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Using energy audits to investigate the impacts of common air-conditioning design and installation issues on peak power demand and energy consumption in Austin, Texas

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ABSTRACT

This study presents an analysis of a unique dataset of 4971 energy audits performed on homes in Austin, Texas in 2009–2010. We quantify the prevalence of typical air-conditioner design and installation issues such as low efficiency, oversizing, duct leakage, and low measured capacity, and estimate the impacts that resolving these issues would have on peak power demand and cooling energy consumption. We estimate that air-conditioner use in single-family residences currently accounts for 17–18% of peak demand in Austin, and we found that improving equipment efficiency alone could save up to 205 MW, or 8%, of peak demand. We estimate that 31% of systems in this study were oversized, leading to up to 41 MW of excess peak demand. Replacing oversized systems with correctly sized higher efficiency units has the potential for further savings of up to 81 MW. We estimate that the mean system could achieve 18% and 20% in cooling energy savings by sealing duct leaks and servicing their air-conditioning units to achieve 100% of nominal capacity, respectively. Although this analysis is limited to the City of Austin, understanding the methods described herein could allow electric utilities in similar climates to make better-informed decisions when considering efficiency improvement programs.

1. Introduction

Air-conditioning has become ubiquitous in buildings in the developed world [1,2] and is typically one of the largest summer electrical loads in residential buildings, particularly in the southern United States. In Texas, 7.7 million households (both single-family and multi-family units) use approximately 43 TWh of electricity for air-conditioning annually [3], and the percentage of electrical load on the Electric Reliability Council of Texas (ERCOT) electric grid attributed to residential users increased from 20% (6139 MW) in the spring to 48% (30,735 MW) in the summer of 2010, mostly due to the operation of residential air-conditioning systems [4]. Several widespread design and installation issues associated with residential air-conditioning systems have been shown to contribute to these loads in the U.S. by increasing both energy consumption (e.g., sub-optimized airflow rates, low refrigerant charge, and excess duct leakage) and peak power demand (e.g., improper equipment sizing and low equipment efficiency) [5–10].

Previous investigations of these common issues have focused on various sample sizes and levels of detail, from case studies using detailed measurements in small samples of residences [6,8] to large regional HVAC diagnostic studies [5,10]. Only a few previous studies have sample sizes large enough and diverse enough to scale to the utility level. Consequently, there is a lack of statistically relevant data about the installed base of air-conditioning systems, which leaves a knowledge gap about air-conditioning operation in the residential sector, particularly in some climates. This work uses a database of 4971 recently performed energy audits on single family homes in Austin, Texas to fill that knowledge gap by (1) investigating the prevalence of the most common air-conditioning system design and installation issues that lead to excess power draw and energy consumption, and (2) estimating the impacts that these issues have on aggregate peak power demand (in units of MW), and (3) quantifying the likely distribution of achievable energy savings (in units of % of kWh) from retrofits in individual residences. Additionally, we identify several shortcomings in the audit database and recommend some additional energy audit procedures that can be implemented in order to improve the database.

2. Energy audit database

Austin, Texas is unique in that it is one of the few cities in the U.S. that requires an energy audit to be performed on a home before it

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can be sold. This mandate is part of the City of Austin's Energy Conservation Audit and Disclosure (ECAD) ordinance [11,12]. A home may be exempted from this ordinance under several conditions, including its participation in utility-sponsored energy efficiency programs within the previous 10 years of the sale of the home, if it is a condominium or manufactured home, or if the change of ownership occurs under a variety of extenuating legal conditions (e.g., foreclosure, exercise of eminent domain, or property settlements). The program hopes to produce market incentives to increase the energy efficiency of on-the-market homes by providing prospective buyers with better information, and also aims to address part of the Austin Climate Protection Plan, which includes reducing the City of Austin's peak power demand by 700 MW by 2020.

There are over 200 companies in the greater Austin area permitted to conduct official ECAD audits. Each auditor receives training by Austin Energy (the local municipally owned electric utility) and is given a detailed handbook explaining the steps necessary to conduct the official ECAD audit. Individual audits typically cost between US $200 and US $300 and audit results are all submitted on a uniform document to Austin Energy who then supplies the completed audit to prospective buyers. Auditors' results are internally checked against similar home audits to determine authenticity [13], and non-compliance with the ordinance is a Class C misdemeanor for the party selling the home. Because of the rarity of Austin's energy audit requirements, the recentness of the audits, and the size of the sample, this information forms a unique dataset in terms of scope, size, and content.

While the ECAD ordinance applies to both residential (single- and multi-family) and commercial buildings, we consider only single-family residences in this study. This work presents an analysis of a database of 4971 energy audits that were performed on single-family detached homes under the mandatory ECAD ordinance between January 2009 and December 2010. To the best of the authors' knowledge, these audits are the first of their kind for southern climates and this analysis is the first with such an extensive dataset. While the results are not directly applicable to other climates, it is expected that some of the findings will have relevance for other southern states.

3. Methodology

3.1. Energy audit procedure

The ECAD handbook provides instructions to auditors to gather information about the homes, including details related to the cooling and/or heating systems and ductwork, window types and shading, attic insulation, obvious pathways of air infiltration, and the number and types of appliances. Thus, information obtained from the energy audit database was used first to describe general building and system characteristics in the audited homes, including building age, floor area, window type, and attic insulation; age, nominal capacity, and manufacturer-rated efficiency of the primary air-conditioning system; and several HVAC system parameters, including estimates of system airflow rates, measurements of duct leakage, and measurements of temperature differences across cooling coils. While some parameters were directly measured, many of the parameters were simply recorded by visual inspection of equipment and building details by the auditors. For example, attic insulation levels were estimated by multiplying the depth of existing insulation in the attic by *R*-values provided to the auditors for typical insulation types found in homes built over the past century in Austin (e.g., fiberglass batts, blown-in cellulose, or spray-foam). System airflow rates were not actually measured during the energy audits, but were estimated by using manufacturer's data for the blower or were assumed to be $193\,m^3\,h^{-1}\,kW^{-1}$ of rated capacity ($400\,ft^3\,min^{-1}\,ton^{-1}$). Duct leakage measurements were made by installing a calibrated fan at a return grille of the system or an access panel of the air handling unit, taping the remaining supply registers and return grille(s), and measuring the airflow rate required to depressurize the duct system to −25 Pa. These leakage measurements thus represent total duct leakage (supply + return) to both interior and exterior spaces. Additionally, the temperature difference across the cooling coil was measured at the return air intake and immediately after the evaporator coil after the system had been operating at least 15 min.

After quantifying several parameters for the audited homes in the database, we attempted to compare the actual (or estimated) performance of the buildings, and the air-conditioning systems within, to design or nominal values of the same parameters. Differences between the two were used to estimate the impacts on peak demand attributed to common design and installation issues present in the homes, and to estimate the potential energy savings of remedying some of these issues in individual homes. Relevant calculations for four parameters of interest are described in the following sections, including (1) installed nominal air-conditioning system efficiency, (2) air-conditioning system oversizing, (3) excess duct leakage, and (4) measured vs. rated system capacity. Finally, some of these estimates were scaled to represent the entire existing single-family residential building stock in Austin, Texas.

3.2. Estimating energy impacts of common problems in the audit homes

3.2.1. Installed nominal air-conditioning system efficiency

The outdoor condenser-compressor unit of a residential air-conditioning system typically accounts for 80–85% of the total power draw of the system (including the outdoor unit and indoor blower fan) [2]. Because the database contained values of nominal system capacities (BTU/h) and rated energy efficiency ratios (EER, in $BTU/h/W_{power}$; SI equivalent = coefficient of performance, or COP – the useful refrigerating effect per power supplied, $kW_{thermal}/kW_{power}$), the power draw of the outdoor condenser-compressor units (W_{power}) during operation under rated conditions was estimated by dividing nominal capacity by EER. The total maximum power draw that all of the units in the database could theoretically demand if operating at the same time is simply the sum of the individual power draw values. To achieve more realistic estimates of aggregate demand during the peak period (where not all systems are operating at the same time), we assumed that 70% of these systems operate during the summer peak hour (our best estimate using the high end of hourly runtimes reported in eight residential air-conditioning systems in Austin in Ref. [2]). Additionally, systems are typically rated at indoor and outdoor temperatures of 26.7 °C and 35 °C, respectively [14], but the outdoor temperature in Austin is typically higher during the summer peak hour. Thus, rated power draws were scaled to increase approximately 10% over rated conditions to match a peak summer temperature of 40.6 °C [15], using an increase of $1.8 \pm 0.8\%/^{\circ}C$ rise in outdoor temperature, as observed in Stephens et al. [2].

We then hypothesized two scenarios where all the homes in the audit database were upgraded to either 12 EER (COP 3.5) or 14 EER (COP 4.1) air-conditioning units, estimated the total maximum power draw, and compared the difference. The low and high ranges of improved efficiency were chosen to approximately reflect the home improvement requirements of the US Environmental Protection Agency's and US Department of Energy's ENERGY STAR program (which requires a minimum EER of 12, COP 3.5) and an upper end of efficiency available on the market today (EER 14, COP 4.1). We also investigated the possible reductions in peak power demand for theoretically replacing all oversized units (estimated using methods in the subsequent section) with correctly sized units of higher efficiency, assuming every unit was replaced with a unit with an EER 12 (COP 3.5) or EER 14 (COP 4.1), which is consistent with Austin Energy's energy efficiency rebate program.

3.2.2. Air-conditioning oversizing

Previous studies have shown that oversized systems use more energy and have a greater peak demand than properly sized systems [6,7,16]. For example, Neme et al. [7], in a review of previous studies, estimated that proper sizing could yield as much as a 10% overall energy reduction and that a comprehensive system overhaul (ensuring proper airflow and proper refrigerant charge, sealing duct leakage, and correctly sizing equipment) could reduce utility aggregated peak power use by up to 25%. In this study, the recommended cooling capacity of air-conditioning equipment for each house in the audit database was determined using the Manual J load calculation procedure, the industry standard for sizing residential HVAC equipment [17]. The method calculates heating and cooling loads using building characteristics, building physics, and climate factors, and determines the cooling capacity required to meet 97.5% of the summer cooling hours. Designs do not account for the top 2.5 percentile of summer hours because doing so would lead to greatly oversized systems. However, there is evidence that even the Manual J calculation includes some inherent oversizing and that units sized at 73% of Manual J can be sufficient to meet cooling demand [18].

A custom spreadsheet program was used to perform the Manual J sizing calculations. The Manual J method allows for two different design scenarios: (1) a peak cooling load procedure and (2) an average load procedure. The latter design scheme is typically used for sizing residential HVAC equipment and is used in this analysis. A portion of the calculation is based on the design temperature difference between the inside and outside of the home. The interior conditions were assumed to be 23.9 °C and 50% relative humidity (RH), which is a standard industry assumption [19] and is in the center of the human comfort zone. Outdoor design conditions for Austin, TX, 35.6 °C and 50% relative humidity, are included in the Manual J literature and were used in the calculations. The resulting estimated design system capacities (referred to as "correctly sized") were compared to the installed rated capacities in order to determine the prevalence of oversized systems in the audited homes. An installed unit with a capacity that is greater than or equal to 120% of the Manual J calculation is considered oversized for the purposes of this investigation, which is consistent with previous studies [6,16].

Only houses that contained one central air-conditioning unit were included in our oversizing analysis (19% were out of range), however there is evidence that homes with multiple air-conditioners are just as, if not more, oversized [8]. Also, only houses between 46.5 and 325 m^2 (500 and 3500 ft^2) of floor area were considered (4% were out of this range). Homes that were missing audit data, such as installed system capacity and attic *R*-values, were also excluded. Missing audit information was not correlated with any specific auditor and is most likely results of difficulty of obtaining some information (e.g., nameplates missing from air-conditioning units).

Several home characteristics were not assessed at all in the energy audits, and some reasonable assumptions were made in their absence. For example, wall insulation *R*-values were not included in the energy audits, as that level of inspection would require significant equipment or penetration of the façade. Thus, wall insulation levels were assumed to meet the City of Austin building codes that coincided with the year of construction of each home: pre-1983 code required RSI of 0.53 m^2 K/W (R-3) and post-1983 (and current) code requires RSI 2 m^2 K/W (R-11). Because infiltration rates were not measured in the homes, the default "leaky" infiltration values that are provided in the Manual J workbook were used for all homes. Also, the number of occupants was not noted by the auditors, so the value was assumed to be one more than the number of bedrooms [19]. Windows were classified as either single or double paned in the audits, so *U*-values for generic double and single paned windows provided in the Manual J literature were used (3.18 and 5.57 W/m^2 K, respectively). The area of windows was missing from the audit database, so we assumed that the percentage of windows per floor surface area was 16.8% for every home, based on the average of previous investigations of single-family residences in the U.S. [6].

The assumptions for wall insulation levels (that every home meets code and no homes have greater insulation than code requirements) and infiltration rates (that every home is "leaky") should over-estimate cooling loads and required cooling capacities overall, which should provide a conservative estimate of the extent of equipment oversizing. The thermal contribution of individual occupants is generally small and not expected to significantly affect the results [19]. Ultimately, for our analysis of the effect of residential air-conditioner oversizing on peak power demand, we compared the rated power draws of oversized installed units to the rated power draws of correctly sized systems of the same efficiency. Rated power draws were again scaled to increase approximately 10% over rated conditions, as previously described.

3.2.3. Duct leakage

Duct sealing is a well-known residential retrofit that has been shown to save significant amounts of energy for space conditioning [20–22]. Some researchers have predicted that sealing duct leaks could also reduce peak power draw of residential air-conditioning units [23], although others have predicted otherwise [24]. Because supply duct leaks should not alter return air temperatures and return leaks should not increase entering air temperatures enough to drastically alter the power draw of outdoor units [25], we assume that the only impact that widespread duct sealing would have on peak demand would be a potential reduction in individual system runtimes, which when aggregated across the building stock, might reduce the likelihood that multiple systems are operating concurrently during hours of peak demand. However, because we are not aware of any work investigating the likelihood of system runtimes with varying leakage conditions, we limit our duct retrofit analysis only to like energy savings achievable in the individual homes.

To estimate the impacts of sealing duct leaks on cooling energy consumption in individual homes, we used data from two field studies that measured actual reductions in cooling energy after duct retrofits [20,22]. We performed a linear regression on cooling energy savings relative to the absolute reduction in total duct leakage fraction (shown in Section 4.3 of this paper). The slope of that regression was used to estimate how much cooling energy could be saved by each system if each system with a duct leakage fraction greater than 10% was reduced to 10% (a value recommended by Austin Energy and other efficiency programs).

3.2.4. Measured vs. rated air-conditioning system capacity

Low measured capacity has been identified in several previous studies, e.g. [2], and may be indicative of low airflow rates [8], improper refrigerant charge [9], and excess duct leakage [25]. Because airflow rates were estimated and temperature differences across cooling coils were measured, we attempted to estimate the actual cooling capacity of the systems in the audit database, and compared those values to the nominal cooling capacity of the units. Actual sensible capacity of the audit homes was estimated using Eq. (1):

$$q_s = Q\rho C\Delta T \quad (1)$$

where q_s = estimated sensible capacity (kW_{cap}), Q = system airflow rate ($m^3\,s^{-1}$), ρ = air density (assumed constant, 1.2 kg m^{-3}),

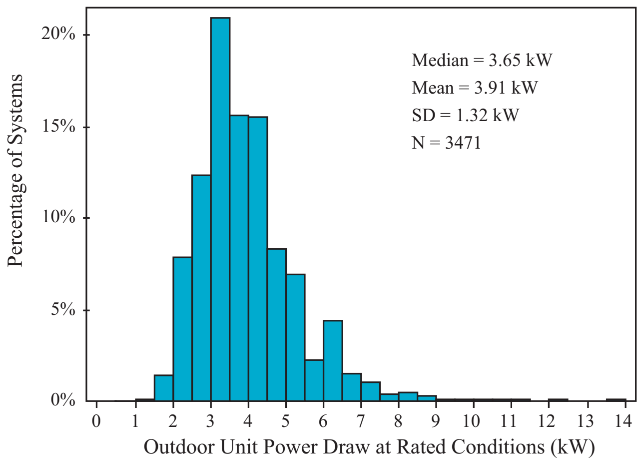

Fig. 1. Distribution of estimated power draw at rated conditions for homes in the ECAD audit database, in increments of 0.5 kW, where N is the number of individual systems.

C = specific heat of air (assumed constant, 1.012 kJ kg^{-1} K^{-1}), and ΔT = temperature difference across the cooling coil (K). Nominal installed sensible capacity was estimated as 80% of the nominal total capacity identified on each unit by the auditors, which is consistent with a typical sensible heat ratio (SHR) of 0.80 in residential systems [2,25]. Systems with measured capacities less than rated capacities were assumed to operate longer and consume more energy at a rate directly proportional to the difference between the two values, which is a common assumption, although we are not aware of experimental justification.

3.3. *Scaling analysis to represent the residential building stock in Austin*

The residential building stock in Austin Energy's service area includes approximately 332,000 housing units, 47.1% of which are single-family detached units [26]. Thus, the dataset of 4971 energy audits used in this work represents over 3% of all single-family residences in Austin. Because the home characteristics (i.e., age and size) in the audit database matched reasonably well with the distribution of home characteristics from US Census data in the Austin area (a Wilcoxon signed-rank test yielded no statistical difference in the distributions of year built between the two databases, $p > 0.05$), we extrapolated the results of our analysis of the ECAD data to all single-family units in the City of Austin. This extrapolation was done simply by a linear extrapolation for each parameter of interest from the number of homes used in the database to the number of single-family homes in Austin.

4. Results

This section describes the prevalence of four common air-conditioner design and installation issues in the audit homes and estimates the impacts they have on peak power demand and energy consumption.

4.1. *Installed system efficiency*

Because new commercially available air-conditioning units continue to increase in efficiency over time, we first attempted to quantify the excess energy consumption and peak power demand associated with older inefficient systems across the homes in the audit database. The estimated distribution of rated power draws for homes in the audit database is shown in Fig. 1.

The average system in the audit database had an EER of 9.9 BTU/h/W (COP 2.9) (SD 1.7 BTU/h/W, COP 0.5) and the average rated power draw across all units is approximately 3.9 kW (SD 1.3 kW). This average is likely a low estimate for summer peak power draw, as the outdoor temperature during the summer peak hour typically exceeds 38 °C (100 °F). Again using an increase in outdoor unit power draw of 1.8 ± 0.8%/°C rise in outdoor temperatures [2], the average peak power draw across all units is likely 4.3 kW (SD 1.4 kW). Our best estimate of the uncertainty in this value is approximately 5%, taken as the standard deviation of the high, medium, and low bounds of the estimated increase in power draw over rated conditions that we calculated using the above reference. Scaling to the approximately 156,000 single-family units in the City of Austin, and considering this dataset to be roughly representative of the distribution all single-family detached homes in Austin, this estimate leads to a collective potential rated power draw of approximately 663 ± 33 MW for air-conditioning (or approximately 464 ± 23 MW if we assume that 70% of air-conditioners are operating during the peak hour). For reference, 464 MW represents approximately 17–18% of Austin's all-time high peak demand of 2628 MW in August 2010 [27].

If every system with a nominal EER less than 12 (COP 3.5) was upgraded to an EER 12 (COP 3.5), we estimate that the collective peak power draw of single-family detached homes in Austin could decrease to 532 MW (or 372 MW assuming 70% of systems operating at peak). In other words, upgrading all systems to EER 12 (COP 3.5) could reduce peak demand by 132 MW, which represents approximately 5% of Austin's all-time high peak demand and approximately 19% of the city's 700 MW peak reduction goal. Similarly, if every system with a nominal EER less than 14 (COP 4.1) was upgraded to EER 14 (COP 4.1), we estimate that peak demand could be reduced by 205 MW, or almost 8% of Austin's peak demand, and almost 30% of its peak reduction goal of 700 MW by 2020.

Holding all else constant, increasing the efficiency of a unit should directly affect the amount of power draw required to meet the same cooling load but should not alter system runtimes, as the system still has the same capacity to remove heat from the airstream. Thus, we estimate that increasing the EER of the average system from 9.9 to 14 BTU/h/W (COP 2.9 to COP 4.1) would likely yield an average reduction in household cooling energy consumption of approximately 29%. We estimate that approximately 70% of homes in the database could save at least 25% in cooling energy by upgrading their air-conditioners to 14 EER (COP 4.1) units.

4.2. *Oversizing*

Air-conditioning systems were also analyzed to determine the appropriateness of their sizing. This analysis was restricted to homes in the audit database that have a single air-conditioner, have a floor area between 46.5 m^2 and 325.2 m^2, and that had enough complete audit information that would allow for a Manual J calculation. Overall, 74% of the homes in the database met these requirements (N = 3669). There did not appear to be any systematic reason for missing data, and so it is expected that this smaller subset is still representative of the Austin housing stock

Fig. 2 compares "correct" cooling capacities estimated using Manual J calculations and the actual installed capacities as found in the audits. Each circle represents an installed unit in the database. Because of the large size of the dataset, it is difficult to clearly see all of the points, but the seemingly solid horizontal lines are closely spaced individual units. Because manufacturers only provide air-conditioning units in certain size intervals, usually in 1.76 kW (½ ton) increments, design capacities recommended by Manual J calculations were rounded up to the nearest 1.76 kW. The rounded values are used for all percentages stated for oversizing, as well

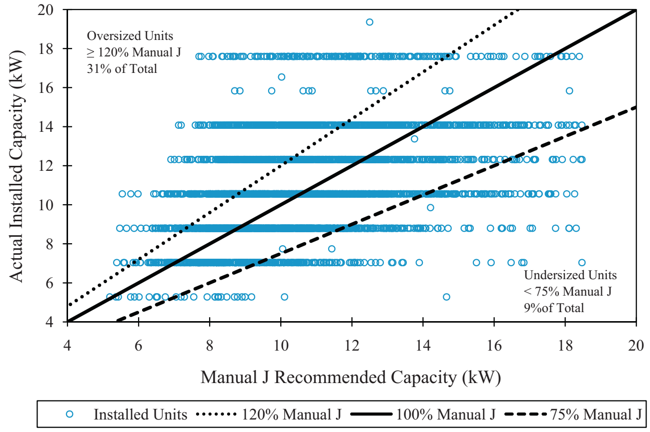

Fig. 2. Distribution of the actual installed air-conditioner capacities vs. calculated (Manual J) capacities for homes in the audit database (*N* = 3669 homes).

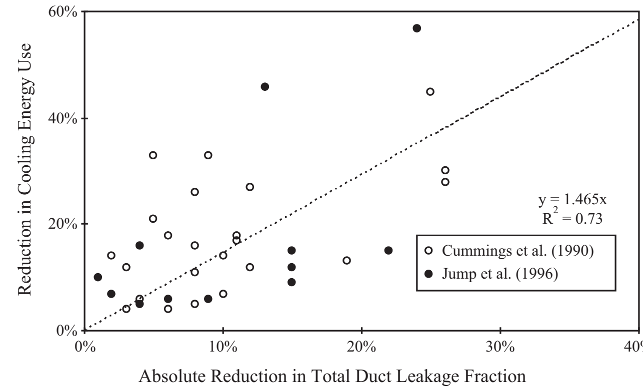

Fig. 3. Estimations of the reduction in cooling energy use associated with reductions in total duct leakage. Plot generated with data taken from [20,22], and ignoring three outliers from Jump et al. [22].

as calculations involving aggregated peak power demand; the pre-rounded Manual J values are left in Fig. 2 for clarity.

Approximately 31% of the Manual J calculations showed the installed units to be sized at least 120% of necessary capacity (units to the left of the dotted line in Fig. 2), and 66% were at least 100% of necessary capacity (units to the left of the solid line in Fig. 2). These results are in general agreement with previous studies on residential air-conditioner oversizing [6,8]. In addition, approximately 9% were undersized (below the dashed 75% line).

The average power draw of oversized units is 4.86 kW (SD 1.45 kW, *N* = 923), compared to 3.54 kW (SD 0.97 kW, *N* = 923) for correctly sized units, both calculated at 5.6 °C above rated conditions. If we consider 31% of all single-family residential units in Austin to be oversized (≥120% Manual J), assume that 70% of these systems operate during the summer peak hour, and assume a 10% increase in power draw at a 5.6 °C temperature increase over rated conditions [2], we estimate that the aggregated excess peak power demand due to all oversized single family residential air-conditioner units is as much as 41 MW (or approximately 1.6% of Austin's peak demand). Furthermore, we estimate that replacing each oversized unit with a correctly sized unit that is also upgraded to an EER of 12 (COP 3.5) or 14 (COP 4.1) would yield a peak power reduction of 67 MW or 81 MW, respectively (or 2.5% and 3.1% of peak). Conversely, if the undersized units in Fig. 2 were simultaneously upgraded in size and efficiency (EER-14, COP-4.1), extrapolated to the entire single-family housing stock, the aggregated realized peak power *gain* would be approximately 1 MW.

However, it is important to note that smaller, correctly sized air-conditioning units should actually run more often to meet the same cooling load in a building. In the only two studies of which we are aware of that measured the additional runtime caused by correctly sizing oversized air-conditioning units, Pigg [28] measured an average increase in runtime of 32% (SD = 21%) in three homes in Wisconsin after reducing unit sizes by approximately 30% and Sonne et al. [29] measured increases in runtimes of 57 ± 19% and 33 ± 17% in two homes in Florida after reducing the units' sizes by one-third. Thus it is reasonable to assume that there is a greater likelihood of multiple units across the building stock operating more often during the peak hour (e.g., more than our assumption of 70%), and that the potential reductions in peak power due to correctly sizing units may not actually be realized without the incorporation of utility-controlled thermostat cycling programs [30].

The energy impacts of correctly sizing systems in individual residences are not as clear. Smaller systems will draw less power when operating, but because cooling loads do not change, the amount of energy required to remove from the air will remain the same. One would expect that decreasing the size of a residential system would then cause longer runtimes that ultimately do not significantly affect overall energy use. This phenomenon has generally been observed in field studies in both Wisconsin [28] and Florida [29]. Additionally, James et al. [6] observed that systems sized 120% greater of Manual J would increase overall cooling energy use by just under 4% and by 13% during the peak hour in the summer in Florida. Although the overall energy impacts of correctly sizing systems are unclear, occupants might benefit from added comfort, as correctly sized systems that operate for longer periods of time should provide more dehumidification [24].

4.3. Duct leakage

Because there was not enough information to perform a detailed model of the ductwork in the homes, we rely on values of energy savings from previous studies of duct retrofits. Fig. 3 shows actual reductions in cooling energy use measured in two previous field investigations of the impacts of sealing duct leaks in residential buildings [20,22].

As previously mentioned, we performed a linear regression on data from previous studies to estimate the average cooling energy savings likely achieved by an absolute reduction in total duct leakage fractions [20,22]. Three outliers from Jump et al. [22] were ignored to achieve some reasonable certainty (slope = 1.47, R^2 = 0.73, 95% CI = 1.16–1.77), as shown in Fig. 3. The regression output means that, for example, if duct retrofits achieve a 20% reduction in total leakage (e.g., from 30% to 10%), approximately 30% savings in cooling energy can be achieved. For comparison, Cummings et al. reduced mean total leakage in 23 homes from 16% (SD 10%) to 5% (SD 4%), which yielded mean cooling energy savings of 18% (SD 11%) [20].

Assuming a target duct leakage of 10%, approximately 76% of the homes (3471 out of 4539) in the database required duct sealing (mean sealing required = 13%, SD = 13%). We multiplied the required duct sealing values (in absolute terms) by the slope in Fig. 3 to yield the likely cooling energy savings achievable by sealing ducts in each eligible home. The distribution of achievable energy savings is shown in Fig. 4. The amount of energy savings is capped at 60% because of data limitations in Fig. 3 and likely invalid values of duct leakage fractions entered at the extreme ends in the audit database.

Repeating the calculations using the confidence intervals for the slopes of the regression line in Fig. 3, we estimate that the mean system could achieve approximately 14–22% in cooling energy savings by sealing duct leaks. Our best estimate of the mean cooling

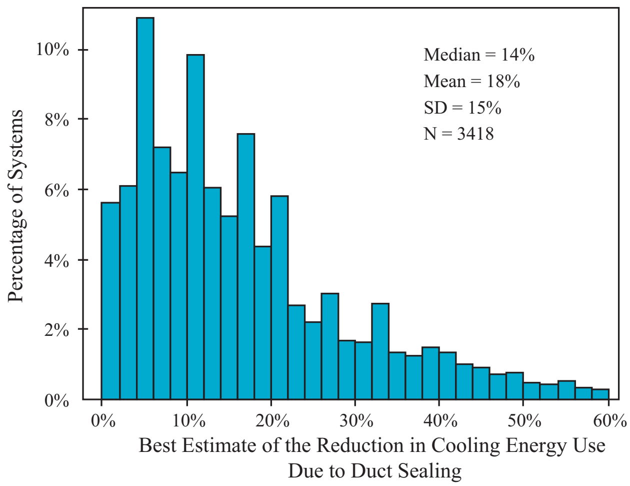

Fig. 4. Distribution of the estimated reduction in cooling energy consumption achievable by sealing duct leaks in the audit homes ($N = 3418$ homes).

energy savings (using only the slope from Fig. 3) is 18% (SD 15%), with a median savings of 14% and an interquartile range of 7–23%. Unfortunately, we cannot extrapolate absolute values of energy consumption from these data because we have no estimates of individual system runtimes, although we can estimate that more than 75% of homes in the audit database (and thus single family homes in the City of Austin) could benefit from sealing duct leaks, with an average cooling energy savings of approximately 18%.

4.4. Measured vs. nominal capacity

Because system airflow rates were estimated (although not very accurately) and temperature differences across cooling coils were measured, we were able to estimate operating sensible capacity and compare that to our estimate of rated sensible capacity, as shown in Fig. 5.

We estimate that the mean system was operating at approximately 77% of rated sensible capacity (SD 21%). Approximately 10% of systems were operating under 50% of rated capacity and approximately 10% were operating over 100% of rated capacity, respectively. Low operating capacity has a direct impact on energy consumption and system runtime, as systems that remove less energy than they are rated for should operate longer. If we assume a linear relationship between deficiencies in delivered capacity and increases in runtime [e.g. 24], the average homeowner could save up to 23% in cooling energy by servicing their air-conditioning units to achieve 100% of nominal capacity (although there is some evidence that this relationship may be nonlinear and the savings may be smaller; for example, Stephens et al. [31] reported that residential air-conditioning systems that observed a 4% decrease in sensible capacity due to the installation of high-efficiency filters did not lead to an increase in cooling energy consumption). Although we have no estimates of the uncertainty of these measurements, these values should be taken as rough estimates because there is a considerable amount of uncertainty in the airflow measurements/estimates, the measured temperature differences, and the assumed sensible heat ratios in the homes (we assumed SHR = 0.8 herein [2,25]). Sensible heat ratios typically range from 0.7 to 0.8 in residential settings [32]. If we assume SHR = 0.7, the mean system would be operating at 88% of rated capacity (SD = 23%), and the average energy savings of tuning equipment would decrease to 12%. Finally, although this analysis focuses on the energy savings to residents achievable by increasing system cooling capacities, reductions in peak demand are likely to be realized when the simultaneous operation of all systems aggregated across the building stock is reduced due to widespread increased cooling capacities, although we do not have enough information to quantify this impact.

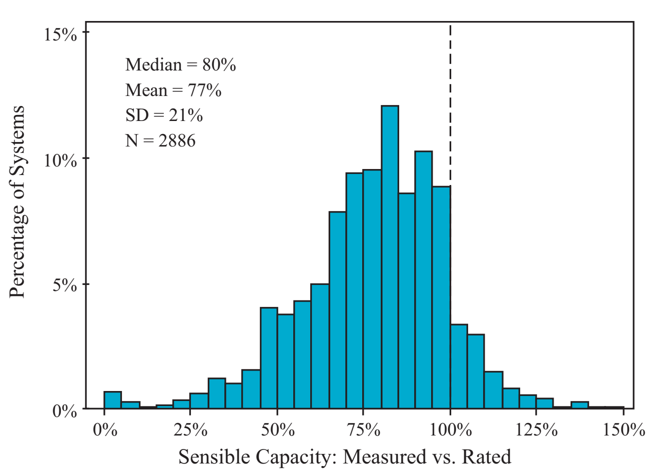

Fig. 5. Distribution of the estimated operating sensible capacity relative to the rated sensible capacity, assuming a sensible heat ratio (SHR) of 0.8 ($N = 2886$ homes).

5. Discussion

Several common design and installation issues that have been found in previous studies were also found in the homes in the audit database. For example, air-conditioning units were inefficient overall, with an average EER of 9.9 (COP 2.9), compared to the ENERGY STAR minimum requirement of approximately EER 12 (COP 3.5), which leads to both excess peak power demand and excess overall cooling energy consumption. Additionally, we estimate that approximately 31% of the units were oversized at least 120% or more relative to Manual J calculations. We also estimate that over 75% of the systems in the audit database had excess duct leakage and that the average home could save approximately 18% in cooling energy consumption by repairing ducts. Finally, the average system was operating at approximately 77% of rated sensible capacity, suggesting widespread problems with low airflow rates, fouled cooling coils, or suboptimal refrigerant charge (albeit with considerable uncertainty). And because less than 0.2% of the homes in the original dataset ($N = 4971$ homes) did not have air-conditioning, all of these issues are likely widespread across the City of Austin.

Peak electrical power demand occurs in the summer in Texas. In 2010, the peak load on ERCOT was almost 66 GW, which exceeded the previous year's peak by almost 4% [4]. The summer of 2009 in Austin almost tied the record heat wave of 1925 of 69 days of over 37.8 °C temperatures [33], and in August 2010 Austin Energy observed an all-time high peak demand at 2628 MW [27]. Here we estimate that the operation of air-conditioning units in single-family residences likely accounts for approximately 17–18% of the peak electrical demand in Austin. We also found that tremendous savings in peak power demand could be achieved by addressing issues related to the efficiency of the air-conditioning units in Austin residences, most importantly by upgrading the rated efficiency of installed units. Our estimate that upgrading all systems to EER 12 (COP 3.5) or EER 14 (COP 4.1) could reduce peak demand by 132 MW and 205 MW, respectively, represents a significant portion of Austin's overall peak demand and could displace the equivalent of three to five of Austin Energy's GE LM6000 simple cycle natural gas peaking power plants. Additionally, we estimate that the average individual homeowner could save almost 30% on cooling energy consumption by upgrading to EER 14 (COP 4.1) units.

Similarly, our estimate that oversized residential units account for approximately 41 MW of peak demand is roughly equivalent to the capacity of one of Austin Energy's natural gas peaking plants. Furthermore, if all oversized units were replaced with correctly sized EER 12 (COP 3.5) or EER 14 (COP 4.1) equipment, the potential savings could increase to 67 or 81 MW, respectively; it may be best to remediate this group of oversized and low-efficiency units first.

It is a common misconception that "bigger" air-conditioners will perform "better" and many air-conditioning contractors have a positive incentive to oversize residential HVAC units. In a survey of HVAC contractors, over 75% reported that customers wanted larger size units, that the homes they designed for required oversizing, or that bigger was simply better [34]. One of the main concerns of HVAC contractors is that if they do not oversize units, the customer will not feel as if the unit cools the space in a timely manner. If this is the case, the contractor might receive a "callback" and be required to install a larger unit. However, Rudd et al. [18] showed that even systems as low as 73% of Manual J suggested capacity were able to meet the cooing load and maintain temperatures in homes during the summer of 1999 in Tucson, AZ. Austin typically has a larger latent load than Tucson, so units may not be able to be undersized to this extent, but our analysis shows that significant peak power savings may be achieved by correctly sizing residential air-conditioning systems in Austin.

5.1. Energy audit recommendations

Although the energy audit procedures detailed herein provide a unique and robust database used to perform our calculations, steps can be taken to improve the quality of information provided by the audits. To aid future analysis, we recommend that detailed window characteristics, such as the area and orientation, be included in the audits. This practice would not add a significant burden to the auditor and would provide an improved characterization of the audit homes. Additionally, air leakage testing using calibrated fans (e.g., blower doors) should be required to establish a baseline value for air infiltration. And because of the importance of air-conditioning in a cooling climate like Austin, there are a few more detailed measurements that could be conducted to provide for better home characterizations overall. For example, airflow rates and duct leakage were not measured using the most accurate and informative methods [35] and refrigerant charge was not measured. These measurements would be a helpful addition to the audits and would possibly allow for a better and more accurate understanding of the link between the typical system issues described herein and overall energy performance, e.g. [9]. Finally, because energy audits have been shown to be highly variable between audit companies [36], steps should always been taken to fully detail audit procedures in order to minimize uncertainty, as the ECAD handbook has done.

5.2. Future research

Energy audits provide only a snapshot of the potential energy consumption of a home. System runtimes, although based on a study of Austin homes [2], were simply assumed herein and are significant when considering aggregated peak demand. Future work will collect more information from a subset of 100 of homes in the audit database that will be selected to directly sub-meter many of the home circuits, including the air-conditioner. This study will result in measurements similar to those in [37,38] and the subsequent data will allow for a better comparison of the energy and peak power penalties associated with all of the system issues discussed herein. Temperature, relative humidity, and occupant survey data will also be recorded to determine levels of occupant comfort, and these data will be analyzed, in conjunction with specific air-conditioner runtimes, to determine the energy and quality of life penalties associated with poor residential air-conditioner system performance.

6. Conclusion

This work analyzed a database of 4971 energy audits on single-family homes in Austin, Texas. Our analysis led to similar conclusions of previous studies: residential air-conditioning systems are typically operating in poor condition. The inefficiencies associated with poor residential air-conditioning performance aggregated on a utility scale can be significant, especially during summer peak demand. Mitigation of typical design and installation issues could result in significantly decreased peak power demands on utilities, and because air-conditioning often constitutes the largest energy consumption for residences, particularly in the summer, the reductions in overall energy consumption for individual homeowners could be significant. We estimate that single-family residential air-conditioning systems account for approximately 17–18% of peak summer electricity demand in Austin. Furthermore, we conclude that efficiency improvements alone (upgrading all systems to EER 14, COP 4.1) could possibly reduce peak power demand by as much as 205 MW, which would achieve almost 30% of Austin's Climate Protection Plan's goal of a 700 MW peak reduction by 2020. Similarly, our analysis suggests that accurately sizing residential air-conditioning equipment could displace as much as 41 MW of peak demand, or nearly the equivalent of one natural gas peaking plant. Additionally, we estimate that replacing oversized units with higher efficiency units (EER 14, COP 4.1) could, at best, double those peak savings to 81 MW.

This analysis is limited to Austin in terms of numbers, but not in terms of scope. Implementation of initiatives similar to Austin's ECAD ordinance in other cities would produce similarly valuable information and the methods used herein can be applied to analyze other databases in other climates. This information would lead to better-informed decisions when assessing energy efficiency programs and climate protection plans.

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