard | Prevalence value for the chiller cases were used (no data available in literature). Cheung and Braun (2015) estimated 60% non-condensable gas entrainment can result in 0.7% increased whole building energy (approximately 9% cooling energy increase). Remaining values were adopted from split system fault. |
| RTU | Biased economizer sensor | 207 | 0.6% | 15.8% | 0.18 | 0.0% | 6.4% | 0.0% | $ 2.96E+06 | $ 5.30E+07 | $ 5.59E+07 | low | Easy | Prevalence assumed as 0.6% from Breuker and Braun (1998a, 1998b) but only including the occurrence of the outside air damper motor fault. Cheung and Braun (2015) reported the economizer return air RH sensor bias at +3% results in 11.5% increased whole building energy (15.3% cooling energy increase) while the economizer ambient air RH sensor bias at –3% results in 12.2% increased whole building energy (16.2% cooling energy increase). |
| RTU | Condenser fan degradation | 96 | 3.5% | 3.8% | 0.13 | 0.0% | 3.8% | 0.0% | $ 3.81E+06 | $ 7.84E+07 | $ 8.22E+07 | medium | Hard | Breuker and Braun (1998a, 1998b) reported 3.5% of major faults of RTU is a result of condenser fan motor degradation. Cheung and Braun (2015) estimated 30% efficiency degradation result in 0.3% increased whole building energy (approximately 3.8% cooling energy increase). |
| Split system | Presence of non-condensable in refrigerant | 77 | 3.0% | 5.0% | 0.11 | -0.5% | 0.0% | -1.0% | $ 2.79E+06 | $ 0.00E+00 | $ 2.79E+06 | medium | Hard | Prevalence value for the chiller cases were used (no data available in literature). Domanski, Henderson, and Payne (2014) estimated 20% non-condensable gas resulting in -5% (-5%) COP, +2% (-1%) capacity, +1% SHR, and +5% (+5%) power for cooling (heating). |



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| Location | Faults | ***AEC***, trillion Btu/yr | ***Prev*** | $r_{degrad}$ | ***AEI***, trillion Btu/yr | $r_{cap}$ | $r_{load}$ | $r_{SHR}$ | $AFI_{utility}$, $/yr | $AFI_{LCC}$, $/yr | $AFI_{fault}$, $/yr | Technical Complexity | Modeling & Validation Feasibility | Comments |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Lighting w/ occ sensor | Occupancy-sensor malfunction | 12 | 13.0% | 3.0% | 0.05 | 0.0% | 3.0% | 0.0% | $ 1.37E+06 | $ 1.07E+02 | $ 1.37E+06 | low | Easy | Prevalence: 0.13. Energy impact: 0.03 |
| Split system | Refrigerant liquid-line restriction | 54 | 2.0% | 3.0% | 0.03 | 2.0% | 0.0% | 1.0% | $ 9.60E+05 | $ 3.60E+07 | $ 3.69E+07 | medium | Hard | Prevalence and energy impact of this fault is assumed as the same as the RTU's percentage and energy impact. Cho et al. (2014) reported +20% restriction resulting in -3% COP, -2% capacity, -1% SHR and 0% power (cooling). |
| HVAC | Temperature-control input error | 500 | | | | | 3.0% | | $ 0.00E+00 | $ 7.50E+07 | $ 7.50E+07 | low | Easy | Not enough references for AEI estimation, but there are references mentioning. (Qin and Wang 2005; Xiao et al. 2014). Roth et al (2004, 2005) estimated energy impact of fault 1%–5%. |
| HVAC | Misplaced thermostats | 500 | | | | | | | $ 0.00E+00 | | $ 0.00E+00 | low | Easy | Not enough references for AEI estimation, but can happen in the field. |
| Refrigeration | Evaporator fouling or frost accumulation | 224 | | | | | | | $ 0.00E+00 | | $ 0.00E+00 | low | Moderate | Not enough references for AEI estimation, but there are references mentioning. (Han et al. 2010; Wichman and Braun 2008). |
| Refrigeration | Excessive cooling in refrigerated cases | 224 | | | | | | | $ 0.00E+00 | | $ 0.00E+00 | low | | Not enough references for AEI estimation, but there are references mentioning (Srinivasan et al. 2015). |
| Refrigeration | Ice buildup on case door | 224 | | | | | | | $ 0.00E+00 | | $ 0.00E+00 | low | Hard | Not enough references for AEI estimation, but there are references mentioning (Srinivasan et al. 2015). |
| RTU | Biased supply-air temperature sensor | 240 | | | | | 1.0% | | $ 0.00E+00 | $ 1.48E+07 | $ 1.48E+07 | high | Easy | Not enough references for AEI estimation. Lee and Yik (2010) reported positive supply air temperature sensor offset (14◦C to 18◦C in summer, and from 16◦C to 20◦C in winter) results in 11% decreased energy consumption and negative supply air temperature sensor offset (14◦C to 10◦C in summer, and from 16◦C to 12◦C in winter) results in 11% increased total energy consumption. Cheung and Braun |



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| Location | Faults | *AEC*, trillion Btu/yr | *Prev* | $r_{degrad}$ | *AEI*, trillion Btu/yr | $r_{cap}$ | $r_{load}$ | $r_{SHR}$ | $AFI_{utility}$, $/yr | $AFI_{LCC}$, $/yr | $AFI_{fault}$, $/yr | Technical Complexity | Modeling & Validation Feasibility | Comments |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | | | | (2015) reported air supply temperature sensor bias at +2K resulting in electricity consumption +11.2% and gas consumption –7.3%. |
| Shading | Inappropriate shade control | | | | | | | | | | | low | | Not enough references for AEI estimation, but there are references mentioning. (Oleskowicz-Popiel and Sobczak 2014). |
| VAV box | Fan control input error | | | | | | | | | | | low | | Not enough references for AEI estimation, but there are references mentioning (Xiao et al. 2014). |
| VAV box | Flow-sensor reading biased | | | | | | | | | | | low | Easy | Not enough references for AEI estimation, but there are references mentioning (Qin and Wang 2005; Xiao et al. 2014). |
| VAV box | Flow-sensor reading frozen | | | | | | | | | | | low | Easy | Not enough references for AEI estimation, but there are references mentioning (Qin and Wang 2005; Xiao et al. 2014). |
| VAV box | Reheat coil fouling | | | | | | | | | | | medium | | Not enough references for AEI estimation. |
| VAV box | Reheat control valve get stuck | | | | | | | | | | | low | | Not enough references for AEI estimation, but there are references mentioning. (Schein and House 2003) |
| VAV box | VAV box damper got stuck | | | 37.0% | | | | | | | | low | | Not enough references for AEI estimation. Lee and Yik (2010) reported fully open stuck damper resulting in 37% more total cooling energy usage. Not enough references for AEI estimation, but there are references mentioning (House, Lee, and Shin 1999; Qin and Wang 2005; Schein and House 2003; Xiao et al. 2014). |
| VAV box | VAV terminal undersized | | | | | | | | | | | low | | Not enough references for AEI estimation, but there are references mentioning (Qin and Wang 2005; Xiao et al. 2014). |



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