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ABSTRACT

Many buildings have a wide range of faults that increase energy consumption, but the national energy impact of specific faults has yet to be quantified. This paper reports the preliminary results of a study to quantify the national energy impact of building faults. Based on a detailed literature review, the authors identified thirteen key faults and developed bottom-up energy impact ranges for each. The key faults are estimated to increase commercial building annual energy consumption by between 0.35 and 1.7 quads (0.4 and 1.8 Exajoules [EJ]). This equals between 4% and 18% of the sum of commercial building HVAC, lighting, and refrigeration energy consumption and is consistent with the typical range of energy waste reported in building commissioning studies. Two faults, “Lights or HVAC Left on When Space Unoccupied” and “Duct Leakage”, account for at least half of the estimated energy impact. Due to data limitations, the faults have large energy impact ranges, particularly controls-related faults.

1. INTRODUCTION

The building commissioning literature, targeted building equipment and systems surveys, and anecdotal information suggest the widespread existence of building equipment and system faults. In this context, faults denote deviations from intended building equipment and systems performance. They compromise the operational efficiency of equipment and system due to improper installation, insufficient maintenance, and a lack of attention to operations. A significant volume of literature suggests that commissioning of existing buildings typically reduces total building annual energy consumption by 5% to 20%, with higher values (up to 30%) in some buildings (see a succinct summary of building commissioning savings in Roth *et al.* 2003). In addition to increasing building energy consumption, faults may degrade climate control and occupant comfort.

The actual energy wasted by different buildings varies greatly and depends on the types of systems in a building, how well building operators maintain the building, and what failures occur. In general, the energy use impact of faults depends on the system details. Some building faults do not have a significant effect on building energy consumption. This often occurs when a fault results in decreased occupant comfort. If a fault results in uncomfortable indoor conditions, it typically generates complaint calls and the problem is addressed. For example, a packaged AC unit with very low refrigerant charge levels will not have sufficient capacity to meet cooling loads on hot days. On a hot day, the occupants notice and complain about the uncomfortable conditions, which will usually lead to a service call and subsequent identification and resolution of the problem. In other cases, building operators or occupants may respond to faults by making adjustments to building systems that resolve the problem without increasing energy consumption. For instance, a space temperature sensor that drifts out of calibration generally leads to adjustment of thermostat setpoints and little change in space temperature levels. On the other hand, a failure that does not impact occupant comfort may escape detection and persist for a long time. If a supply air or chilled water temperature sensor drifts out of calibration, it causes the air or chilled water temperature to increase or decrease. The building operator or tenants often will not notice the problem because it may not affect their comfort. Because the fault is not noticed and fixed, energy use often increases. Other faults may actually reduce energy consumption, for example, an incorrect damper position that reduces the intake of outdoor air for a building located in a hot and humid climate.

Although past commissioning studies yield an estimate for the total energy impact of building faults, estimates of the national energy impact of specific building faults have yet to be developed. A breakdown of the national energy impact of specific building faults can help to prioritize building maintenance activities and the development of cost-effective diagnostic tools that address the more common faults that have the greatest energy impact.

2. IDENTIFICATION OF KEY FAULTS

The authors performed a literature review to identify problems that arise in building HVAC, lighting, water heating, and refrigeration systems and may increase building energy consumption. This uncovered more than 100 faults that occur in commercial building systems. A calculation methodology was developed to estimate the annual energy consumption impact, AEC_{fault}, of each fault based on information found in the literature. Specifically, the authors synthesized the information found in the literature to develop estimates for the three primary factors that affect AEC_{fault}. The *fault relevant AEC*, AEC_{RE}, equals the quantity of national energy consumption potentially impacted by the fault. These values come from breakdowns of the approximately 17 quads [18 EJ] of commercial building energy consumption shown in Table 1. The *fault frequency*, $Frequ_{Fault}$, denotes how frequently the fault occurs in relevant equipment and system types such that it causes an appreciable increase in energy consumption beyond as-intended performance. The *average percent increase in energy consumption* due to the fault, $Degrade_{fault}$, refers to the average increase in energy consumption due to the fault. The product of these three estimates equals AEC_{fault}:

$$AEC_{fault} = AEC_{re} \cdot Frequ_{fault} \cdot Degradation_{fault} \,. \qquad (1)$$

Table 1: Commercial Building Annual Primary Energy Consumption Breakdown (circa 2000)

End-use	Primary Energy quads (EJ)	% of Total	Source
Lighting	4.2 (4.4)	27%	Navigant Consulting (2002)
Water Heating	1.2 (1.2)	8%	EIA (2003)
Refrigeration	1.0 (1.0)	6%	ADL (1996)
Ventilation/Pumping	1.5 (1.5)	10%	ADL (1999)
Supply/Return Fans	*0.7 (0.8)*	*5%*	
Exhaust Fans	*0.5 (0.5)*	*3%*	
Water Pumps	*0.1 (0.1)*	*1%*	
Other Parasitics	*0.1 (0.1)*	*1%*	
Heating	1.7 (1.8)	11%	ADL (2001)
Furnaces	*0.3 (0.4)*	*2%*	
Boilers	*0.4 (0.4)*	*2%*	
Packaged Unitary	*0.4 (0.5)*	*3%*	
Other Heating Equipment	*0.5 (0.5)*	*4%*	
Cooling	1.4 (1.4)	9%	
Packaged Unitary AC	*0.7 (0.8)*	*5%*	
Chillers	*0.4 (0.4)*	*3%*	
Other Cooling Equipment	*0.2 (0.2)*	*1%*	
Other Building End-Uses	6.3 (6.6)	29%	Difference between above estimates and total
Total	17.2 (18.1)		EIA (2003)
U.S. Energy Consumption	97 (102)		EIA (2003)
Note: sums may not equal totals due to rounding.			

The preliminary energy impact estimates for each fault were used to select thirteen "key" faults for further evaluation (see Table 2). The authors then developed more refined national energy impact estimates for all key faults. This consisted of a thorough literature review of numerous potential sources of information about the prevalence and energy impact of the key faults. Building case studies from the building commissioning literature proved to be particularly fruitful information sources. After identifying sources with relevant information about the key faults, the authors compiled information about fault frequency and energy impact for each fault. They also noted information that could help to extrapolate the energy impact findings to a national context, such as building types, systems, location and sizes. Altogether, more than 100 different references yielded in excess of 600 pieces of information about the key faults. Supporting analyses were also performed to provide supplemental information about energy impacts.

Table 2: Faults Selected for More Refined Evaluation

Fault Type	Fault	Description of Fault, Common Causes
Lighting and HVAC	Lights or HVAC Left on When Space Unoccupied	Malfunctioning, unprogrammed, or incorrectly programmed setback thermostats; EMCSs with inappropriate schedules or that lack schedules, (improper configuration, system reset after a power failure, user overrides of schedules, etc.)
Air Distribution	Duct Leakage	Causes include: Torn and missing external duct wrap, poor workmanship around duct take-offs and fittings, disconnected ducts, improperly installed duct mastic, temperature and pressure cycling also can wear out duct seals over time, particularly for poorly supported ducts; duct connections tend to be very leaky.
Air Distribution	Dampers not Working Properly	Causes include: Corrosion and degradation that cause dampers or their actuators to seize, broken linkages, economizer control system failure; and failure of sensors that determine damper position.
Air Distribution	Airflow Not Balanced	Causes include: Poor design, incomplete or negligible testing and balancing (T&B), difficulty implementing design intent due to system complexity, post-T&B system modifications, space load changes without reconsideration of air flow and system capacity
Air Distribution	Insufficient Evaporator Airflow	Causes include: Damaged, dirty, clogged coils and filters; improper duct design, low blower speed, and dirty blower wheels
Controls	Software Programming Errors	Causes include: Improper setpoints, improper control logic, improper equipment operation, and improper operation of controlled device (e.g., VAV box, Damper, VFD, etc.)
Controls	Improper Controls Hardware Installation	High energy impact examples include: Unconnected economizers (or lacking temperature sensor) prevent economizing; VAV systems without variable-speed operation enabled operate as CAV; poor thermostat location can increase energy consumption
Controls	Improper Controls Setup / Commissioning	• Poor system operating setpoints (supply air or chilled water temperatures, etc.) • Improper equipment operating temperature ranges; • Improper control parameter coefficients for control loops (e.g. PID coefficients) • Improper reset schedules (VAV system duct pressure control, chilled or heating water temperature, etc.)
Controls	Control Component Failure or Degradation	Sensors (often temperature) out of calibration; sensor or controller failure
Waterside Issues	Valves not Closing Properly	Control valve, shutoff valve, and steam trap leakage due to valve wear (e.g., at seat or packing), valve seizure
Refrigeration Circuits	Air-Cooled Condenser Fouling	Outdoor matter deposits on the condenser coil surfaces; often comes from surroundings (e.g., dust) or seasonal (pollen in spring, leaves in autumn)
Refrigeration Circuits	Improper Refrigerant Charge	Includes over- and under-charging. Reasons include: poorly brazed joints, inadequately sealed threaded joints, fatigue of piping components, inherent component leakage (e.g., open-drive compressors, automotive-style refrigerant hose)

Section 3 presents the key findings of the analysis of key faults.

3. RESULTS

3.1 National Energy Impact of Key Faults

On a national basis, the key faults analyzed result in between 0.35 and 1.7 quads of additional energy consumption (see Table 3). Two faults, "Lights or HVAC Left on When Space Unoccupied" and "Duct Leakage," appear to account for at least half of the total fault energy impact.

Table 3: The AEC Impact of Faults Selected for Evaluation

Fault	**AEC Range quads (EJ)**	**How the Fault Can Increase Energy Consumption**
Lights or HVAC Left on When Space Unoccupied	0.1 – 0.5 (0.1 – 0.6)	Often goes undetected precisely because building unoccupied; does not include intentional after-hours lighting
Duct Leakage	0.15 – 0.4 (0.2 – 0.4)	Leakage of heated or chilled air increases heating or cooling equipment duty cycle; VAV blowers run "harder" to deliver the heating or cooling
Dampers not Working Properly	0.02 – 0.10 (0.02 – 0.11)	Economizer and outdoor air / return air damper problems that remain open and take in excess outdoor air have greatest energy impact
Airflow Not Balanced	0.02 – 0.16 (0.02 – 0.16)	• Lower T_e decreases EER of unitary equipment. • Can lead to: lower supply air temperature setpoints (increases cooling and, possibly, reheat energy), decreased chilled water temperature setpoint (increases chiller energy) • Excessive balance damper throttling or excessive air delivery increases supply and/or return fan energy • Excessive outdoor air delivery increases cooling and heating loads • Negative indoor pressure causes greater building infiltration and increases cooling and heating loads
Insufficient Evaporator Airflow	0.012 – 0.08 (0.013 – 0.08)	Evaporator airflow below design levels decreases evaporator refrigerant saturation temperature, which decreases cycle COP
Software Programming Errors	0.001 – 0.035 (0.001–0.035)	• Improper setpoints – Can increase HVAC energy consumption • Improper control logic – Can cause simultaneous heating and cooling, impede economizer function • Improper equipment operation • Improper operation of controlled device (VAV box. Damper, VFD, etc.)
Improper Controls Hardware Installation	0.0025 – 0.05 (0.025 – 0.05)	Unconnected economizers (or lacking temperature sensor) prevent economizing; VAV systems without variable-speed operation enabled operate as CAV; poor thermostat location can increase energy consumption
Improper Controls Setup / Commissioning	0.005 – 0.12 (0.005 – 0.13)	• Poor system operating setpoints – Low chilled water temperature setpoint increases cycle lift, decreases efficiency • Improper operating temperature ranges – Can cause simultaneous heating and cooling, poor (or no) economizer operation • Improper control parameter coefficients, Improper reset schedules – Subpar performance in one or more operating regime
Control Component Failure or Degradation	0.005 – 0.12 (0.005 – 0.13)	Sensors failed or out of calibration – Unnecessary heating or cooling, improper economizer operation
Valves not Closing Properly	0.0004 – 0.02 (0.0004–0.02)	Steam trap failure and leaking chilled water valves; energy waste most likely in buildings with year-round operation of a thermal system
Air-Cooled Condenser Fouling	0.004 – 0.012 (0.005–0.013)	Fouling reduces condenser coil air flow, which increases condensing pressures and increases compressor power draw
Improper Refrigerant Charge	0.02 – 0.13 (0.02 – 0.13)	Undercharge reduces evaporator's two-phase heat transfer region, decreasing P_e and increasing evaporator superheat. This increases compressor T_d, while reduced condenser inventory improves T_c approach to T_o, but with negligible subcooling. Reduced refrigerant flows through capillary expansion device decreases refrigerant flow to evaporator. Overall, P_s and P_d decrease and the system pressure ratio, increases, resulting in lower cycle efficiency. Overcharging also increases cycle pressure ratio (by increasing P_c).
TOTAL	0.35 – 1.7 (0.35 – 1.8)	Totals may not sum due to rounding

Placed in the context of commercial buildings, the key faults account for between 3% and 11% of all energy consumed by commercial buildings. Considering only systems primarily affected by the faults, that is, HVAC, lighting, and refrigeration energy consumption, the key faults represent 4% to 18% of the 9.7 quads of energy consumed by those end uses. This range is consistent with the 5% to 20% energy savings potential range found for retrocommissioning projects (see prior discussion, Roth *et al.* 2003).

Table 4 presents the ranges for the three factors that are used in the methodology to develop the estimated annual energy consumption impact, AEC_{fault}, for each key fault.

Table 4: Fault Energy Impact Calculation Parameters

Fault	**AEC_{re} quads (EJ)**	**$Freq_{fault}$**	**$Degrade_{fault}$**	**Comments**
Lights or HVAC Left on When Space Unoccupied	8.7 (9.2)	See Comment	10 – 30%	Prevalence – Lighting: 5-10%, HVAC: 15-30%
Duct Leakage	3.1 (3.3)	50 – 80%	See comment	Degradation different for CAV and VAV systems; larger buildings tend to have less leakage than smaller buildings
Dampers not Working Properly	0.9 (0.9)	25 – 40%	10 – 30%	Estimate for economizers, based primarily on prevalence and energy impact findings for packaged unitary
Airflow Not Balanced	3.1 (3.3)	25 – 50%	2 – 10%	Relevant to duct-based systems
Insufficient Evaporator Airflow	1.5 (1.5)	20 – 40%	4 – 13%	Primarily based on for packaged unitary AC prevalence and energy impact findings
Software Programming Errors	1.1 (1.2)	10 – 30%	1 – 10%	Assumed primary energy impact on central systems; rough estimate, very little data
Improper Controls Hardware Installation	9.9 (10.4)	5 – 10%	0.5 – 5%	Includes HVAC, lighting, and water heating energy; rough estimate, very little data
Improper Controls Setup / Commissioning	9.9 (10.4)	5 – 25%	1 – 5%	Includes HVAC, lighting, and water heating energy; rough estimate, very little data
Control Component Failure or Degradation	9.9 (10.4)	5 – 25%	1 – 5%	Includes HVAC, lighting, and water heating energy; rough estimate, very little data
Valves not Closing Properly	0.8 (0.8)	5 – 25%	1 – 10%	Primary impacts hot and/or chilled water systems
Air-Cooled Condenser Fouling	1.5 (1.5)	5 – 10%	6 – 8%	Prevalence reflects limited packaged unitary AC data; degradation from laboratory studies
Improper Refrigerant Charge	1.1 (1.1)	40 – 80%	5 – 15%	Primarily impacts packaged unitary AC and smaller units

An explanation of the derivation of the energy impact calculation parameters for a single fault, in this case "Improper Refrigerant Charge," provides insight into how the methodology was applied to all of the key faults. The *fault relevant AEC*, AEC_{re}, is the quantity of national energy consumption potentially affected by the fault. In theory, this would equal the AEC of all commercial building equipment that uses compressors, or 1.8 quads. In practice, supermarket refrigeration systems and chillers are much less likely to have improper refrigerant charge levels that degrade system performance because those systems tend to be better maintained and often have built-in diagnostic systems to alert users of problems and/or refrigerant receivers. Thus, the relevant AEC equals about 1.1 quads, of which packaged unitary AC accounts for 80%. The *fault frequency*, $Frequ_{Fault}$, range of 40% to 80% reflects the authors' synthesis of field measurements of packaged unitary AC charge levels from several sources (Downey and Proctor, 2002; Modera and Proctor, 2002; Jacobs *et al.*, 2003; Goody *et al.*, 2003; Davis *et al.*, 2002; Hewett *et al.*, 1992; Carl and Smilie, 1992; Hoover, 2001). The *average percent increase in energy consumption* due to the fault, $Degrade_{fault}$, comes from analytical estimates for EER degradation (Davis *et al.*, 2002; Jacobs *et al.*, 2003; Modera and Proctor, 2002) and laboratory testing to evaluate how different refrigerant levels effect the EER and SEER ratings of small (around 3-ton) packaged unitary AC (Farzad and O'Neal, 1993; Breuker and Braun, 1998; Goswami *et al.*, 2001). The data sources estimated different values for the energy impact of different refrigerant charge levels, and the energy impact range of 5% to 15% reflects the authors' evaluation of the universality of the different sources. Ultimately, the total fault energy impact range, AEC_{fault}, equals the product of the estimated ranges of the three factors. That is, the lower value equals: 1.1 quad(relevant energy)*40%(prevalence)*5%(energy impact) = 0.02 quad, while the upper value equals: 1.1 quad(relevant energy)*80%(prevalence)*15%(energy impact) = 0.12 quad.

3.2 Data Gaps

Another goal of the study, beyond estimating the energy impact of key faults, was to uncover and describe data gaps that increase the uncertainty of the fault energy impact estimates. The energy savings ranges reported in Table 3 clearly show the high degree of uncertainty of the potential energy impact of building faults. Controls-related faults, in particular, have very large energy impact ranges. Many controls-related faults occur in larger, more complex central systems controlled by an EMCS where their ultimate energy impact is often ambiguous. Furthermore, most studies did not provide sufficient information about controls-related faults and their application context (building systems) to reliably estimate the energy impact of controls faults and extrapolate the information to a national context. This parallels the findings of Ardehali and Smith (2002). In no case could the data support an analysis of fault energy consumption that reflects fault energy impact based on the full range of building types, systems, and equipment by geographical region, i.e., similar to the Commercial Building Energy Consumption Survey (CBECS) performed by the Energy Information Administration (EIA).

Nonetheless, this study offers useful information about several aspects of building faults. First, it provides a bottom-up estimate for the overall magnitude of building faults, i.e., 0.35 to 1.7 quads (0.4 to 1.8EJ), which confirms the significance of building faults. Second, it identifies the faults that likely have the greatest national energy impact. This, in turn, points out the best opportunities for approaches, such as diagnostics, that have the greatest national energy savings potential and helps to prioritize research into those approaches. For example, diagnostics may increase its economic attractiveness by focusing on a subset of high-impact faults while ignoring other faults. Third, it clarifies the specific type(s) of faults that have the largest impact within each broader fault type, including primary causes for specific faults in several cases. Fourth, it calls out the data needed to improve the energy impact estimate for each fault. When combined with the national fault energy impact estimates, this information enables prioritization of future data gathering activities to focus on collecting the data that add the most value.

Each fault has particular data gap issues and several general issues often arise with the data sources, many of which came from the building commissioning literature (see Table 4).

Table 4: Common Fault Energy Impact Data Issues

Issue	Effect	Comment
Inconsistent Reporting of Faults between Studies	Complicates aggregation of data from multiple studies, notably for prevalence	Depth and focus of commissioning studies can vary greatly from case to case
Focus on Problem Buildings	Tends to increase prevalence and impact of problems	Several commissioning studies targeted buildings identified as having high energy consumption or comfort issues
Data Format / Detail	Reduces usable data, impedes aggregation of fault-specific results from different studies	Many sources did not isolate the energy or cost impact of certain faults or presented values for an aggregate of faults (e.g., entire building)
Geographical Bias	Unclear how prevalence extrapolates to nation	Very large portion of studies performed in California, Texas, and (to a lesser extent) the Pacific Northwest and Florida

The data needed to address these gaps likely exist, but not in the public literature. Energy Service Companies (ESCOs) collect a wide range of proprietary information about the buildings they service to understand the cost-benefit relationship of different energy saving measures, including maintenance and commissioning. Utilities also may have collected similar, proprietary information in support of demand-side management (DSM) programs or their own ESCO activities.

A national study of faults in a set of buildings that adequately represents the national building stock, i.e., per CBECS, could provide similar information, albeit it at great expense. A more modest approach would be to improve and standardize the quality of fault-related data collected from commissioning studies. This would increase the ability to improve the accuracy of both fault frequency and impact.

6. CONCLUSIONS

Many buildings have a wide range of faults that increase energy consumption, and this paper presents the first estimates of the national energy impact of specific building system and equipment faults in commercial buildings. Based on a comprehensive review of the buildings literature, the authors identified and analyzed the energy impact of thirteen key faults. The study has reached the following conclusions:

- The key faults appear to increase building energy consumption by between 0.35 and 1.7 quads (0.4 and 1.8 EJ), or between 4% and 18% of the sum of commercial building HVAC, lighting, and refrigeration energy consumption. This value agrees with the general range of energy waste identified by commissioning studies of existing buildings.
- Two faults, "Lights or HVAC Left on When Space Unoccupied" and "Duct Leakage," appear to account for at least half of the estimated energy impact.
- Many of the key faults have large potential energy impact ranges, particularly controls-related faults.
- Several data gaps prevent the development of a statistically rigorous (e.g., similar to CBECS) impact estimate including: inconsistent and incomplete reporting of key fault-related information in the literature, the tendency of commissioning studies to focus on problem buildings, and geographic bias in buildings studied.

The final version of this analysis (TIAX 2004) will be published in a DOE report later in 2004.

NOMENCLATURE

AEC	Annual Energy Consumption	(quadrillion Btu/Exajoules)
CBECS	Commercial Building Energy Consumption Survey	(none)
P	Pressure	(Pa)
T	Temperature	(^{O}C)

Subscripts

c	condensing
d	discharge
e	evaporator
fault	fault
o	outdoor
re	relevant energy
s	suction

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