# Device-Level Data Analytics to Guide Policy

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## Abstract

This dissertation is comprised of four studies that examine issues where submetered device-level energy use data can be used to inform energy efficiency policy and investment decision making in residential buildings. In addition to identifying applications and developing the methods for incorporating these data in engineering and economic analyses, the nontechnical aspects of these issues are also considered as implementation of these solutions depends on more than their technical feasibility.

The first study frames the existing methods being used today to build a device-level accounting of where energy is used in the residential sector in the US. Three methods are identified and categorized: direct metering methods, non-intrusive load monitoring, and statistical methods. Two of the most prominent studies are compared, and a method is proposed by which the Department of Energy (DOE) and others could easily and cost-effectively incorporate existing submetered data into their estimates of device-level energy consumption in the US.

In the second study, energy audit and survey records are used to model 106 homes in the DOE's EnergyPlus building simulation software. Simulation results are compared to submetered data from the audited homes to provide a device-level measure of the accuracy of EnergyPlus models in a large sample of homes. Results show the models do not accurately or consistently estimate occupied home energy use due to factors such as occupant behaviors and appliance stocks which are not well-captured in traditional audit reports. These results provide context for the growing use of EnergyPlus models for homes, and highlight that care is needed to ensure that decision-makers are aware of its limitations.

The third study uses device-level data to assess the technical and economic feasibility of distributing direct current (DC) power in homes with solar photovoltaic (PV) arrays. Monte Carlo simulation is used to estimate the costs and benefits of this intervention while accounting for uncertainty in the engineering, economic, and other parameters. Results show significant energy savings potential, but at present DC equipment prices these savings are not cost-effective. In addition to quantifying energy and cost savings, a number of major nontechnical barriers to implementing DC distribution in homes are identified.

In the final study, an expert elicitation is conducted with 17 experts on DC systems to better understand these barriers. Results show that the two biggest barriers to adoption are industry professionals unfamiliar with DC and small markets for DC devices and components. To address these, experts proposed developing training programs for engineers and electricians, and developing pilot projects to prove the benefits of DC in niche applications where DC power distribution holds a clear advantage over alternating current (AC). Experts also identified lasting and inherent benefits of DC that make these systems better suited to serve future building loads.

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## List of Abbreviations

| | |
|---|---|
| **AC** | Alternating current |
| **AHRI** | Air conditioning, Heating, and Refrigeration Institute |
| **AMI** | Advanced metering infrastructure |
| **ANSI** | American National Standards Institute |
| **ARRA** | American Recovery and Reinvestment Act of 2009 |
| **ASHRAE** | American Society of Heating, Refrigerating, and Air Conditioning Engineers |
| **BLDC** | Brushless direct current |
| **CBECS** | Commercial Building Energy Consumption Survey |
| **CFL** | Compact fluorescent |
| **CRF** | Capital recovery factor |
| **DC** | Direct current |
| **DOE** | Department of Energy |
| **DR** | Demand response |
| **DSM** | Demand-side management |
| **EER** | Energy efficiency ratio |
| **EERE** | Office of Energy Efficiency and Renewable Energy |
| **EIA** | Energy Information Administration |
| **EPA** | Environmental Protection Agency |
| **EPRI** | Electric Power Research Institute |
| **EV** | Electric vehicle |
| **GFCI** | Ground fault circuit interrupter |
| **HVAC** | Heating, ventilation, and air conditioning |
| **ICC** | International Code Council |
| **IECC** | International Energy Conservation Code |
| **IEEE** | Institute of Electrical and Electronics Engineers |
| **IoT** | Internet of things |
| **LAC** | Levelized annual cost |
| **LBNL** | Lawrence Berkeley National Laboratory |
| **LED** | Light-emitting diode |
| **LEED** | Leadership in Energy and Environmental Design |
| **NEC** | National Electric Code |
| **NEMA** | National Electrical Manufacturers Association |

| | |
|---|---|
| **NFPA** | National Fire Protection Association |
| **NILM** | Non-intrusive load monitoring |
| **NIST** | National Institute of Science and Technology |
| **PNNL** | Pacific Northwest National Laboratory |
| **PV** | Photovoltaic |
| **RECS** | Residential Energy Consumption Survey |
| **RESNET** | Residential Energy Services Network |
| **SGDP** | Smart Grid Demonstration Project |
| **SGIG** | Smart Grid Investment Grant |
| **VAC** | Alternating current voltage |
| **VDC** | Direct current voltage |

# 1 Introduction

## 1.1 Motivation

A transition to sustainable energy systems that address climate change, provide energy services with low environmental and health effects, and are affordable and environmentally just will likely include a broad deployment of energy efficiency and conservation strategies. Energy efficiency technologies and solutions have the ability to help address all of these concerns, while maintaining the same energy services enjoyed today and improving economic competitiveness.

While potential efficiency improvements exist across all sectors of the economy, buildings are of special interest. In 2010, the National Academies' Panel on Energy Efficiency Technologies found that electricity savings in US commercial and residential buildings present the greatest opportunity for cost-effective energy savings economy-wide [1]. That panel estimated that efficiency savings from these buildings alone could offset growing loads in other sectors and eliminate the need to increase net US electricity generation capacity through 2030. Buildings are also a high priority because of their long intended lifetimes. Decisions made about the energy performance of a building during its design and construction will determine its energy consumption for many decades into the future.

In addition to estimating potential energy savings, the National Academies' panel also investigated the barriers preventing more widespread adoption of energy efficient technologies. Among a number of economic factors, a lack of information across all levels of decision-makers was identified as one of the most persistent barriers. Put simply, consumers, building owners, and facility managers often do not know how much energy their buildings consume, do not know what opportunities exist to reduce that consumption, and do not know how quickly those savings will pay for their investment in efficient technologies.

Broadly, the approach to filling these information gaps has been to provide these decision-makers with more data about their buildings' energy consumption. The deployment of advanced metering infrastructure, a key component of the smart grid, is the most visible example of this move to provide utilities and their customers more information about how energy is being consumed. But attention is now turning to even more granular end-use or device-level data. Such detailed data is proposed as a major step towards enabling more informed investment in energy efficient technologies. Consumers would benefit by knowing what devices most affect their energy bills, allowing them to make behavioral and investment decisions to more effectively reduce those bills. Manufacturers would be better positioned to develop and market efficient appliances and devices. Utilities and grid operators could incorporate these data to better forecast loads. And policymakers and utility program designers could use this information to develop viable energy efficiency, demand response (DR), and demand side management (DSM) initiatives that deliver sustainable, cost-effective, and verifiable results.

Sources and methods for generating these data are diverse. The largest and most detailed disaggregated load dataset to date was collected by the Pecan Street Research Institute as a research demonstration project funded by the Department of Energy (DOE) [2]. Non-intrusive load monitoring (NILM) methods are being researched that could reduce the cost and equipment installation time required to measure and disaggregate individual loads in a building. The Electric Power Research Institute (EPRI) and Eaton are currently developing a smart breaker panel with a similar goal of reducing cost and installation time while delivering direct-metered disaggregation [3]. Lastly, while its deployment and application is not currently well-understood, the coming Internet of things (IoT) promises connectivity with end uses that will almost certainly provide energy consumption data.

Whatever the source, it is clear that more device-level energy use data is going to become available in the near future. What is also clear – given the largely untapped potential for cost-effective energy efficiency gains in the buildings sector – is that the current application of these data lags behind their potential to inform and drive adoption of energy efficient technology adoption. This dissertation serves as an example of the type of effort that is needed to translate raw data into meaningful and actionable information for homeowners, manufacturers, utilities, and policymakers.

## 1.2 Data

Data for this dissertation was provided by the Pecan Street Research Institute, a 501(c)(3) not-for-profit corporation and research institute headquartered at the University of Texas at Austin. Pecan Street was awarded a Smart Grid Demonstration Project (SGDP) grant in 2009 as part of the Department of Energy's American Recovery and Reinvestment Act (ARRA) programming. In the years since, the group has compiled the world's largest database of residential energy use data and made it available to utilities, technology companies, devices manufacturers, and researchers [2].

Pecan Street has installed device-level submeters in over 700 homes and apartments with as many as 28 circuits or devices monitored in each home. Residents from in and around the city of Austin elect to join the study and work with Pecan Street researchers to decide which circuits and appliances in their home or apartment to monitor. The first residences in this sample begin reporting data in January 2012, and installations and monitoring continue to date. The resulting dataset includes monitored demand readings at 1-minute and 15-minute intervals. Studies in this dissertation use 15-minute interval data to calculate end-use consumption.

In addition to monitored data, results of energy audits and four annual surveys administered to participants are available to provide physical characteristics of the homes, as well as sociodemographic and other descriptions of the occupants and their behaviors. As part of their ongoing research, Pecan Street has also implemented several interventions in volunteer residents' homes and apartments. These include providing residents access to an online portal to observe their energy use, simulating time-of-use pricing schemes, and providing new appliances to homeowners, among others. A description of these programs and the number of participants in each can be found in Appendix A.

## 1.3 Applications of device-level energy consumption data

This dissertation is comprised of four studies that examine issues where device-level energy use data from the Pecan Street Research Institute can be used to inform energy efficiency policy and investment decision making in residential buildings.

Chapters 2 and 3 study how this type of data can be used to validate existing models and tools for understanding residential energy use. Chapter 2 discusses and categorizes the methods currently used to build a device-level accounting of where energy is used in the residential sector in the US. The Pecan Street data is compared to the Energy Information Administration's (EIA) Residential Energy Consumption Survey (RECS), and a method is proposed by which the Pecan Street data could be incorporated into future releases of this study. Chapter 3 uses the energy audit records and survey responses to model 106 homes in the DOE's EnergyPlus building simulation software. Simulation results are then compared to monitored data to provide the first device-level measure of the accuracy of EnergyPlus in a large number of homes.

Chapters 4 and 5 evaluate an intervention to reduce the energy consumption of homes by distributing direct current power in homes with solar PV arrays. In Chapter 4, DC circuits are simulated in 120 Pecan Street homes to estimate the energy savings and cost-effectiveness of those savings. As part of this technical analysis, a number of major nontechnical barriers to implementing DC distribution in homes are identified. Chapter 5 investigates these barriers in an expert elicitation to better understand the opportunities and challenges of more widespread use of DC in buildings.

Finally, Chapter 6 summarizes all of these studies and discusses their implications for existing and forthcoming policies.

# 2 Using advanced metering infrastructure to characterize residential energy use

A version of this chapter was published in The Electricity Journal as:

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## 2.1 Abstract

Decades of effort have been dedicated to understanding precisely where energy is consumed in residences to help consumers, device manufacturers, utilities, and policymakers better manage this consumption. We review and classify the three most prevalent methods currently used to build this understanding. Each method is described, and recent example studies are summarized. We then compare two prominent studies, and make recommendations for how existing datasets can inform estimates of device-level energy consumption in the US.

## 2.2 Background

Many energy efficiency and conservation strategies and policies to date have focused on the residential sector. This makes strategic sense, as residential buildings in the United States currently account for about 22% of all energy consumption [4] and 21% of all US greenhouse gas emissions, 71% of which is a result of electricity use in homes [5]. Despite decades of effort to better understand and reduce the energy consumed by US residences, detailed appliance level data on actual energy consumption is still sparse.

Building this understanding of precisely where energy is consumed in residences is crucial to managing residential energy use and reducing its effect on our environment. Consumers would benefit by knowing what devices most affect their energy bills, allowing them to make behavioral and investment decisions to more effectively reduce those bills. Manufacturers would be better positioned to develop and market efficient appliances and devices. Utilities and grid operators could incorporate these data to better forecast loads. And policymakers and utility program designers could use this information to develop viable energy efficiency, demand response (DR), and demand side management (DSM) initiatives that deliver sustainable, cost-effective, and verifiable results.

There are a number of technological and analytical methods currently being used to meet this need for more granular data on residential energy use. We break these methods into three classes: (i) direct metering of end-use devices and circuits, (ii) non-intrusive load monitoring, and (iii) statistical methods for disaggregation.

In Sections 2.3 and 2.4, we provide a description of these different methods and review studies that use these approaches in the United States. There are many more studies looking at estimating overall residential electricity consumption, but we focus only on those that have appliance level estimates. In Section 2.5 and 2.6, we describe two of these datasets in detail and describe – to the best of our knowledge – the first ever comparison between circuit level monitored data and the estimates from the EIA's Residential Energy Consumption Survey. In Sections 2.7 and 2.8 we present results of the analysis, conclusions reached, and recommendations for future work.

## 2.3 Methods for disaggregating residential energy use

### 2.3.1 Direct metering methods

Direct metering methods are the most basic means of generating disaggregated energy use data in residences. These methods measure actual power flow at the device or circuit level using distributed sensors, and therefore have the potential to provide the most accurate ground truth data about where energy is being used in a building. In residences installed with direct metering, the generated data can be used to provide direct real-time feedback to occupants about their energy use, DR and DSM opportunities, and the performance and operating characteristics of critical devices and equipment.

The drawbacks of these systems are primarily related to the cost of installing and maintaining extensive networked meter deployments, and of collecting and managing the resulting dataset. In a report for the EIA, Leidos Inc. conducted interviews with submeter suppliers and found the hardware cost alone to submeter a single home ranges from approximately $120 to over $1,000 [6]. In large deployments of the type implemented for utility or research purposes, these costs increase due to installation and data management requirements, resulting in final costs estimated to be on the order of $2,000 per home. In the same study, Leidos found a complete lack of a regulatory framework for submeter deployments in the US. Lacking this regulatory involvement, which was in place prior to the deployment of smart-meters, the authors conclude that submeters will not be widely used by utilities or others in the near future.

Despite these barriers, a number of pilot projects are under way to better understand the benefits and challenges of submeter deployments. A summary of these projects can be found in Table 2.1.

### 2.3.2 Non-intrusive load monitoring (NILM) methods

Non-intrusive load monitoring refers to methods of extracting device-level energy use estimates from a single-point whole-residence sensor measuring voltage and current signals at frequencies up to 500 kHz [7]. NILM methods analyze these signals to observe real power, reactive power, and harmonics in the line, and apply algorithms to extract device-specific features that allow power consumption to be attributed to various devices. The biggest benefit of these methods is the reduced monitoring equipment and installation needs, while maintaining real-time device-level energy disaggregation.

As a result of the reduced monitoring requirements of NILM, there are several drawbacks associated with these methods. These include the need for more advanced sensors and data acquisition, the need for some level of calibration to match observed signals to specific end uses, and energy allocations that depend on the ability of algorithms to detect device consumption. Current research is largely focused on better refining these algorithms and improving methods for disaggregation. A number of these studies are summarized in Table 2.1.

### 2.3.3 Statistical methods

Statistical methods for disaggregation refer to a broad range of analytical approaches to estimating device-level energy use from detailed residence descriptions and existing aggregate energy use data. Without the need for additional on-site monitoring, these methods can be applied to large numbers of homes and are therefore often used in national-level analyses of residential energy use. The EIA's Residential Energy Consumption Survey (RECS) is the most prominent example of this type of study. Some common methods used in these analyses include various regression models, conditional demand analysis, engineering methods, and neural network modeling.

The obvious drawback of these methods is the need to collect or otherwise obtain enough information about a large number of residences and their occupants to specify a model. Most commonly, this information gathering takes the form of a survey administered to residents that asks questions about income, occupancy, appliance ownership, building parameters, and other characteristics known to influence energy consumption.

As these methods often rely on utility-provided energy use data, they benefit from increasingly shorter metering intervals. Smart-meter data, collected at 15-minute or hourly intervals, has greatly improved the ability of models to attribute energy use to end uses. This ongoing shift towards advanced metering infrastructures (AMI) is seen as support for the increased use of these methods.

## 2.4 Sample studies

Table 2.1 summarizes prominent studies using the three methods described above.

**Table 2.1. Summary of studies using direct metering, NILM, and statistical methods to disaggregate residential energy use**

| Method of Disaggregation | Examples | Description | Results / Findings |
|---|---|---|---|
| Direct metering | Pecan Street Research Institute (2012-present) [2] | Funded by a $10.4M DOE stimulus grant, the Pecan Street Research Institute has installed device- and circuit-level submeters in over 700 volunteer residences in Austin, TX. | Pecan Street has curated the world's largest dataset of appliance- and circuit-level residential electricity data intended for research purposes. These data are made available to volunteer participants, and are also anonymized, licensed, and made available for download to the public. |
| | Duke Energy (2014-2015) [6] | Implemented submetering in a 61 home pilot project in Charlotte, North Carolina. | Pilot project was implemented to help better understand how Duke's residential customers consume energy, and "help develop optimization algorithms and strategies for their electric distribution grid operations." Results are not publicly available. |
| | San Diego Gas and Electric (2013) [6] | Implemented submetering in a 30 home pilot project in San Diego, California. | Pilot project was implemented to build an understanding of end use energy consumption as a means of improving future utility programs. Results are not publicly available. |
| | Community Power Partners (2014-2016) [6] | Partnered with the Pecan Street Research Institute to implement submetering in 48 homes in Boulder, Colorado. | The pilot is intended to research how residences consume energy and what tools and information occupants need to better manage their energy use. Results are not publicly available. |
| Non-intrusive load monitoring | Berges, Goldman, Matthews, and Soibleman (2009) [8] | Tested the ability of four disaggregation algorithms to classify features of a monitored dataset generated using a laboratory setup of common appliances connected to a single electrical outlet. | Machine-learning classification with the 1-nearest-neighbor algorithm was found to be the most successful at identifying features. 90% of lab-generated events were successfully identified. |
| | Kolter, Batra, and Ng (2010) [9] | Used a sparse coding algorithm to learn devices' power signals, and then apply the learned information to disaggregate power consumption | The algorithm is able to correctly estimate up to 55% of energy consumed over one week. Discriminative training is found to improve |

| | | | |
|---|---|---|---|
| | | from a single meter. | algorithm performance in nearly all cases. |
| Statistical methods | RECS (2009) [10] | Collected monthly energy bills and administered a survey to a nationally representative sample of over 12,000 US residences. | Collected data are combined in a nonlinear regression model to estimate end-use energy consumption for five fuel types and five end uses of energy. Results are released to the public and serve as a primary data source for other EIA publications and residential sector research. |
| | Torres, Blackhurst, Bouhou (2015) [11] | Tested the RECS disaggregation models used to estimate air conditioning loads. Used the RECS data, and submetered air conditioning use data and energy audit records from the Pecan Street Research Institute to test different model forms and independent variables. | Found statistically significant differences between the RECS and Pecan Street datasets, and found that cooling energy might be underestimated in RECS. The authors recommend including several predictors not currently collected in the RECS survey, and makes recommendations on how to improve end-use disaggregation estimates. |
| | Borgeson (2013) [12] | Explores various applications of smart-meter data to improve efficiency program targeting. Part of this analysis includes a disaggregation of heating and cooling loads from 30,000 PG&E customers into base and thermal loads. | Two methods are proposed for disaggregation: a simple linear regression of utility use on heating and cooling degree days, and simply taking the difference between observed base load and actual consumption. Findings are used to draw conclusions about targeting of homes for space heating and cooling initiatives from utilities or PUCs. |
| | Birt, et al. (2012) [13] | Uses a submeter dataset to estimate segmented regression models that disaggregate smart-meter data into five load categories based on activity level and space conditioning loads. The resulting model is then applied to hourly smart-meter data for a sample of 327 homes which underwent a utility survey. | The model is able to disaggregate base loads, activity loads, temperatures at which AC is used, cooling season gradients, and heating season gradients in most of the sampled homes. The authors find limitations to the model, but argue that this type of analysis provides insight into end use consumption data that is already being collected that can help direct DSM and efficiency initiatives. |
| | Tiedeman (2007) [14] | Uses multivariate regression with utility billing data as the dependent variable and weather and customer survey data as independent variables to estimate end-use energy consumption estimates. | The model is used to generate disaggregate energy consumption estimates for 14 end uses and potential energy savings from 4 conservation opportunities. |

## 2.5 Data

For this analysis we rely on data from the EIA's RECS and submeter data from the Pecan Street Research Institute. These datasets are described in detail below.

### 2.5.1 RECS data

The most comprehensive study of energy use in American homes is the EIA's Residential Energy Consumption Survey (RECS). These surveys are administered to a nationally representative sample of primary housing units from which energy use, physical residence characteristics, and household demographics are assessed [15]. The raw data is released to the public, where it is widely used in the peer-reviewed literature on energy systems, energy policy, energy efficiency, and other topics. The resulting data also serve as inputs to other EIA publications such as the Annual Energy Outlook and the Annual Energy Review.

The first RECS survey was administered starting in 1978, with annual updates until 1982. As the length of the surveys grew, subsequent releases became less frequent and since 1997 have been conducted every four years [15]. The most recent RECS survey, now in its twelfth iteration, was conducted in 2009 and became available to the public in 2012.

The 2009 RECS was administered to a sample of homes chosen to represent all 113.6 million primary US residences [16]. Homes are selected through a process beginning with the random selection of counties across the country to be surveyed. Each of these counties is then divided into groups of census blocks. A fraction of these census blocks are then chosen at random and the houses within each listed. The final homes to be surveyed are then selected randomly from this list. In the most recent survey conducted in 2009, this method was used to select 19,000 residences to survey. Approximately 15,300 of these were occupied primary residences, and of these approximately 12,083 housing units replied to the survey. In order to present the results of the work at a national scale, each response is assigned a sample weight between approximately 500 and 96,000 that describes how many residences in the US that surveyed residence represents [15].

Data for the survey is collected in two parts. A team of trained interviewers first conducts extensive in-person interviews of residents and landlords [16]. These surveys are known as the Household Survey and Rental Agent Survey. Questions attempt to identify behavioral patterns of residents that impact energy consumption, as well as physical characteristics of the building and its appliances. The only physical measurement taken by the interviewer during this session is the square footage of the residence. All other recorded results are based on the perceptions of the interviewee. For example, the survey asks of homeowners "Would you say that your home is well insulated, adequately insulated, or poorly insulated?", but does not measure the thickness or record the type of insulation present. Once these survey responses have been collected, the Energy Supplier Survey (ESS) is sent to each housing unit's utility providers to quantify, both in energy units and dollars, how much electricity, natural gas, fuel oil, and propane the residence consumed in the past year.

Once validated and edited, the results of these two surveys are input into non-linear regression models that disaggregate the total annual consumption of each utility into five components: space heating, air conditioning, water heating, refrigeration, and other. The models vary by appliance and fuel, but rely on factors such as the size and type of the appliance, building age and size, weather, and number of residents, among others to estimate each load's contribution to annual energy consumption [10].

The results of these surveys and models provide the EIA with not only a static breakdown of how residences in the US consume energy, but observable long-term trends in energy consumption patterns across the residential sector. Findings from these studies are also fed directly into the EIA's Annual Energy Outlook reports. These provide projections of national energy supply, demand, and prices under current policies out to 2040 and provide decision support for government and industry.

### 2.5.2 Pecan Street data

Residence- and device-level energy consumption data used in the analysis were obtained from the Pecan Street Research Institute's Dataport [2]. Pecan Street Inc. is a 501(c)(3) not-for-profit corporation and research institute headquartered at the University of Texas at Austin. Volunteers from in and around the city of Austin elect to join the study and work with Pecan Street researchers to decide which circuits and appliances in their home or apartment to monitor.

The first residences in this sample begin reporting data in January 2012, and installations and monitoring continue to date. The resulting dataset includes monitored demand readings for over 700 homes and apartments at 1-minute and 15-minute intervals. For this analysis, we use 15-minute interval data to calculate end-use consumption.

In addition to monitored data, results of energy audits and four annual surveys administered to participants are available to provide physical characteristics of the homes and sociodemographic descriptions of the occupants. We also note that as part of their ongoing research, Pecan Street and its commercial partners have implemented several interventions in volunteer residents' homes and apartments. The earliest such intervention involved providing a detailed report to homeowners about their energy use in early 2012. Subsequent interventions included providing residents access to an online portal to observe their energy use, simulating time-of-use pricing schemes, and providing new appliances to homeowners, among others. We assume that these interventions do not significantly alter the appliance-level energy consumption in the monitored homes. A description of these programs and the number of participants in each can be found in Appendix A.

## 2.6 Methods

Using the metadata included in the RECS dataset, we filter the nationally representative sample to include only respondents similar to the Pecan Street residences: single-family homes and apartments in Texas with central cooling. Using the weighting factors provided in the RECS dataset, these 595 homes and 200 apartments are representative of around 5.0 million homes and 1.7 million apartments across Texas.

To filter the Pecan Street dataset, we apply validation criteria requiring at least one year of whole-home or whole-apartment use data with less than one week of missing values. We also require the residence to have completed a survey to ensure the availability of demographic details. From the original sample of homes and apartments, this reduces the sample size to 339 homes and 104 apartments. Monitored appliances vary by residence, resulting in fewer records for each appliance. Energy use values for final comparisons are calculated from the most recent year of data available for each home or apartment.

Lastly, Austin Energy sales data from 2012 show the average residential customer calculated as total billed kWh divided by number of residential customers. It should be noted that the Austin Energy average includes both homes and apartments. This level of consumption is, therefore, likely an underestimate of average home consumption in Austin and an overestimate of average apartment consumption.

## 2.7 Results

### 2.7.1 Summary statistics of RECS and Pecan Street datasets

Table 2.2 shows a comparison of the RECS and Pecan Street samples. Pecan Street summary statistics are taken from all homes and apartments in the study meeting minimum data validation criteria. Surveys and energy audits were not administered to every home or apartment in the sample, so not every field is known for every residence in the study.

**Table 2.2. Summary statistics for Pecan Street and RECS homes and apartments**

| | | RECS | | Pecan Street | |
|---|---|---|---|---|---|
| Residence | Characteristic | Mean | Std. Dev. | Mean | Std. Dev. |
| Homes | Sample size[a] (qty) | 595 | -- | 339 | -- |
| | Age (yrs) | 35 | 20 | 28 | 25 |
| | Area ($ft^2$) | 2,400 | 1,300 | 2,000 | 740 |
| | Cooling degree days (qty) | 2,900 | 650 | 2,940 | 30 |
| | Residents (qty) | 2.9 | 1.5 | 2.6 | 1.2 |
| | Household income [b] ($/yr) | $60k | $36k | $156k | $135k |
| Apartments | Sample size [a] (qty) | 200 | -- | 104 | -- |
| | Age [c] (yrs) | 38 | 15 | 4 | 0 |
| | Area ($ft^2$) | 870 | 290 | 1,100 | 240 |
| | Cooling degree days (qty) | 3,000 | 630 | 2,940 | 10 |
| | Residents (qty) | 2.2 | 1.4 | 1.7 | 0.9 |
| | Household income [b] ($/yr) | $30k | $23k | $52k | $42k |

a Meeting minimum data validation requirements
b Household incomes were provided as a range. Values above were calculated using the median of this range except for the bottom bracket (<$10k) and top bracket ($1M+)
c Ages were only available for (3) of the (104) apartments meeting data validation requirements.

This comparison shows the greatest differences in the two datasets are related to the age, size, and household incomes of the sampled residences. Homes in the RECS sample are only slightly older than those in the Pecan Street study. Only three apartments in the Pecan Street study have a reported age, and all three report being only 4 years old. Pecan Street homes are smaller, on average, than the RECS homes, but the opposite is true of apartments. Lastly, the largest difference between the samples relates to household income. Both home and apartment occupants in the Pecan Street study report much higher incomes than those in the RECS sample.

In addition to the demographic differences in the samples, the 3-year gap between the RECS data collection period and the beginning of Pecan Street's monitoring efforts is another reason to expect that the energy consumption of these two samples will differ. During those three years, major energy-consuming appliances became more efficient, existing efficiency-enabling technologies and controls became more affordable and widely available, and public awareness of the benefits of reducing energy consumption was improving. All of these factors, and others, limit the conclusions that can be drawn from the comparison of the two samples.

### 2.7.2 Total residence consumption

Total annual home and apartment electric consumption are shown in Figure 2.1.

The median of the Pecan Street home consumption data, around 10,100 kWh/yr, is outside of the interquartile range of the RECS sample. The boxes in all of the boxplots below show the median, $25^{th}$, and $75^{th}$ percentiles of the data. The whiskers extend to 1.5 times the interquartile range above and below the 75th and 25th percentiles, respectively. Values outside of this range are marked as outliers. Nearly all of the Pecan Street homes fall within this range of the RECS data. Comparing medians, the Pecan Street homes consume around 33% less electricity than the RECS homes and around 13% less than the average Austin Energy residential customer. When separated into income brackets, Pecan Street homes' median consumption is similarly less than that of homes in the RECS across all income ranges. See Appendix B for these figures.

Looking at apartments, the median of the Pecan Street data, around 4,800 kWh/yr, is again outside of the interquartile range of the RECS sample. Comparing medians, the Pecan Street apartments consume around 48% less electricity than the RECS apartments, and nearly 60% less than the average Austin Energy customer. Again, this reduced use exists across all income brackets as seen in Appendix B.

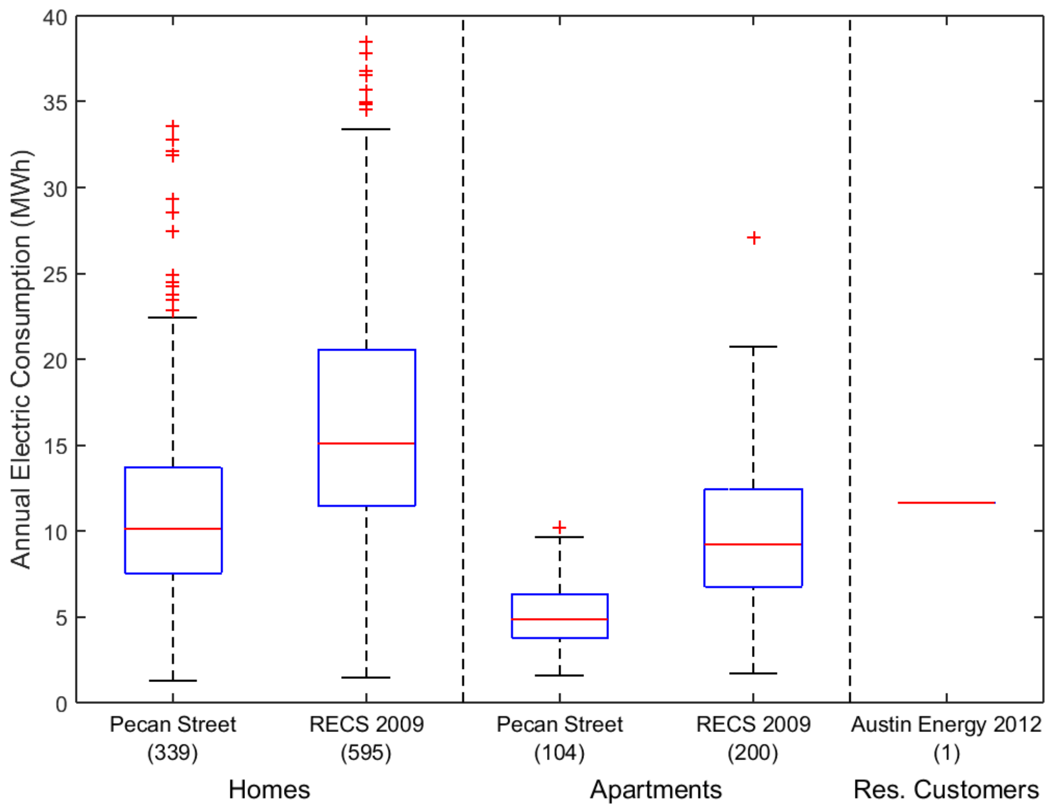



**Figure 2.1. Comparison of Pecan Street monitored data to RECS 2009 data and Austin Energy 2012 sales data. Box plots show the median, 25% quartile, 75% quartile, maximum, minimum, and outliers. The left box shows Pecan Street data, the middle box shows the RECS reported annual consumption, and the right box shows Austin Energy data. The number of data points represented in each plot is shown below the source.**

The reduced energy use in Pecan Street homes and apartments is likely due to selection bias as participants volunteer to be included in the Pecan Street sample. These individuals are likely more energy-conscious, make more energy-aware purchase decisions, and exhibit more energy-aware behavior than average residents in the RECS. A portion of this reduced use is likely also due to the Hawthorne effect, which has been shown to reduce energy use when individuals know they are participating in a study of household energy use [17].

### 2.7.3 Device-level consumption

Next, we show the total annual home and apartment air conditioning, water heater, and refrigerator electric consumption data in Figure 2.2. The RECS data present the results of the EIA's statistical models in estimating energy consumed by air conditioner condensing units, electric water heaters, and refrigerators.

Median air conditioning consumption in the Pecan Street homes is within the interquartile range of the RECS data and is around 67% of the RECS median. The use of the RECS model outputs instead of measured data introduces a potential source of error in the RECS estimate. Median AC consumption in the Pecan Street apartments is outside the interquartile range of the RECS data at around 40% of the RECS median.

Total annual home and apartment electric water heater consumption are shown in the middle two boxes of each figure. The RECS data present the results of the EIA's statistical models in estimating energy consumed by all-electric water heaters in homes and apartments. Here, the same filters were applied to the RECS sample, but sample sizes are smaller than previously presented as many households use natural gas water heaters. Using the reported weighting factor for each home, these 220 and 148 samples are representative of approximately 1.8 million and 1.2 million American homes and apartments. Despite similar occupancy in both homes and apartments, medians of monitored consumption are around 53% and 41% of RECS reported values, respectively.

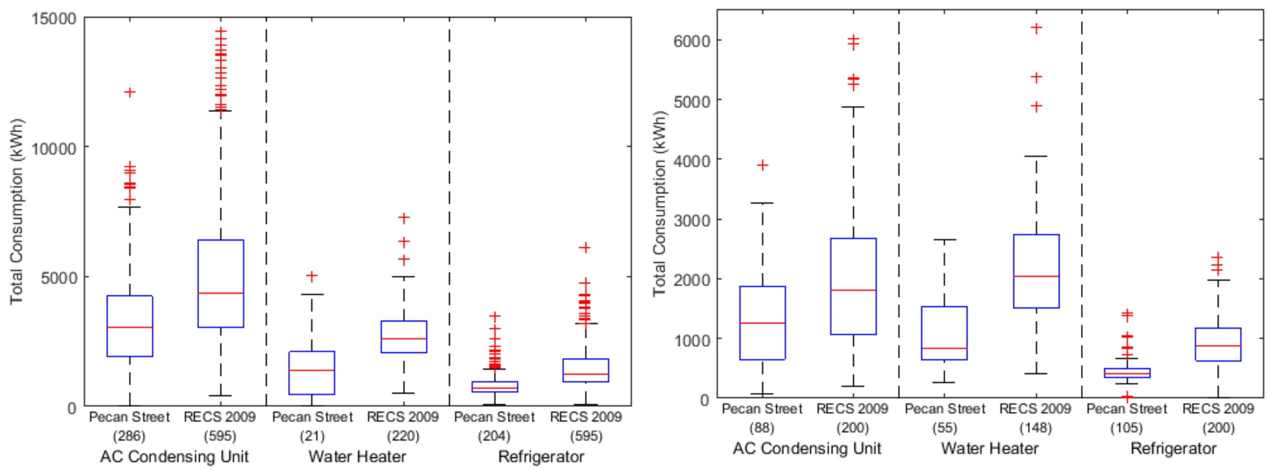



**Figure 2.2. Device-level energy consumption for homes (left) and apartments (right). Box plots show the median, 25% quartile, 75% quartile, maximum, minimum, and outliers. For each appliance, the left box shows Pecan Street data and the right box shows RECS data. The source and number of data points represented in each plot is shown below each box.**

Median refrigerator consumption in the monitored homes is outside of the interquartile range of the RECS data, and is around 57% of the RECS median. Median refrigerator consumption in the Pecan Street apartments is also outside of the interquartile range of the RECS data, and is around 48% of the RECS median.

The RECS appliance-level consumption estimates are all calculated as a fraction of whole-residence use, so comparing each appliance's contribution to total energy use may be a more appropriate comparison of the two datasets. Figure 2.3 shows boxplots of these comparisons.

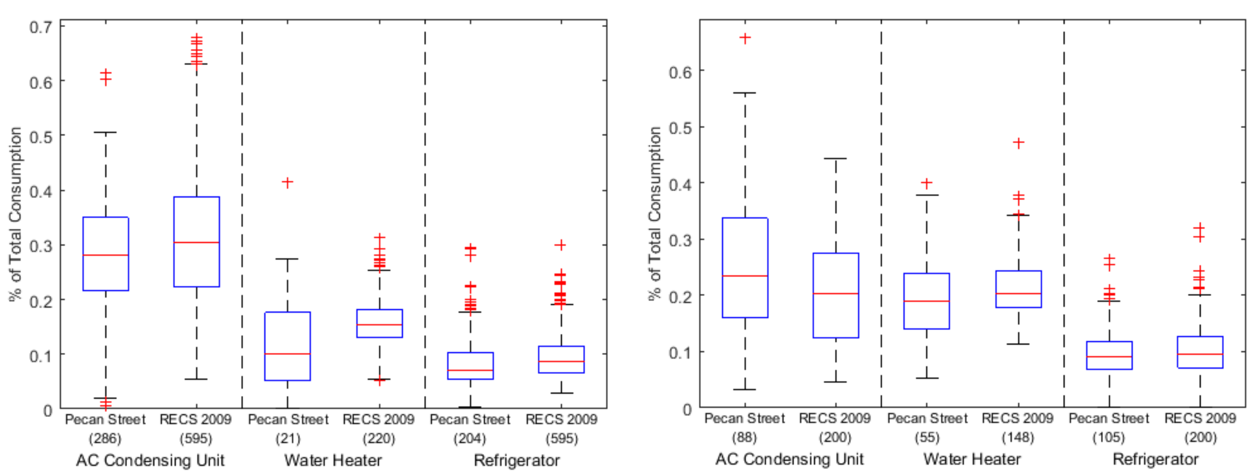



**Figure 2.3. Device-level energy consumption as a fraction of total residence consumption for homes (left) and apartments (right). Box plots show the median, 25% quartile, 75% quartile, maximum, minimum, and outliers. For each appliance, the left box shows Pecan Street data and the right box shows RECS data. The source and number of data points represented in each plot is shown below each box.**

In homes, the largest gap between the RECS and Pecan Street fraction of home load by a single device is around 5 percentage points for water heater consumption. In the RECS sample, models estimated that these devices represent around 15% of total electricity consumption. In the Pecan Street monitored data, median consumption is around 10% of total consumption. In apartments, all appliances are in better agreement. The largest gap between medians is for AC condensing units. RECS models estimate these devices consume 20% of total home energy use, while in the Pecan Street sample this number is around 23%.

## 2.8 Discussion and conclusions

In this study, we provide a review of the types of data available to estimate appliance level electricity consumption in US homes, and a comparison between two specific methods – the survey data collected by the EIA in the Residential Energy Consumption Survey, and detailed submetered data from the Pecan Street Research Institute.

Comparisons of resident demographics, home sizes, and whole-residence energy consumption reveal critical differences between the Pecan Street population from Austin and the RECS' broader sample of Texas residences. These differences mean that the differences between the measured and RECS-estimated appliance-level energy consumption cannot be attributed to problems with the RECS modeling technique.

Overall, we find that Pecan Street homes and apartments consume less energy than comparable residences in the EIA's RECS. The same is true of device-level energy consumption. Submetered Pecan Street appliances consume significantly less energy on average than the RECS device-level consumption estimates. However, the EIA disaggregation model results and the Pecan Street submeter data show similar results in estimating the fraction of total residence energy consumption by air conditioning, refrigeration, and water heating loads in this sample of homes and apartments.

There are several recommendations that arise from this work:

*Nationally representative submetered data could help improve a characterization of U.S. residential electricity consumption at the appliance level.*

In addition to the Department of Energy's interests in submetering projects, utilities and city governments have already begun to explore the potential of device-level monitoring to improve their understanding of their residential loads. The efforts of Pecan Street, Duke Energy, San Diego Gas and Electric, and the city of Boulder's Community Power Partnership, detailed in Table 2.1 are evidence of this interest.

In line with recent efforts at EIA, we recommend further consideration of existing submeter installations as a means to continually improve the RECS dataset, and more importantly the understanding of residential electricity consumption. The existing Pecan Street data could be used as a cost-effective way for the EIA to validate end-use disaggregation methods.

*Large submetered datasets are becoming more widely available and can be utilized to improve confidence in study findings*

At current equipment and labor prices, monitoring the 12,083 housing units included in the most recent RECS would be prohibitively expensive at approximately 20% of the EIA's annual budget [18]. See Appendix B for cost estimates. But as the cost of monitoring equipment drops, it may become feasible to monitor a fraction of the residences in the RECS sample. Not all residences and not all loads would need to be included. Figure 2.3 above shows that approximately 50% of homes' and apartments' electricity use is consumed by just three devices. Further, Figure 2.2 shows relatively little variation in refrigerator energy consumption, so monitoring of these devices could be implemented in only a small number of residences.

Alternatively, given the size and level of detail of the Pecan Street dataset, the existing data could be used as a more cost-effective way for the EIA to validate end-use disaggregation methods. Pecan Street homes could be added to the RECS sample and end-use consumption estimated using the existing disaggregation models. These estimates could then be compared to the homes' and apartments' existing submeter data to validate the standard models, assumptions, and adjustments used by the EIA in these estimates.

Further, the use of these types of datasets should not be considered limited to validating end-use consumption estimates. Monitored device-level data captures a number of factors such as occupant behavior, appliance stock characteristics, and usage patterns, among other things, that have the potential to lend greater confidence to various types of studies. Incorporating these data in place of generic load profiles or aggregate consumption estimates in any type of study or survey can provide a more realistic measure of how energy is actually used in homes, and can serve to better understand and optimize efficiency and conservation methods that will reduce the environmental impacts of residential energy use in the US.

# 3 Assessing the value of information in residential building simulation

A version of this chapter is under review at Applied Energy as:

Glasgo, B., Hendrickson, C., Azevedo, I.L. Assessing the value of information in residential building simulation: Comparing simulated and actual building loads at the circuit level.

## 3.1 Abstract

Building energy simulation tools are now being used in a number of new roles such as building operation optimization, performance verification for efficiency programs, and – recently – building energy code analysis, design, and compliance verification in the residential sector. But increasing numbers of studies show major differences between the results of these simulations and the actual measured performance of the buildings they are intended to model. The accuracy and calibration of building simulations have been studied extensively in the commercial sector, but these new applications have created a need to better understand the performance of home energy simulations.

In this paper, we assess the ability of the DOE's EnergyPlus software to simulate the energy consumption of 106 homes using audit records, homeowner survey records, and occupancy estimates taken from monitored data. We compare the results of these simulations to device-level monitored data from the actual homes to provide a first measure of the accuracy of the EnergyPlus condensing unit, central air supply fan, and other energy consumption model estimates in a large number of homes. We then conduct sensitivity analysis to observe which physical and behavioral characteristics of the homes and homeowners most influence the accuracy of the modeling.

Results show that EnergyPlus models do not accurately or consistently estimate occupied whole-home energy consumption. While some models accurately predict annual energy consumption to within 1% of measured data, none of the modeled homes meet ASHRAE criteria for a calibrated model when looking at hourly interval data. The majority of this error is due to appliance and lighting energy overestimates, followed by AC condensing unit use. These inaccuracies are due to factors such as occupant behaviors and differences in appliance and lighting stocks which are not well-captured in traditional energy audit reports. We identify a number of factors which must be specified for an accurate model, and others where using a default value will produce a similar result.

The use of building simulation tools reflects a shift from a component-focused approach to a systems approach to residential code analysis and compliance verification that will serve to better identify and deploy efficiency measures in homes. By better understanding the limitations of home energy simulations and adopting strategies to mitigate the effects of model errors, simulation models can serve as valuable decision making tools in the residential sector.

## 3.2 Background

Increased attention to building energy performance, improved software packages, and decreasing computing power requirements have led to the use of building energy simulation tools in a large and growing number of applications [19–21]. These tools are now being used in their traditional role as decision support for building and retrofit design in the commercial sector, but also in new roles such as building operation optimization [19], performance verification for energy efficiency programs like LEED [22], and – recently – building energy code analysis, design, and compliance verification in the residential sector [21,23]. However, increasing numbers of studies show major differences between the results of these simulations and the actual measured performance of the buildings they are intended to model [24–31]. These discrepancies, combined with the new application of building simulation tools to policy and investment decision-making in the residential sector, have created a need to better understand the accuracy of their results and develop methods for calibrating them to ensure reliable outputs. Doing so will allow policymakers to apply these tools in a way that will ensure that residential building energy codes continue to deliver the cost-effective energy savings for which they are intended.

The Department of Energy's EnergyPlus is the most prominent simulation package being used in these new applications. As part of their work for the Department of Energy's Building Energy Codes Program, Pacific Northwest National Laboratory (PNNL) established a method for analyzing potential changes to residential building codes based on EnergyPlus [21]. While there are dozens of widely used building simulation tools, EnergyPlus was chosen for this application due to its long history of development and use by the DOE. For an overview of other simulation tools, including the features and capabilities of 20 of the most widely used simulation packages, see [32]. The method first involved the construction of prototype EnergyPlus models of simple single- and multi-family residences that meet existing region-specific building codes. The cost-effectiveness of potential changes to these codes is evaluated by incorporating a proposed change in the model – reducing allowable building leakage rate, for instance – simulating the building's energy performance using local weather data, and observing the resulting change in energy consumption. The simulated energy cost savings are then compared to the first cost to estimate the lifecycle cost of implementing the change. These results then serve to inform the DOE's position on whether to approve a code change proposed by the International Code Council (ICC), but are also used to inform state and local jurisdictions about the expected effects of adopting a new code when they are considering a change.

EnergyPlus is also in the process of being incorporated into a tool being developed by the Residential Energy Services Network (RESNET) to standardize residential energy benchmarking for energy code compliance. RESNET is a not-for-profit membership corporation that develops standards used in home energy efficiency ratings [33]. RESNET's Home Energy Rating System (HERS) is an industry standard calculation specification that allows certified energy raters to assign efficiency scores to homes that can be used to demonstrate their energy code compliance in most states and jurisdictions [23,34]. Efficiency scores are currently calculated using a number of software programs that have been approved and accredited by RESNET [35]. In March of 2016, however, RESNET and the DOE announced that this suite of software packages is going to be replaced by a single-source tool based on EnergyPlus [23]. While the tool has not yet been released or described in detail, its announcement alone highlights the need to better understand the ability of EnergyPlus to accurately model residential buildings.

Previous studies of the accuracy of building energy simulations have focused almost exclusively on the commercial sector and have often found large discrepancies between modeled and actual performance. These studies typically involve the construction of a model of a building in which extensive data gathering has been conducted. Using measured and observed details of the building and its operation, a detailed model is constructed and its simulated performance is compared to measured data such as electric or gas utility data [28], environmental sensor data [29], or submetered system-level data [26,30,31]. Based on these results, conclusions are drawn about the suitability of the chosen model and application, and recommendations are made to improve modeling efforts in the future.

In addition to studies which generate and analyze building energy simulations, there are a growing number of papers dedicated solely to the methods by which these models can be calibrated. Coakley et al. summarized these methods in a literature review of around 70 papers addressing issues of calibration in building simulation modeling [36]. The paper generally finds no consensus method for building simulation calibration, nor does it find a widely accepted set of criteria for validating these models. However, given the large body of literature found by the authors, they conclude that the work already available could inform the development of standardized methods for model calibration.

Both types of studies are typically limited by data availability to a small number of buildings. The conclusions that can be reached from such studies are therefore limited as well. To address this issue and increase sample sizes, research is now turning to batch simulations in which large numbers of buildings are modeled in parallel. Rhodes et al. used one such method to simulate 54 homes in the Pecan Street study using energy audit and survey records as model inputs [37]. In this study, a baseline model of each home was built using actual building characteristics and simulated using Typical Meteorological Year (TMY) data. Three alternate scenarios were then simulated which 1) used actual weather data, 2) updated default thermostat settings with actual thermostat settings, and 3) simplified each home's geometry into a rectangular footprint. Each set of simulation results were compared to measured whole-home annual electricity consumption. Results indicate that including actual thermostat settings improves model accuracy, actual weather data unexpectedly worsened accuracy, and simplifying home geometries had little effect on outcomes. Errors for individual homes ranged from underestimating actual annual consumption by 60% to overestimating by over 100%. However, when results are aggregated to measure the model's ability to predict the combined electricity consumption of all the homes, errors are reported as less than 3%.

In this paper, we advance this approach by modeling and simulating 106 homes from the same Pecan Street study used by Rhodes et al [37]. We use PNNL's residential prototypes as a starting point, then modify these prototypes with information from Pecan Street's energy audit records, homeowner survey results, and occupancy profiles estimated from device-level energy consumption data to more closely resemble the actual monitored homes. We compare the results of these simulations to device-level monitored data from the actual homes to provide a first measure of the accuracy of the EnergyPlus condensing unit, central air supply fan, and other energy consumption model estimates in a large number of homes. By comparing simulated and actual energy consumption at this detailed level, we are able to more closely identify the source of EnergyPlus model errors and provide detailed recommendations on how to address them and mitigate their effect on decision-making in the residential sector.

We then conduct a sensitivity analysis to observe which physical and behavioral characteristics of the homes and homeowners most influence the accuracy of the modeling. These results provide context for the use of EnergyPlus as a decision-making tool in the residential sector. Specifically, they show the approximate level of accuracy that researchers can expect when simulating homes displaying a range of physical characteristics, appliance stocks, and occupant behaviors. Sensitivity analysis results also provide a measure of which characteristics most influence model accuracy and need to be included for accurate system-level modeling.

The rest of this paper is organized as follows. Section 3.3 describes the data, modeling methods, and assumptions used in the analysis. Section 3.4 presents results of the modeling and sensitivity analysis. Sections 3.5 and 3.6 provide a discussion of these results, conclusions reached, and policy implications.

## 3.3 Material and methods

### 3.3.1 Residential building prototypes

As a starting point for our modeling, we use PNNL's single-family detached home EnergyPlus prototypes built according to the IECC 2006 residential building energy code. Prototype models are available that were built to simulate homes compliant with IECC 2006, 2009, and 2012 [38]. The oldest available prototypes were chosen to more closely match the older Pecan Street building stock. For a short discussion of the IECC building energy code adoption process, see Appendix C. Prototypes are also differentiated by location to account for variations in building energy codes by climate zone. Homes in the Pecan Street sample are located in and around Austin, Texas, so we select prototypes designed for San Antonio, which is located in the same climate zone [39]. Finally, prototypes are available with different combinations of foundation or basement type and primary space heating fuel type. Using the Pecan Street energy audit records, we select and assign prototypes to match these factors for the homes in our final sample. A summary of some of the key characteristics of these prototypes can be found in Table 3.1.

### 3.3.2 Appliance-level energy use data

Appliance- and home-level energy consumption data were obtained from the Pecan Street Research Institute's Dataport for the year 2015 [2]. Pecan Street Inc. is a 501(c)(3) not-for-profit corporation and research institute headquartered at The University of Texas at Austin. Volunteers from in and around Austin elect to join the study and work with researchers at Pecan Street to decide which circuits and devices in their homes to monitor. The resulting dataset includes records for over 700 homes, with data available for up to 28 circuits per home at 15-minute intervals. We apply validation criteria which require at least one full year of whole-home use data with less than one week of missing values.

To ensure a fair comparison between EnergyPlus simulations and monitored data, energy consumption from electric vehicles, garages, pool lights, pool pumps, and sprinklers are subtracted from monitored whole-home consumption when these devices were monitored. These devices are not modeled in EnergyPlus simulations and would otherwise be a source of error.

Average whole-home electricity consumption in the Pecan Street sample is around 33% less than comparable homes in the EIA's 2009 Residential Energy Consumption Survey (RECS) and around 13% less than the average Austin Energy customer [40,41]. Thus, while the sampled homes are more efficient than the average Texas home, they are likely to provide a reasonable estimate of household electric consumption around Austin.

### 3.3.3 Energy audit and homeowner survey records

Energy audit and homeowner survey records are available for many homes in the Pecan Street sample. As part of their ongoing research, the Pecan Street Research Institute has implemented several interventions in volunteer residents' homes and apartments. These include providing residents access to an online portal to observe their energy use, simulating time-of-use pricing schemes, and providing new appliances to homeowners, among others. A description of these programs and the number of participants in each can be found in Appendix A.

Energy audits were conducted and recorded in the Pecan Street dataset between January 2011 and September 2014 as part of two separate programs. The majority of audits were conducted by an outside contractor before monitoring installations began in January 2012. The remaining audits, conducted in late 2013 and early 2014, were conducted by Pecan Street personnel. Annual surveys are administered to participants in the Pecan Street study. Records from these surveys provide demographic and other information about the homes and their occupants.

In selecting homes to be included in final simulations we include only those which meet the monitored data validation criteria described above, and which also have an energy audit record and at least one annual survey record. A total of only 106 homes remain that meet these requirements. Of these, 102 have complete condensing unit data and 75 have complete central air supply fan data.

A summary of key data collected in the audits, surveys, and monitoring installations is shown below in Table 3.1.

**Table 3.1. Summary statistics for PNNL prototype models and simulated Pecan Street homes.**

| | PNNL Prototype | Pecan Street | | |
|---|---|---|---|---|
| | Value | Min | Mean | Max |
| **Occupant characteristics** | | | | |
| Residents (qty) | 3.0 | 1.0 | 2.6 | 6.0 |
| Household income ($/yr) | -- | $30k | $130k | $230k |
| **Building envelope characteristics** | | | | |
| Number of floors | 2 | 1 | 1.5 | 2 |
| Foundation type (slab / pier) | Varies | -- | 94 / 12 | -- |
| Home age (yrs) | ~ 10 | 6 | 28 | 96 |
| Area (ft2) | 2,400 | 800 | 2,100 | 4,000 |
| Ceiling height (ft) | 8.5 | 7.5 | 9 | 14 |
| Building infiltration (ELA, cm2) | 960 | 310 | 960 | 2,400 |
| Window U-factor ($W/m^2K$) | 4.3 | 2.2 | 4.1 | 7 |
| Attic insulation R-value ($m^2K/W$) | 4.3 | 1.1 | 5.3 | 9.2 |
| **Appliance characteristics** | | | | |
| Condensing unit efficiency (EER)[a] | 13.5 | 5.0 | 10.9 | 17.0 |
| Condensing unit age (yrs) | 0 | 4 | 10.1 | 27 |
| Heating setpoints (daily avg., °F) | 72 | 63 | 69 | 75 |
| Cooling setpoints (daily avg., °F) | 75 | 68 | 77 | 82 |
| Heat pump / Gas furnace (qty / qty) | Varies | -- | 7 / 99 | -- |
| Programmable thermostat (y / n) | Yes | -- | 98 / 8 | -- |
| Water heater fuel (gas / electric) | Varies | -- | 100 / 6 | -- |

[a] Nameplate efficiency

### 3.3.4 Occupancy estimation

Home occupancy is an important determinant of the timing and quantity of energy consumption in homes. Survey results provide an incomplete accounting of occupied hours for each home, so we estimate occupancy based on device-level monitored data.

To do this, monitored circuits and devices are separated into accompanied and activated loads. Accompanied loads are loads which indicate that the home is likely occupied if they are consuming energy. Activated loads are loads which can be consuming energy even if the home is unoccupied. For these loads, occupancy can only be estimated by looking for events where the device or circuit sees a significant change in load, indicating that someone has activated or deactivated the circuit. See Table 3.2 for a list of accompanied and activated loads. Note that loads which do not vary significantly based on occupancy, such as refrigerators or air conditioners, are not included in either load class and are not used to estimate occupancy with this method.

**Table 3.2. Appliance type allocations for occupancy estimation**

| Accompanied Loads | Activated Loads |
|---|---|
| Electric vehicles, laundry machines, dishwashers, in-sink disposals, microwaves, ovens, electric ranges | Bathroom circuits, bedroom circuits, dining room circuits, garage circuits, kitchen circuits, lighting circuits, living room circuits, office circuits, outdoor lighting circuits, pool lighting, utility room circuits, ventilation hoods |

Using these allocations, annual energy consumption profiles for each appliance or circuit in the 106 homes are used to estimate occupancy for every 15-minute interval for the year 2015. If any accompanied load in a home is consuming over 50W in a given interval, the home is flagged as being active in that period with *P(Active)=1.0.* Similarly, if any activated load sees an increase or decrease in demand of over 50W, the home is flagged as being active in that period with *P(Active)=1.0.* If no activity is identified, the home is flagged as inactive with *P(Active)=0*. Averaging these activity profiles for every day in 2015, we generate a probabilistic daily activity profile for each home.

Because this method relies on device activity, it fails to identify hours where homes are likely occupied, but the residents are inactive or sleeping. To correct for this, we assume that most homes follow a typical occupancy pattern of waking up between 3AM and 11AM and arriving home between 6PM and midnight. To estimate inactive – but likely occupied – hours, peak activity is identified for each of these periods. Prior to peak activity in the morning, and following peak activity in the evening, it is assumed the home is always occupied with *P(Occupied)=1.0*. Between each home's wakeup and arrival hours, it is assumed that activity actually reflects occupancy, with *P(Occupied)=P(Active)*.

A sample home showing the difference between the calculated activity profile and estimated occupancy profile is shown in Figure 3.1. This method is used to estimate an occupancy profile for each home in the final sample.

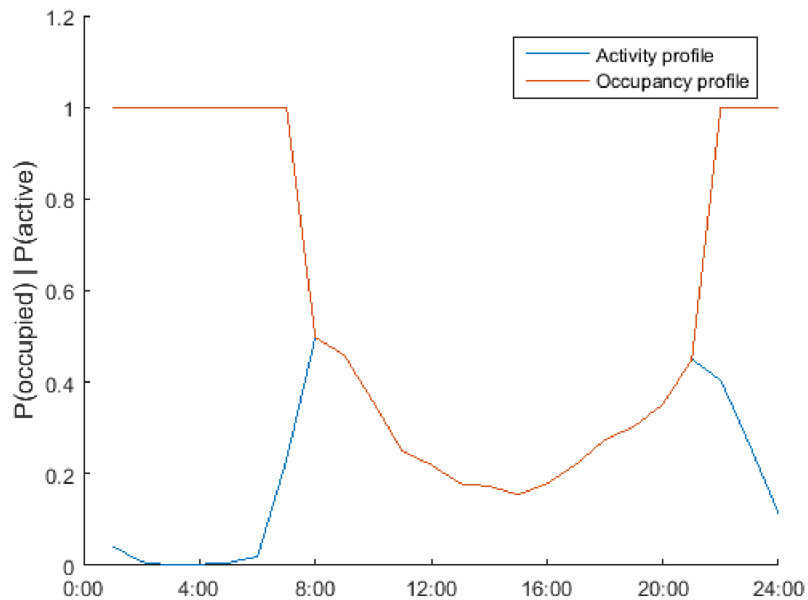



**Figure 3.1. Estimated activity and occupancy profiles for a single home where morning activity peaked at 8AM and evening activity peaked at 9PM.**

### 3.3.5 Modeling operations

Fully specified EnergyPlus models of the 106 Pecan Street homes are generated by modifying the PNNL prototypes' input data files (IDFs) with the home and occupant characteristics described above. These IDFs are text files which describe the physical, operational, and behavioral characteristics of the modeled homes and their occupants. To modify the prototype IDFs, a Matlab program was used to open each file, locate the fields to be edited, and replace the default values or descriptions with the actual home's characteristics. The characteristics for which we have data from either Pecan Street's energy audit or survey records are listed and described below.

- Number of floors
- Building square footage – Building square footage was available for each of the 106 homes. Length, width, and building footprint shape are not specified, so we model Pecan Street homes as rectangular homes with width 1.4 times the length. This is a reasonable assumption, as Rhodes et al. showed in [37] that simplifying the geometry of homes does not significantly impact EnergyPlus modeling performance.
- Attic insulation R-value – Attic insulation value was recorded in energy audit records. When data was missing, it was replaced with the average value from the remaining homes.

- Ceiling height – When ceiling height was not reported for an individual home, it was replaced with the average value from the remaining homes.
- AC condensing unit efficiency – In addition to the nameplate efficiency of each home's condensing unit, the age of each unit was known. To account for performance degradation over time, we estimate actual operating efficiency according to the method described in [42].
- Water heater fuel – Water heater fuel was determined based on energy audit reports and the availability of monitored data.
- Building shell infiltration – Building shell infiltration was reported in Pecan Street energy audits as the result of a blower door test conducted on each home. Results were reported in units of air changes per hour at 15Pa. PNNL's prototypes specify infiltration in terms of equivalent leakage area. To convert between the two units, we use the method described in [43].
- Occupancy schedule – Home occupancy was estimated as described above.
- Building orientation – The orientation of each home was reported for all homes as one of the 16 cardinal, intercardinal, or secondary-intercardinal directions.
- Number of residents – When number of residents was not reported for an individual home, it was replaced with the average value from the remaining homes.
- Heating and cooling setpoints – Heating and cooling setpoints were reported in one of Pecan Street's annual surveys. Residents reported their heating and cooling season thermostat setpoints for their sleeping, morning, workday, and evening hours without reporting actual hours. Because explicit hours for these periods were not identified, we assign sleeping hours as midnight to 7AM, morning hours as 7AM to 9AM, workday hours as 9AM to 6PM, and evening hours as 6PM to midnight. When setpoints were not reported, we assign these values the average of the reporting homes. Homes without programmable thermostats were assigned the same value for all periods.
- Window area per wall – Window area for each external wall, by orientation, was reported in Pecan Street audit records. When window area was not reported, values were assigned as the average of all reporting homes.
- Window type – Windows were described in Pecan Street energy audit records as a combination of frame material and number of panes. EnergyPlus describes windows by their overall U-value, which is primarily a function of these two factors. Overall U-factor for each window type was determined according to [44]. When window type was not reported, values were assigned as the average of all reporting homes.

The final input required to simulate the Pecan Street homes in EnergyPlus is weather data. To ensure that simulated conditions match actual conditions for the monitored period as closely as possible, recorded weather data for Austin in 2015 is taken from [45].

To measure the degree to which the EnergyPlus simulations match monitored data, accuracy will be reported in terms of the hourly coefficient of variation of the root mean square error (CVRMSE).

$$CVRMSE = \sqrt{\frac{\sum_{t=1}^{n}\left(y_{i,t}-\hat{y}_{i,t}\right)^2}{n}} \Big/ \bar{y}_i \tag{1}$$

This metric is used in ASHRAE Guideline 14 to define a model as calibrated if its hourly CVRMSE is less than 30% [46].

### 3.3.6 Modeling assumptions

In addition to the assumptions described above, we assume that any changes made by homeowners based on recommendations from the energy audits are minor and do not significantly affect 2015 energy consumption. We also rely on the accuracy of these energy audit records to describe the physical characteristics of the home and its appliance stock.

Additional data gathering would obviously improve simulation accuracy, as numerous important characteristics of the modeled homes are missing. In using the PNNL prototypes, we assume that these missing fields are relatively accurately represented by the default values used in these models.

### 3.3.7 Sensitivity analysis

Once the prototype home models have been modified with the actual monitored homes' characteristics and occupant behaviors, sensitivity analysis is conducted to determine which factors have the greatest impact on the accuracy of the simulations. This is done by specifying all fields but one with the actual homes' reported characteristics. The remaining field is assigned the default value used in the PNNL prototype models. The effect of this modification is measured as the change in CVRMSE between the fully specified baseline case and the less specified sensitivity analysis case.

$$\Delta CVRMSE = CVRMSE_{SensAnalysis} - CVRMSE_{Baseline} \tag{2}$$

For sensitivity analysis of floor area, condensing unit efficiency, building infiltration, heating and cooling setpoints, home orientation, ceiling height, window type, window area, attic insulation R-value, occupancy pattern, and number of residents, the actual values are simply reset to the default values used in the PNNL prototype models. We test sensitivity to correcting nameplate condensing unit efficiency for its age by simply using the nameplate efficiency, without the age correction factor described above. For lighting, we change the modeled homes' lighting power density from the default value in the IECC 2006 prototype to the updated IECC 2012 value, thereby greatly increasing the efficiency of each home's lighting array. Finally, we vary the exterior construction material from its default stucco construction to standard brick masonry construction.

## 3.4 Results

### 3.4.1 Baseline model accuracy – whole-home consumption

Figure 3.2 shows a scatter plot with the EnergyPlus simulated annual energy consumption of the modeled homes on the x-axis and measured annual energy consumption on the y-axis. The black diagonal shows where simulated energy consumption exactly matches actual consumption. The two red lines show ±50% relative annual error bounds.

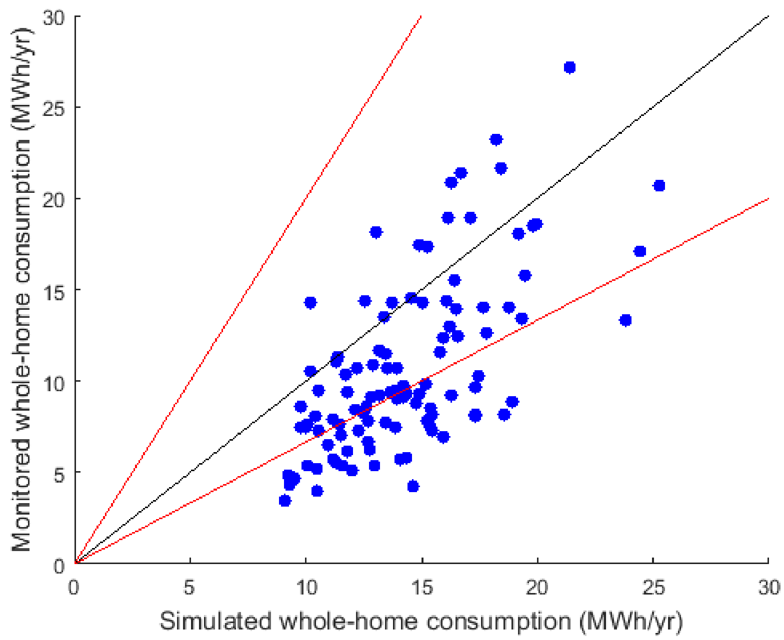



**Figure 3.2. Scatter plot showing simulated whole-home energy consumption on the x-axis and actual measured energy consumption on the y-axis. The black diagonal shows perfect agreement, while red diagonals show ±50% error bounds.**

EnergyPlus simulations are seen to generally overestimate energy consumption in the simulated homes. Of the 106 homes simulated, 46 homes saw their annual energy consumption overestimated by over 50%, 44 homes were overestimated by 0-50%, and only 16 homes were underestimated. Average monitored whole-home consumption is around 10,700 kWh/yr, while average EnergyPlus simulated consumption is around 14,300 kWh/yr. Nearly all of the >50% overestimates occurred in homes whose actual annual consumption is less than 10,000 kWh/yr, indicating that EnergyPlus simulations are less accurate in accounting for the physical characteristics and behaviors seen in these exceptionally efficient homes.

### 3.4.2 Baseline model accuracy – condensing unit consumption

A convenient and important measure of a simulated home's estimated cooling load is the cooling capacity of the condensing unit or heat pump that EnergyPlus calculates based on building characteristics, occupant behaviors, and internal loads. Figure 3.3 shows a scatterplot of these autosized condenser capacities on the x-axis and the nameplate capacities of the condensers in the actual homes on the y-axis.

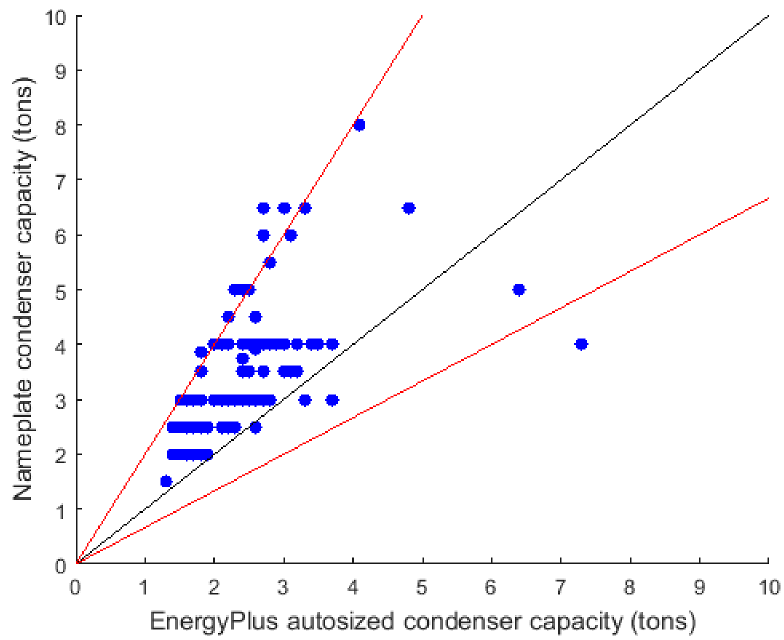



**Figure 3.3. Scatterplot of autosized condenser capacities on the x-axis and nameplate capacities on the y-axis. The black diagonal shows perfect agreement, while red diagonals show ±50% error bounds.**

This shows the autosized condenser capacities are nearly all between 50% and 100% of the installed condenser capacities. This could indicate that the EnergyPlus calculated cooling load is lower than the actual cooling load, or the actual condensers could be oversized by design. Note that installed condenser capacities follow manufacturer's nominal sizes that typically specify condensers in half-ton increments, while EnergyPlus autosized capacities can be assigned any value. If autosized capacities are rounded up to the nearest half-ton increment, they more closely match nameplate capacities. See Appendix C for this figure.

Next, Figure 3.4 shows the simulated and actual annual energy consumption of these condensing units. Of the 106 homes simulated, only 102 had monitored data available for their condensing unit, so only this smaller sample is presented.

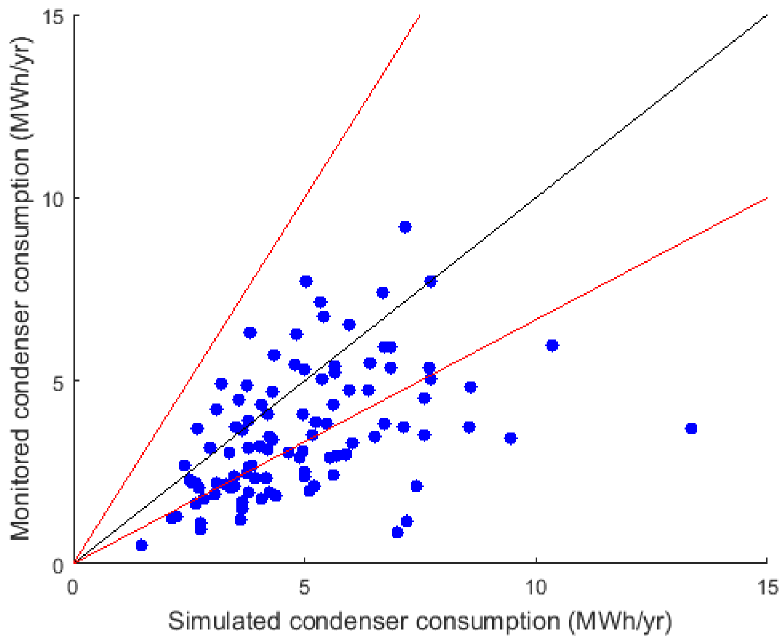
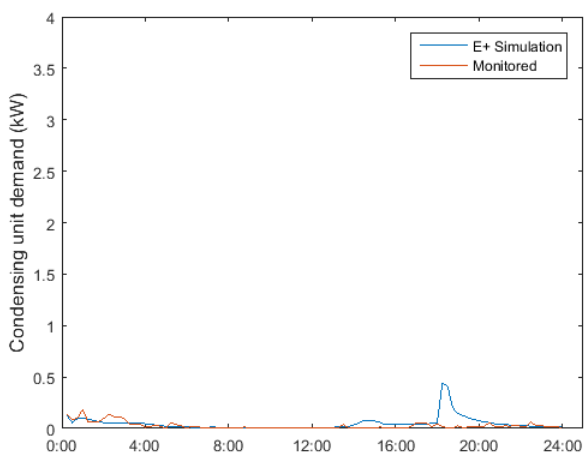
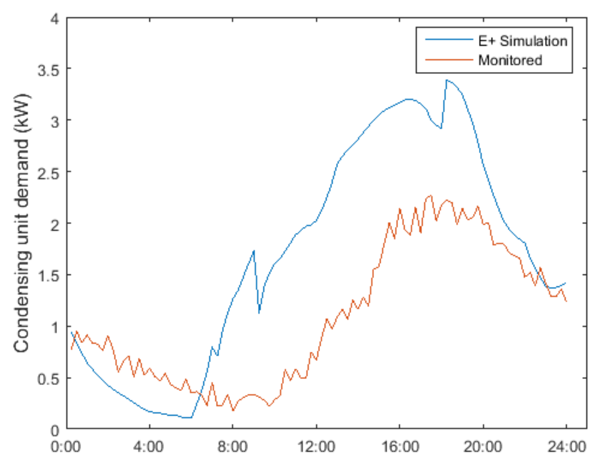



**Figure 3.4. Scatter plot showing simulated condensing unit energy consumption on the x-axis and monitored condensing unit consumption on the y-axis. The black diagonal shows perfect agreement, while red diagonals show ±50% error bounds.**

This figure shows annual condensing unit energy consumption being overestimated by >50% in nearly half of simulated homes. Average simulated condenser consumption is around 1,300 kWh/yr more than monitored condenser consumption, which explains around 36% of whole-home simulation error. To determine the source of this error, 15-minute monitored and simulated interval data profiles were plotted for homes where condensing unit consumption was overestimated by >50% in EnergyPlus.




(a)




(b)

**Figure 3.5. Average condensing unit demand for homes where EnergyPlus overestimated annual condensing unit energy consumption by >50%. (a) Shows average condensing unit demand for a day with negligible heating or cooling energy. (b) Shows average condensing unit demand for a peak cooling day.**

Figure 3.5 shows the average monitored and simulated condensing unit demand for the 47 homes in which EnergyPlus simulated energy consumption was >50% more than actual monitored consumption. The left figure shows average simulated and monitored demand profiles for a day with negligible heating or cooling energy. This shows EnergyPlus correctly identifying no significant cooling load and very closely matching the monitored condenser use on this day on average across all 47 homes. The right figure shows a peak cooling day. This shows the EnergyPlus simulation overestimating both the hours where cooling is required and the condensing unit demand during cooling hours. Interval data profiles for homes with <50% error and underestimated condensing unit consumption can be found in Appendix C.

### 3.4.3 Baseline model accuracy – central air fan consumption

Figure 3.6 shows the simulated and actual annual energy consumption of central air supply fans. Of the 106 homes simulated, only 75 had monitored data available for their supply fan, so we only present this smaller sample.

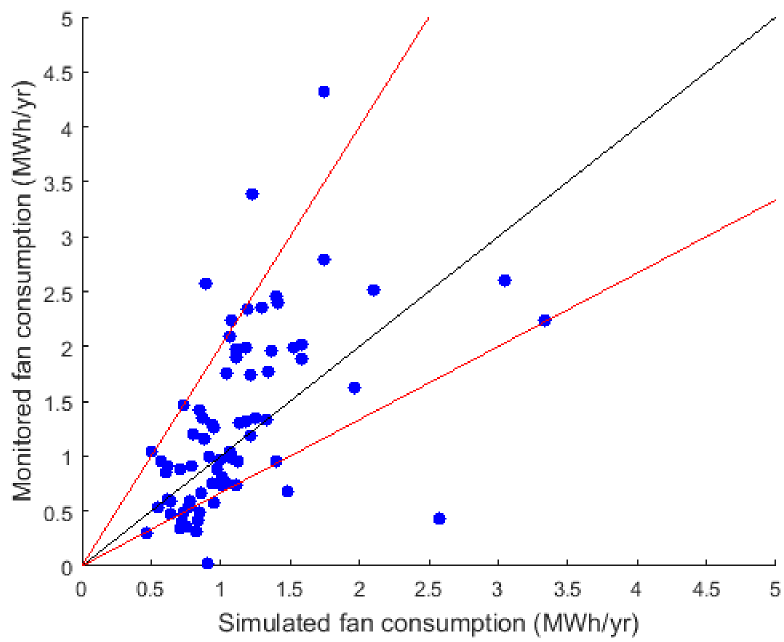
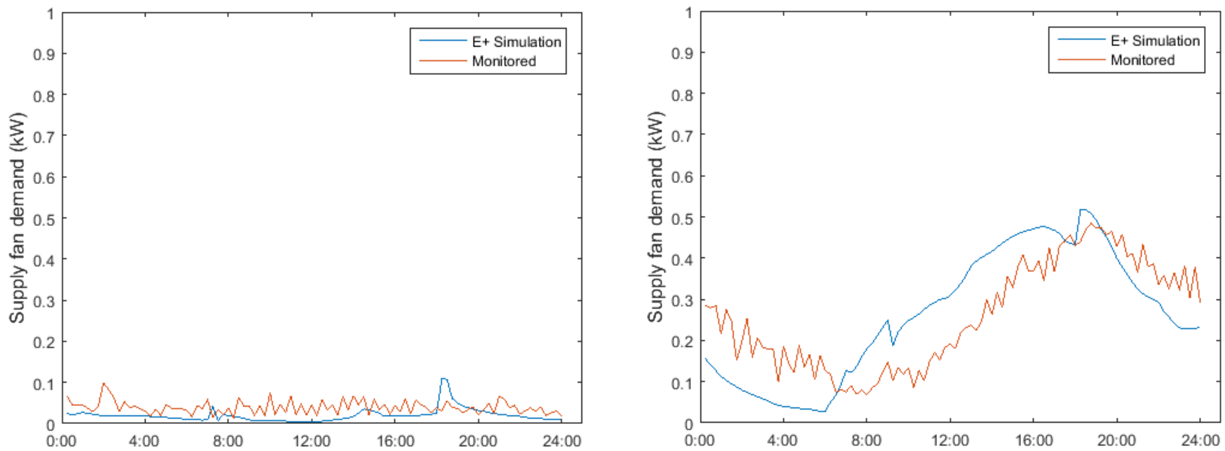



**Figure 3.6. Scatter plot showing simulated central air supply fan energy consumption on the x-axis and monitored consumption on the y-axis. The black diagonal shows perfect agreement, while red diagonals show ±50% error bounds.**

Central air supply fan energy is more accurately simulated than condensing unit energy. Only 19 of the 75 homes included are outside of the 50% error bounds, with average annual consumption around 1,300 kWh/yr in the monitored sample and around 1,100 kWh/yr in EnergyPlus simulations. In general, fan energy consumption is underestimated for homes with high fan consumption and overestimated for homes with low fan consumption. This indicates that the factors which describe the high variance in actual consumption have not been accounted for in the models.




(a) (b)

**Figure 3.7. Average central air supply fan demand for homes where EnergyPlus overestimated annual central air supply fan energy consumption by <50%. (a) Shows average demand for a day with negligible heating or cooling energy. (b) Shows average demand for a peak cooling day.**

Figure 3.7 shows the average monitored and simulated central air supply fan demand for the 23 homes in which EnergyPlus simulated energy consumption was from 0-50% more than actual monitored consumption. The left figure shows average simulated and monitored demand profiles for a day with negligible heating or cooling energy. This shows EnergyPlus correctly identifying no significant fan load and very closely matching the monitored fan use on this day in all homes. The right figure shows a peak cooling day. This shows EnergyPlus simulates fan demand earlier in the day than in the monitored homes. Peak fan loads roughly coincide both in timing and in actual kW. Interval data profiles for homes with >50% error and underestimated fan consumption can be found in Appendix C.

Finally, Figure 3.8 shows annual energy consumption errors of condensing units on the x-axis and supply fans on the y-axis. This shows that fan and condenser errors are highly positively correlated (r=0.58), indicating that fan and condenser energy errors generally track together, and neither is compensating for the other.

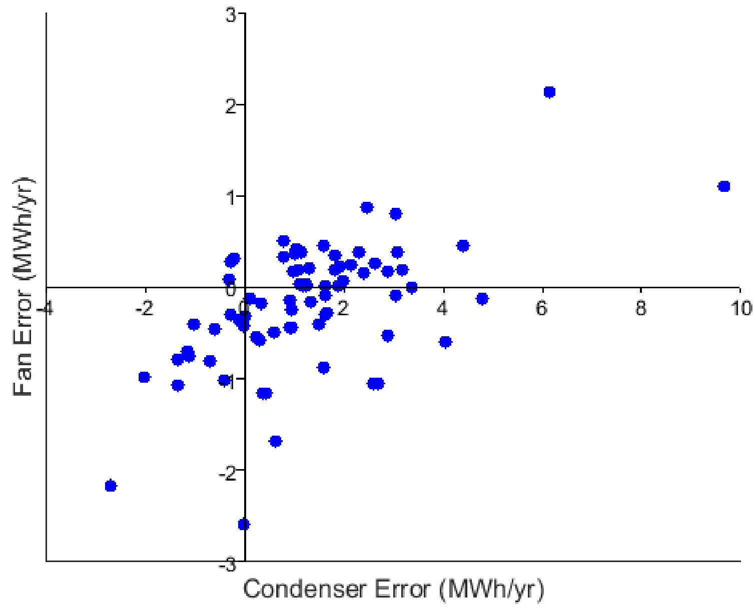



**Figure 3.8. Scatter plot of EnergyPlus simulation condenser errors on the x-axis and fan errors on the y-axis.**

### 3.4.4 Baseline model accuracy – non-HVAC energy use

Figure 3.9 shows the simulated and actual annual energy consumption of all other end uses in the simulated homes. This includes interior and exterior lighting, a refrigerator, miscellaneous plug loads, kitchen appliances, a dishwasher, and washer and dryer. To properly account for these loads in the monitored data, we require monitored data for the whole home, the condensing unit, and the central air fan. This leaves 74 homes of the original 106 with the necessary data for this comparison.

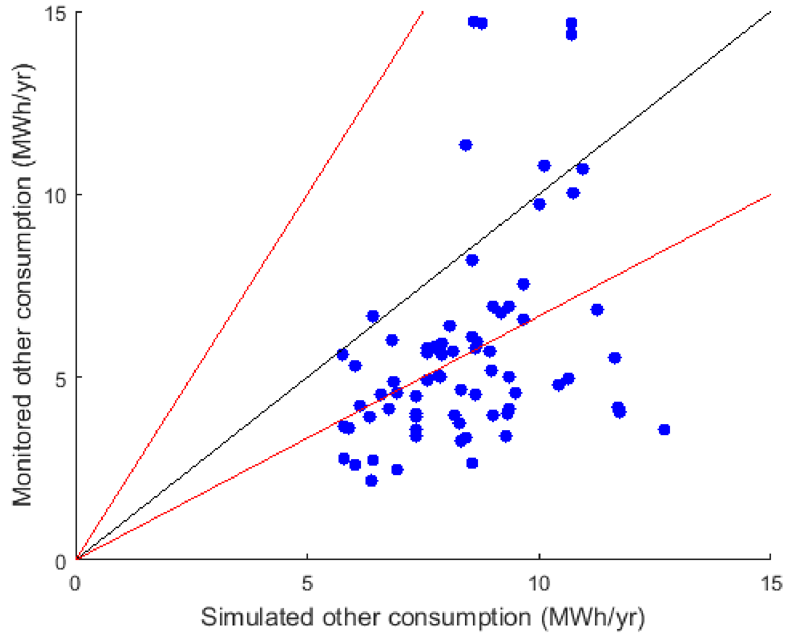


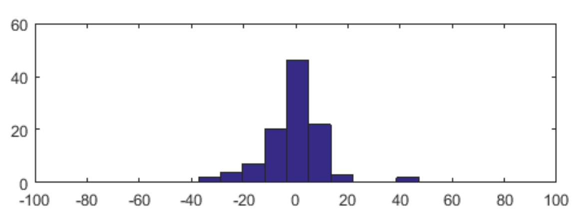

**Figure 3.9. Scatter plot showing simulated non-HVAC energy consumption on the x-axis and measured consumption on the y-axis. The black diagonal shows perfect agreement, while red diagonals show ±50% error bounds.**

EnergyPlus simulations again overestimate energy consumption for these loads in nearly all included homes. Average simulated consumption is around 8,500 kWh/yr, and monitored consumption around 5,900 kWh/yr, meaning around 75% of the whole-home error is due to these other loads.

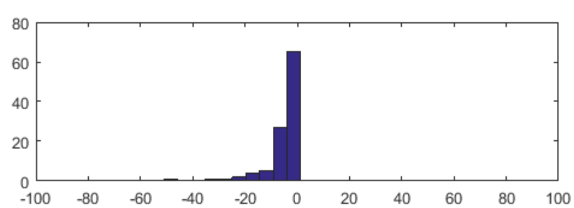
This other energy use also contributes to the overestimated condensing unit energy consumption discussed above. Extra internal energy use increases the homes' cooling loads during Austin's long cooling season. Because most homes are heated by gas and Austin's heating season is short, the corresponding reduction in heating energy use is minimal.

### 3.4.5 Sensitivity Analysis

Figure 3.10 below shows the change in CVRMSE of whole-home energy consumption when individual factors are changed from their actual values as described above. Positive values indicate that CVRMSE increased when a home characteristic was replaced with a default value.




(a) Square footage




(b) Age correction for condensing unit efficiency

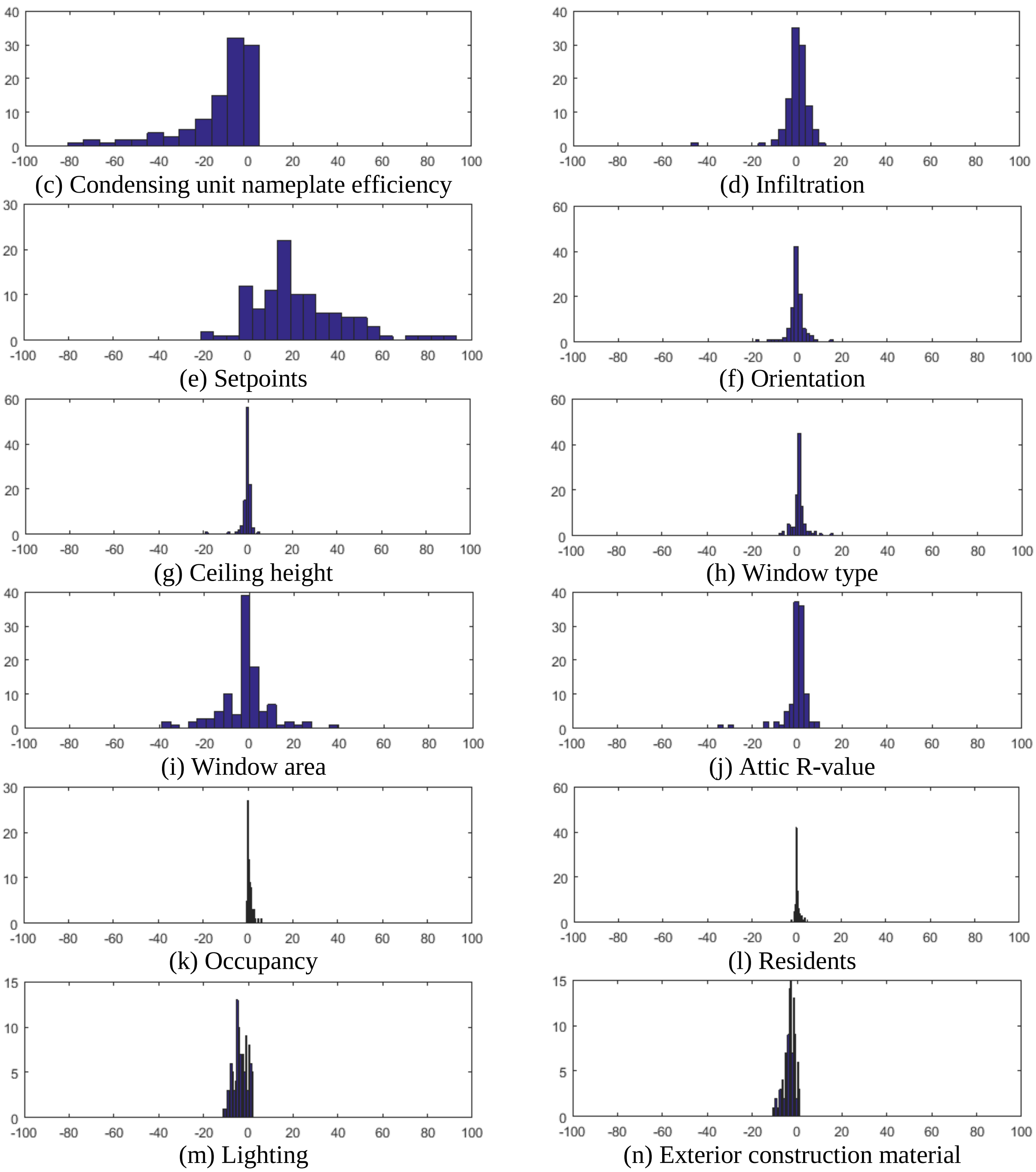



**Figure 3.10. Histograms showing change in whole-home energy consumption CVRMSE resulting from a change in the factors listed below each figure. The x-axis shows the change in CVRMSE, and the y-axis shows the number of homes in each bin.**

These results show that the CVRMSE between EnergyPlus simulations and actual consumption at the whole-home level is most sensitive to home square footage, condensing unit age and nameplate efficiency, building shell infiltration and heating and cooling setpoints. When these factors are changed in EnergyPlus from their actual value back to the PNNL prototype default value, CVRMSE changes by upwards of 40% in some homes.

Results are slightly less sensitive to correcting for window area and attic insulation R-value, which change CVRMSE by over 20% in some cases. Building orientation, ceiling height, window frame material and number of panes, lighting power density, and exterior construction material change CVRMSE by over 10% each. Finally, changes in occupancy schedule and number of residents result in a change in CVRMSE of less than 10% in all cases.

In these figures, a negative change in the error term – indicating that model accuracy improved when actual values were replaced with defaults – does not necessarily mean the default value is more accurate, or EnergyPlus is handling these values incorrectly. Instead, it reflects the fact that the baseline simulations do not match metered consumption. Most homes' total energy consumption is overestimated, so any time these homes have an actual value replaced with a default that makes the EnergyPlus model more efficient, the error term will decrease.

## 3.5 Conclusions

A summary of simulation accuracy results, in annual relative error and hourly CVRMSE terms, is shown in Table 3.3.

**Table 3.3. Summary of model accuracies in terms of relative annual errors and hourly CVRMSEs.**

| | Relative error (annual) | | | CVRMSE (hourly) | | |
|---|---|---|---|---|---|---|
| | Min | Mean | Max | Min | Mean | Max |
| Whole-home | < 1% | 55% | 250% | 41% | 100% | 360% |
| AC condensing unit | < 1% | 70% | 730% | 65% | 200% | 1,400% |
| Central air supply fan | < 1% | 110% | 4,800% | 50% | 220% | 6,600% |
| Other | 2% | 74% | 250% | 44% | 110% | 270% |

These results show that EnergyPlus simulations of single-family homes, as has been reported in commercial buildings, do not consistently or accurately predict actual energy consumption at either the whole-home or device level when specified as described above. As with any model, the quality of inputs determines the quality of the result and more comprehensive energy audit records would allow for more accurate modeling of all systems.

Despite the considerable extent to which the PNNL prototypes were modified with characteristics of the actual monitored homes, whole-home annual energy consumption was consistently overestimated, in many instances by more than 100%. When accuracy is measured by annual relative error, some models appear to be well calibrated as shown in Table 3.3. But when those same models' accuracies are measured by hourly CVRMSE, none of the models meet ASHRAE's tolerance of 30% CVRMSE. Much of this error can be attributed to the fact that the Pecan Street homes consume far less electricity than average, and the PNNL prototypes were intended to model average ICC code-compliant homes. Any field that was not included in the energy audit records was not changed from the PNNL default, so the models simulated here still have many characteristics in common with the prototypes.

At the device level, condensing unit energy consumption was generally overestimated. Central air supply fan energy is fairly accurately simulated, with the remainder of the whole-home overestimate coming from other end uses, including lighting and all non-HVAC loads. To better understand the source of these errors and how various home and occupant characteristics affect them, the sensitivity analysis conducted here identifies the factors that are most crucial to developing accurate models in the future.

Finally, the modeling of these homes demonstrates the difficulty of generating accurate simulations, even when provided with considerable building and occupant characteristic data. The relative inaccuracy of the models developed here goes to show that many determinants of home energy consumption are not captured during a traditional energy audit and survey, and many more appliance stock, appliance use, and occupant behavioral characteristics are needed to generate accurate residential building simulations.

### 3.6 Policy discussion and recommendations

These results provide additional context for the growing use of EnergyPlus in single-family homes. Results here, and previous research in the commercial sector, show that simulations do not accurately estimate actual energy consumption in occupied buildings. There are too many variables affecting energy use in occupied homes that cannot be accurately included in building simulations. Simulation tools do likely provide a reasonable estimate of as-built building performance under default operational settings, device stocks, and occupancy and behavioral assumptions. But these tools should not be used to estimate or predict actual occupied building energy consumption.

The DOE Building Energy Codes Program should consider the inaccuracies seen here and in previous research as their work continues to use EnergyPlus as a tool for evaluating future energy codes. The current method of simulating incremental changes to building codes and estimating energy savings and lifecycle costs can be a valuable tool. But the fact that simulations typically do not accurately predict actual energy consumption once homes are occupied means that these simulations should not be used to predict actual realized energy savings in future homes.

Finally, details of RESNET’s EnergyPlus-based compliance tool have not yet been released, but it can be assumed that it will likely simulate a designed home’s performance over a year, and compare that to some baseline code-compliant version of the same home. This would reflect a major transition to a systems-level approach to code compliance, as any whole-building simulation model would consider interactions between the building envelope, internal loads, and the heating and cooling systems. If this is the case, a set of assumptions and standard conditions will have to be established that fairly value the future occupants' levels of efficiency, but that also limit the effects of model inaccuracies. Whole-building simulation can be a powerful decision-making tool, but care is needed to ensure that decision-makers are aware of their limitations, and not let the relative ease of simulating building energy performance get ahead of the capabilities of the tool.

# 4 Understanding the potential for electricity savings and assessing feasibility of a transition towards DC powered buildings

A version of this chapter was published in Applied Energy as:

Glasgo, B., Azevedo, I.L., Hendrickson, C. How much electricity can we save by using direct current circuits in homes? Understanding the potential for electricity savings and assessing feasibility of a transition towards DC powered buildings. Appl Energy 2016 (66-75).

## 4.1 Abstract

Advances in semiconductor-based power electronics and growing direct current loads in buildings have led researchers to reconsider whether buildings should be wired with DC circuits to reduce power conversions and facilitate a transition to efficient DC appliances. The feasibility, energy savings, and economics of such systems have been assessed and proven in data centers and commercial buildings, but the outcomes are still uncertain for the residential sector.

In this work, we assess the technical and economic feasibility of DC circuits using data for 120 traditionally-wired AC homes in Austin, Texas to understand the effect of highly variable demand profiles on DC-powered residences, using appliance-level use and solar generation data, and performing a Monte Carlo simulation to quantify costs and benefits.

Results show site energy savings between 9-20%when solar PV is distributed to all home appliances. When battery storage for excess solar energy is considered, these savings increase to 14-25%. At present DC equipment prices, converting all equipment to DC causes levelized annual costs of electricity to homeowners to roughly double. However, by converting only homes' air conditioning condensing units to DC, the costs of direct-DC are greatly reduced and home site energy savings of 7-16% are generated.

In addition to quantifying savings, we find major nontechnical barriers to implementing direct-DC in homes. These include a lack of standards for such systems, a relatively small market for DC appliances and components, utility programs designed for AC power, and a workforce unfamiliar with DC. Experience with DC is growing in other sectors, and with time this will be transitioned to a broader audience of engineers, electricians, and building inspectors to ensure that not only are the systems themselves safe, but that the image of direct current circuits becomes less foreign over time. Direct current may very well have a place in the residential sector, and research and development should continue to explore other potential benefits that might make a stronger case for a more widespread transition to what now appears a promising technology.

## 4.2 Background

Direct current power distribution systems and microgrids have become the topic of substantial research due to their potential to reduce power conversion losses, improve power quality, increase system reliability, reduce system costs, and facilitate a transition to inherently more efficient DC-based devices in buildings [47–65]. The resulting research has led to the recent adoption of DC distribution systems in data centers and commercial lighting installations, among others [66,67]. As these systems have been proven in niche applications, a discussion has emerged as to whether more buildings should be wired with DC circuits in addition to – or in place of – AC. Around 50% of the energy presently used in buildings is either consumed as DC in electronic loads or passes through a transient DC state as a means of motor control, resulting in significant losses when grid distributed AC is rectified using inefficient, distributed power supplies [58]. When a source of DC generated electricity such as a solar PV array is available, dedicated DC circuits reduce the usual losses that occur both in the inversion from generated DC to grid AC, as well as the rectification back to DC at the end load.

The residential sector is seen as a potential candidate for a transition to DC. Residential buildings currently account for about 22% of all energy consumption in the US [4] and 21% of all greenhouse gas emissions, 71% of which are a result of electricity use in homes [5]. Making up approximately 35% of all home energy consumption are appliances, electronics, and lighting, which can all operate on DC [40,59]. Lastly, sharply declining module costs, the federal solar investment tax credit, utility net energy metering programs, and renewable portfolio standards have together resulted in consistent growth in residential PV installations that is not expected to slow [68,69]. Together these factors have made home DC microgrids the topic of substantial research which has detailed several aspects of these systems.

Earlier studies looked at this opportunity in the commercial sector and found that the reduction of power conversions associated with DC circuits had the potential to reduce conversion losses, reduce lifecycle PV system costs, and improve the reliability of power electronic-dependent systems [48,50]. Building on these findings Thomas, Azevedo, and Morgan [60] analyzed direct-DC LED lighting in a modeled 48,000 $ft^2$ office building. Analyzing several configurations of AC and DC lighting circuits, the authors estimate that DC lighting circuits could reduce capital costs by 4-21% and levelized annual costs by 2-21% compared to an equivalent grid-connected AC photovoltaic LED system. Indeed, such systems with centralized AC-to-DC conversion are now being installed in commercial applications by companies such as Redwood Systems [66].

In the residential sector, studies have primarily focused on three areas: establishing the feasibility of DC circuits and appliances to serve home loads, exploring the technical issues of future DC homes, and estimating the energy savings associated with these systems.

Feasibility of DC in homes is now well established as presented in [59], which concluded that all major home appliances and end uses were compatible with direct current. Technical analyses of DC circuits in homes cover a range of issues including voltage levels, system architectures, and potential applications [61,63,65]. A broad consensus on a future DC system voltage has yet to be reached, but proposed levels have been presented by Lawrence Berkeley National Laboratory [53] and the Emerge Alliance [70]. Lastly, a number of studies have now estimated the potential energy savings associated with DC systems in homes. A study by Savage at al. looked at centralizing the conversion from grid AC to DC from distributed “wall warts” to a central home-level rectifier. This study estimated 25% energy savings across the US residential sector [58]. Most recently, under a Department of Energy (DOE) initiative investigating DC power in residential and small commercial markets, Garbesi et al. [59] catalogued and characterized a range of existing and future appliances that are compatible with DC power. In a follow-up study [62], the same group estimated the energy savings associated with a direct-DC home with PV using simulated home loads and solar generation profiles in 14 cities across the US. This study estimated a 5% electric savings in direct-DC homes without storage for generated solar energy and 14% savings with storage. In the summary report filed for that initiative, the authors identify four areas for continuing research in direct-DC power systems: developing direct-DC products, developing standards and test procedures, building demonstration projects, and improving techniques for modeling energy savings.

This work makes two key and novel contributions to the literature. First, this is the first paper in the literature that we are aware of that uses real load profiles with energy consumption measured at the end-use level for a large number of homes. All previous studies had to rely on simulated load, which obviously induces uncertainty on the potential energy savings that could be derived from a DC transition strategy. Second, this is the first paper ever published in the literature that assesses the cost-effectiveness of DC strategies for residential households.

The lack of these two contributions in the literature has previously been identified by the DOE, in a study performed by LBNL, which identified the use of simulated data as a limiting factor in that work [62].

We use data from 120 traditionally-wired, grid-connected AC homes to accurately account for the effects of highly variable homeowner behavior, energy consumption patterns, and solar generation profiles on DC-powered residences.

In addition to estimating the energy effects of direct-DC PV systems in the sampled homes, we also provide the first in-depth analysis of the economic feasibility of such systems using levelized annual cost of electricity to the customer and the cost-effectiveness for avoided $CO_2$ emissions.

The method established for this analysis uses Monte Carlo simulation to account for uncertainty in the engineering, economic, and other inputs to the model. Additionally, we investigate utility billing and incentive programs, appliance and component markets, and building codes to determine their effects on increased use of DC power in the residential sector.

The rest of this paper is organized as follows. Section two details the data and methodology used in the analysis. Section three presents the results of the analysis. Sections four and five provide a discussion of results, conclusions reached, and policy implications.

## 4.3 Methods and data

### 4.3.1 Appliance-level energy use data

Appliance-level and home-level energy consumption data, as well as solar PV generation data used in the analysis were obtained from Pecan Street Research Institute's Dataport [2]. Pecan Street Inc. is a 501(c)(3) not-for-profit corporation and research institute headquartered at The University of Texas at Austin. Volunteer homeowners in and around Austin elect to join the study and work with Pecan Street to decide which circuits and appliances to monitor. The resulting dataset includes records for over 700 homes, with data available for up to 28 circuits per home at one-minute intervals. The first homes in this sample begin reporting data in January 2012, and installations are ongoing.

Average electricity consumption for households in Pecan Street's sample is approximately 85% of the local utility's average residential customer [41]. These households are therefore likely to provide a reasonable approximation of household electricity consumption around Austin.

For final whole-home simulations in our analysis, we select homes which had total electricity use and at least air conditioner condensing unit use, central air supply fan use, and refrigerator use monitored for over one year with less than one week of missing data. In Table 4.1 we provide information on the number of houses for which we have different levels of information. From the original sample of homes, 279 have over one year of whole-home use data. Of these only 120 had monitored the appliances listed above. Of these remaining 120 homes, 40 had data for an electric vehicle charger and 45 had data for a solar PV array. For houses without PV, we use a proxy monitored PV generation profile from similar houses.

**Table 4.1. Data validation criteria for final simulations.**

| Validation criteria | Qty. of homes |
|---|---|
| Total homes in dataset | >700 |
| Homes with ≥1 year of whole-home use monitored | 279[a] |
| + Whole-home, AC condensing unit, central air supply fan, and refrigerator use monitored | 120[a] |
| + Electric vehicle charger monitored | 40[a] |

[a] Counts include only datasets with less than one week of data missing

### 4.3.2 Appliance class allocations

To estimate energy, emissions, and cost savings associated with a transition to DC circuits, monitored appliance data for each home was separated into five classes based on power supply and load type. In simulating energy savings from a conversion to DC, appliances in each class will see the same change in efficiency.

Each appliance class in an individual home can include monitored data from 0, 1, or multiple appliances depending on the home's specific monitoring configuration. The difference between the sum of monitored loads in each home and the home's total metered use was assigned to 'Other Loads' which we attribute to electronics, lighting, kitchen appliances, and plug loads. These devices were not consistently monitored but are known to contribute substantially to total home load [40]. Table 4.2 summarizes these allocations.

**Table 4.2. Appliance class allocation.**

| Refrigeration Loads | AC Motor Loads | Electric Vehicle Loads | Resistance Heating Loads | Other Loads |
|---|---|---|---|---|
| HVAC condensing unit, freezer, refrigerator, wine cooler | Kitchen disposal, clothes washer, central air supply fan, gas clothes dryer, vent hood fan | Electric vehicle charging | Oven, range, electric clothes dryer[a], dishwasher[b], electric water heater | All electronics, CFL and LED lighting, kitchen appliances, miscellaneous plug loads |

[a] Electric clothes dryer energy consumption is comprised of resistance heating and AC motor load. By comparing Pecan Street data for gas dryers and electric dryers, we assign 20% of total energy consumption to AC motor loads and 80% to resistance heating.

[b] Dishwasher energy consumption is similarly comprised of resistance heating and AC motor load. We assign 30% of total energy consumption to AC Motor Loads and 70% to Resistance Heating based on [71].

### 4.3.3 DC compatible appliances

Every major appliance in a modern home could be replaced by a more efficient device that can operate on DC [59]. Most of these devices are currently intended for off-grid applications, where high equivalent electricity prices incentivize high efficiencies. While prices for such equipment are now prohibitively expensive for widespread residential use, their fundamental designs and capacities are suitable for the residential sector [59]. Garbesi at al. catalogued the manufacturers of many of these devices in [59]. For example, the motors currently found in home appliances are primarily a mix of AC induction motors for larger loads and universal motors for smaller loads [56]. Brushless DC permanent magnet (BLDC) motors are inherently more efficient than both types of motors, with savings estimated at 5-15% for constant speed applications [59]. In variable speed configurations, BLDC motors operate even more efficiently and generate substantial savings when compared to AC motors.

In air conditioner condensing unit applications, existing variable speed refrigerant compressors driven by BLDC motors achieve cooling efficiencies nearly twice the minimum requirement for Energy Star certification [72,73]. By comparing the energy efficiency ratios (EERs) of these units to those recorded in Pecan Street's energy audit records, we establish an efficiency improvement for converting a traditional condensing unit to a BLDC equivalent. Because the same vapor-compression cycle is used in refrigerators, freezers, and wine coolers, we apply the same efficiency improvement to the entire refrigeration load appliance class.

Resistance heating elements can be powered by AC or DC. While alternatives for resistance heating exist that utilize heat pumps or induction heating, we assume no change in resistance heating energy consumption with a transition to DC.

Of the 120 homes included in our final simulations, 40 have plug-in electric vehicles (PEVs) with home chargers. Plug-in electric vehicles have been the topic of substantial recent research due to advances in lithium based battery technologies, vehicle-to-grid storage architectures, and potential charging advantages associated with DC microgrids [74,75]. For this analysis, we assume the PEVs in the simulated homes will remain simply as DC-internal loads, requiring rectification of the existing AC supply and a subsequent DC-DC voltage transformation. In a DC home, this power supply would be simplified to a sole DC-DC converter, eliminating rectification losses.

Remaining loads in the monitored data are assumed to be comprised of lighting and consumer electronics. All modern consumer electronics operate internally on DC and therefore require variants of switched-mode power supplies to generate their necessary DC voltage. Similar to EV charging circuits, these consist of a rectification stage typically followed by a DC-DC voltage transformation. A DC circuit would eliminate the losses associated with the initial rectification.

Based on Pecan Street survey results, compact fluorescent lamps (CFLs) are the most common primary lighting technology in the sampled homes. One DC alternative is to use light emitting diodes (LEDs), which are the chosen technology for direct-DC lighting microgrids in the commercial sector. We use DOE lighting efficacy values to determine the efficiency improvement associated with converting the existing homes' lighting to LED.

### 4.3.4 DC home configurations

For homes in our sample, we perform simulations for the scenarios shown in Table 4.3. Figure 4.1 shows schematic diagrams of these configurations.

**Table 4.3. Summary of simulated scenarios**

| DC Appliance(s) | Battery Storage |
|---|---|
| All | No |
| All | Yes |
| Lighting only | No |
| Lighting only | Yes |
| Air conditioner condensing unit only | No |
| Air conditioner condensing unit only | Yes |
| PEV charging station only | No |
| PEV charging station only | Yes |
| Refrigerator only | No |
| Refrigerator only | Yes |

Figure 4.1(a) shows a home with no solar array and traditional AC circuits. Figure 4.1(b) shows a home with a net-metered PV array connected to traditional AC circuits. All of the homes in the sample dataset are represented by one of these two configurations. These will therefore serve as baselines for the analysis as their exact consumption and solar generation were monitored.

The system shown in Figure 4.1(c) is similar to that analyzed by Vossos et al. in [62]. This configuration features a solar PV connected DC circuit supplying all home loads with and without battery storage (depicted by dashed line). When solar power is available, either as direct feed-in from the array or as stored energy, savings are generated as the initial inversion from generated DC to AC for distribution and the rectification back to DC required for electronic and EV charging loads are eliminated. When solar power is not available or is insufficient in meeting the home's load, grid power is rectified in a central home bi-directional inverter to meet the balance. When solar power exceeds the home's load, this device acts as a traditional inverter and allows excess power to be sold to the grid under existing net metering agreements [41,62]. In both the case of net energy exporting and purchasing, no energy or cost savings are generated on the exported or purchased energy, as this configuration is equivalent to the base PV scenario. In addition to generating savings by eliminating conversion stages, the simulations for these configurations assume the transition to more efficient DC compatible loads discussed in Section 4.3.3.

The remaining systems shown in Figure 4.1 simulate direct-DC circuits supplying individual appliances or appliance classes. Given that the transition to DC circuits in the commercial market began with a single type of load – lighting – we simulate four appliances with substantial contributions to home energy consumption and energy savings potential to determine if a similar opportunity exists in homes. This strategy may be the most cost-effective if a large proportion of potential whole home energy savings from DC conversion can be generated by a single appliance.

Each of these four appliances was simulated with and without storage for each house individually. Storage allows solar power generated during the day that exceeds the instantaneous load to be stored and consumed later. This avoids the conversion losses associated with inverting the excess power to sell to the grid and rectifying grid power to meet unmet demand at night. Advances are being made that will likely lead to a transition towards lithium based batteries for residential energy storage in the future [76]. However, for this analysis we assume current industry-standard lead acid batteries will be employed and we use the associated costs and charge and discharge efficiencies as shown in Table 4.4.

Lighting data was not consistently available, as lighting and plug loads are often on common circuits. Lighting energy allocations are therefore based on the DOE’s Residential Lighting Usage Estimate Tool, a companion to a report released in 2012 [77]. By comparing the annual lighting energy consumption values in this tool to the unaccounted “Other Use” in the RECS data, we estimate 25% of “Other Use” is due to lighting.

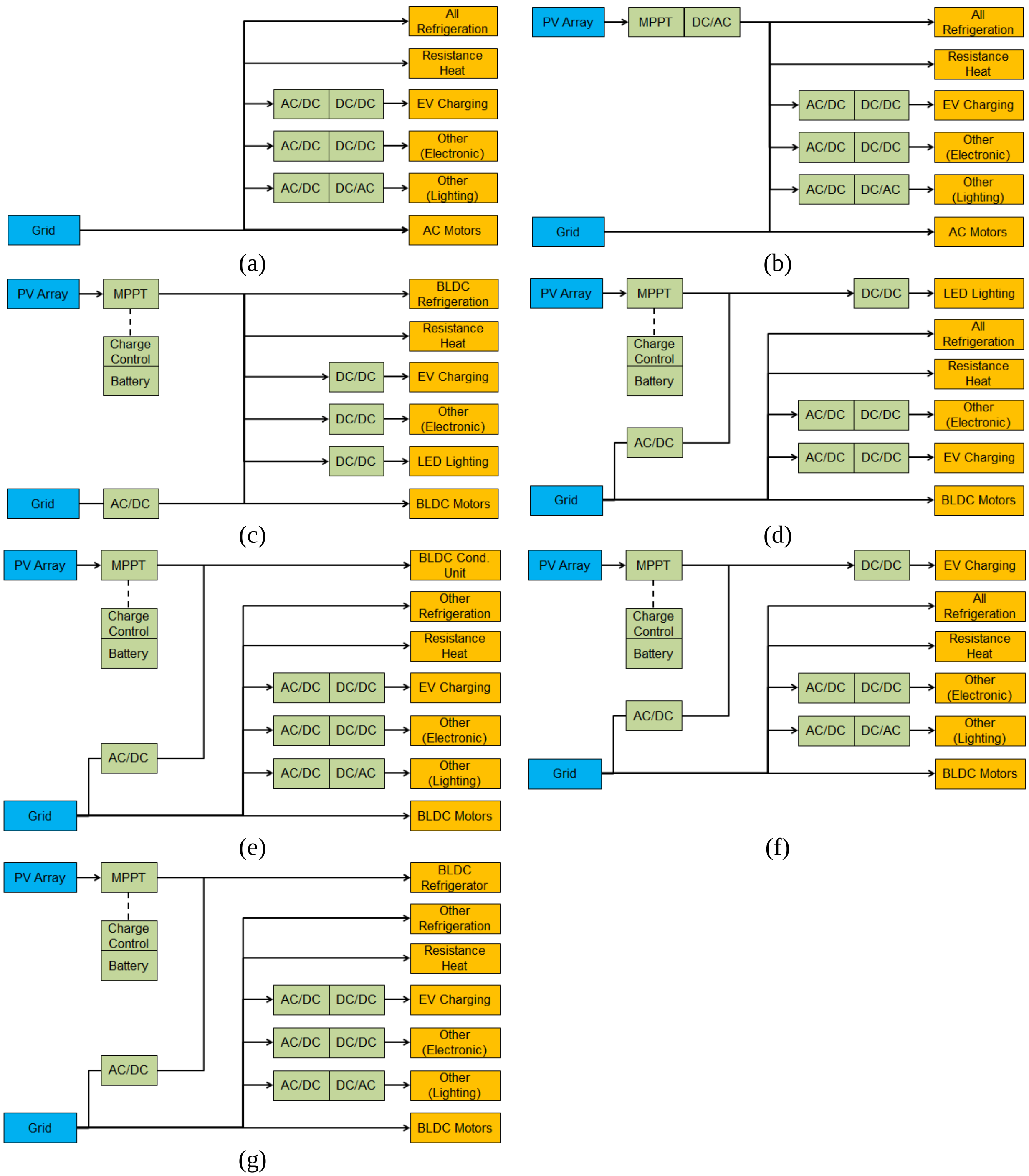



**Figure 4.1. Schematic diagrams of simulated home configurations: (a) traditional home with AC distribution, without PV (b) traditional home with AC distribution and net-metered solar PV (c) home with DC distribution to all loads and net-metered PV with grid-rectified backup (d) home with DC distribution to a lighting circuit and net-metered PV with grid-rectified backup (e) home with DC distribution to a condensing unit and net-metered PV with grid-rectified backup (f) home with DC distribution to a PEV charger and net-metered PV with grid-rectified backup (g) home with DC distribution to a refrigerator and net-metered PV with grid-rectified backup.**

### 4.3.5 Modeling operations

Each of the ten scenarios depicted in Figure 4.1(c) through Figure 4.1(g) (five scenarios with and without storage) simulates 1,000 iterations of every home in the final sample. Each simulation selects a unique combination of the parameters listed in Table 4.4. These 1,000 combinations of parameters are then applied to each home in the simulation. This results in 1,000 annual energy consumption profiles, bills, and levelized annual costs (LACs) for each home. Each simulated scenario uses all (120) homes with complete data, except for EV simulations. Only (40) homes in the sample had monitored data available for electric vehicles, so the simulations depicted in Figure 4.1(f) use this smaller sample of homes. Note all simulations are applied to 15-minute interval profiles for the most recent year of data available for each home, resulting in 35,040 readings for 1 year.

For each appliance class *j* that is simulated being served by DC, a new load profile is calculated as a function of existing and proposed power supply and end use efficiencies as shown.

$$NewDCLoad_{j,t} = \frac{MonitoredLoad_j \cdot \eta_{existing,powersupply} \cdot \eta_{existing,enduse}}{\eta_{new,powersupply} \cdot \eta_{new,enduse}} \quad (1)$$

$$t = 1, \ldots, 35{,}040$$

The variable *t* indexes the 15-minute interval data profile for each day of the year (i.e. 365*24*4). Each home's available DC solar generation profile is calculated as eliminating the losses associated with an inverter.

$$NewPV_t = \frac{MonitoredGeneration}{\eta_{existing,inverter}} \quad (2)$$

The savings associated with direct-DC distribution of solar power is determined by the amount of the home's load that can be met by this new solar generation. Any load that exceeds the output of the solar array must be met by rectifying grid power to meet the home's DC load, which reintroduces a conversion loss. Alternatively, any solar array output which cannot be consumed or stored must be inverted and sold to the grid, again reintroducing a conversion loss. We determine new whole-home consumption as follows.

$$MetbyPV_t = \min(NewPV, \sum NewDCLoads) \quad (3)$$

$$GridRectified_t = \frac{(\sum NewDCLoads) - MetbyPV}{\eta_{new,rectifier}} \quad (4)$$

$$NewHomeLoad_t = MetbyPV + GridRectified \quad (5)$$

With annual electric consumption calculated, LAC is used to evaluate the economic feasibility of each proposed scenario. Only new home applications are considered, as an AC-to-DC retrofit would have a large capital cost – on the order of $6,000 to $10,000 – that would not soon be recovered by even the largest energy cost savings realized here [78]. LAC takes into account varying lifetimes of system components as well as the time value of money. Capital costs for each major system component *k* include equipment and installation costs, as well as applicable Austin Energy rebates. Electric costs and solar energy credits are calculated using Austin Energy's tiered rate structure for residential customers. CRF, the capital recovery factor, is used to annualize a capital expenditure over the lifetime of *n* equipment capital investments with discount rate *i*.

$$LAC_l = NetAnnualElectricCost_l + \sum_{m=1}^{n}[AddedCapitalCost_m \times CRF_m] \quad (6)$$

$$CRF_m = \frac{i}{1-(1+i)^{-lifetime_l}} \quad (7)$$

To account for the uncertainty in prices and efficiencies of the proposed systems, ranges of possible values were established for all uncertain engineering and economic parameters, shown in Table 4.4. This study analyzes the cost-effectiveness of these systems in 2016. The values shown are therefore taken from the most recent and reliable sources available for each parameter. The year of each source is shown in the final column. Older sources should not be considered outdated, but simply reflect that these data are still relevant for this analysis based on the state of the technology and its development since the source date. Monte Carlo simulations draw from uniform distributions between these ranges to calculate energy savings, electric cost savings, and LACs. Uniform distributions were used as data for better defining distributions was not readily available. Similarly, correlation between variables (e.g. between component efficiencies, lifetimes, and costs) is not considered here for the same reason.

**Table 4.4. Parameters and ranges used in Monte Carlo simulations.**

| | Min | Max | Unit | Source | Source Year |
|---|---|---|---|---|---|
| **Engineering Parameters** | | | | | |
| Existing or New Inverter Efficiency | 0.85 | 0.99 | | [79] | 2016 |
| Existing or New Rectifier Efficiency | 0.90 | 0.95 | | [55,80] | 2008, 2008 |
| DC-DC Converter Efficiency | 0.80 | 0.90 | | [81] | 2015 |
| Battery Charge Efficiency | 0.95 | 0.95 | | [82] | 2010 |
| Battery Discharge Efficiency | 0.95 | 0.95 | | [82] | 2010 |
| Pecan Street Condenser Efficiency | 7.6 | 13.5 | EER | [2] | 2016 |
| DC Condenser Efficiency | 16 | 22 | EER | [72] | 2014 |
| BLDC Motor Efficiency Gain | 0.05 | 0.15 | | [59] | 2011 |
| CFL to LED Efficiency Gain | 0.07 | 0.28 | | [83] | 2014 |
| Circuit Breakers per Home | 20 | 20 | | | |
| Battery Storage Capacity | 2 | 2 | hours | [84] | 2014 |
| Battery Minimum Charge | 0.2 | 0.2 | | [62] | 2014 |
| **Economic Parameters** | | | | | |
| PV Module Cost | 750 | 910 | $/kW-AC installed | [85] | 2013 |
| PV Balance of System Cost | 3,440 | 4,200 | $/kW-AC installed | [85] | 2013 |
| Inverter Cost | 250 | 310 | $/kW-AC installed | [85] | 2013 |
| Rectifier Cost | 250 | 310 | $/kW-AC installed | | |
| Bidirectional Inverter Cost | 500 | 620 | $/kW-AC installed | | |
| AC Condensing Unit Cost | 640 | 1,000 | $/kW-AC installed | [86] | 2016 |
| AC Supply Fan Cost | 2,000 | 4,100 | $/kW-AC installed | [86] | 2016 |
| AC Refrigerator Cost | 1,200 | 1,700 | $/unit | [86] | 2016 |
| AC Circuit Breaker Cost | 10 | 12 | $/unit | [87] | 2016 |
| DC Condensing Unit Cost | 2,400 | 2,400 | $/kW-DC installed | [88] | 2014 |
| DC Supply Fan Cost | 3,800 | 5,300 | $/kW-DC installed | [86] | 2016 |
| DC Refrigerator Cost | 1,600 | 3,000 | $/unit | [89] | 2016 |
| DC Circuit Breaker Cost | 14 | 17 | $/unit | [87] | 2016 |
| Battery Cost | 250 | 500 | $/kWh storage | [87] | 2016 |
| Discount Rate | 0.05 | 0.10 | | | |
| **Austin Energy Parameters** | | | | | |
| Austin Energy Solar Rebate | 2,990 | 2,990 | $/kW-AC installed | [41] | 2016 |
| Electric Rate | Varies | Varies | $/kWh consumed | [41] | 2016 |
| Solar Credit Rate | 0.107 | 0.107 | $/kWh generated | [41] | 2016 |
| **Lifetime Parameters** | | | | | |
| PV Panel Lifetime | 20 | 20 | Years | [90] | 2016 |
| Balance of System Lifetime | 20 | 20 | Years | | |
| Inverter Lifetime | 10 | 10 | Years | [60] | 2012 |
| Rectifier Lifetime | 10 | 10 | Years | | |
| Bidirectional Inverter Lifetime | 10 | 10 | Years | | |
| Battery Lifetime | 10 | 10 | Years | [60] | 2012 |
| AC Appliance Lifetime | 10 | 10 | Years | | |
| DC Appliance Lifetime | 10 | 10 | Years | | |
| Circuit Breaker Life | 20 | 20 | Years | [60] | 2012 |
| **Simulation Parameter** | | | | | |
| Number of runs | 1,000 | 1,000 | | | |
| **Environmental Parameter** | | | | | |
| ERCOT grid emission factor | 1,218 | 1,218 | lb$CO_2$/MWh | [91] | 2014 |

### 4.3.6 Modeling assumptions

In final simulations, we make several assumptions about the efficiency, operation, and costs of the simulated systems.

First, we assume similar degradation of efficiencies of AC-DC and DC-DC power supplies under part load conditions. Because we use monitored load data, the lower efficiencies typically seen at part load in today's power electronics are included in the monitored load profiles. Therefore, in applying the new power supply efficiencies associated with direct-DC relative to the existing efficiencies as shown in Equation 1, we effectively account for degradation in the proposed systems' efficiencies at part load.

We also assume that the high efficiencies currently seen in niche DC appliances will be maintained in the first generation of residential products. Many of these products are already available for off-grid monitoring stations, military installations, and mobile applications such as boats and RVs, among others. In these scenarios, high equivalent electricity costs put a premium on energy efficiency. We assume that in bringing these products to a larger residential market, these high efficiencies would be maintained and we therefore use these existing efficiencies in our calculations.

Lastly, we assume line losses in the home are comparable to those in a traditional AC home. There is presently no consensus on a future residential DC voltage standard between key stakeholders such as the IEEE, EMerge Alliance, and SAE. This standard will have implications for wiring and component specifications to ensure safe, efficient, and cost-effective power delivery in residential settings. For this modeling, we assume no significant changes in line losses, wiring costs, or components. This would be the case if the future DC voltage standard is at or near the existing 120 VAC standard.

## 4.4 Results

### 4.4.1 Direct-DC energy savings

Figure 4.2 shows the resulting site electricity savings of the ten simulated scenarios as a percentage of each home's baseline consumption. Average savings in whole-home DC simulations are between 9-20% (mean ±1 standard deviation) and increase to 14-25% with storage.

The majority of these savings are attributed to DC condensing units, which alone generate around 12% mean savings that increase only slightly with storage. These savings are a result of the large fraction of home energy consumption that these devices contribute, the efficiency gains associated with BLDC units, and load profiles that align well with solar output.

Lighting loads and EV charging loads generate little energy savings when converted to DC due to their relatively small contribution to whole-home load and the modest savings associated with a conversion to DC. Additionally, these appliances typically have load profiles that do not align well with solar generation and therefore would not be expected to be good candidates for direct-DC.

The relatively flat load profiles, substantial energy consumption, and the same efficiency improvements seen in air conditioning condensing units result in whole-home savings of around 1-6% when refrigerators are converted to DC.

The median annual kWh saved per home is around 1,400 kWh/yr and 1,900 kWh/yr for whole-home DC simulations without and with storage, respectively. As in Figure 4.2, the majority of these savings come from air conditioning condensing units, which alone generate median savings of around 1,100 kWh/yr and 1,200 kWh/yr without and with storage, respectively.

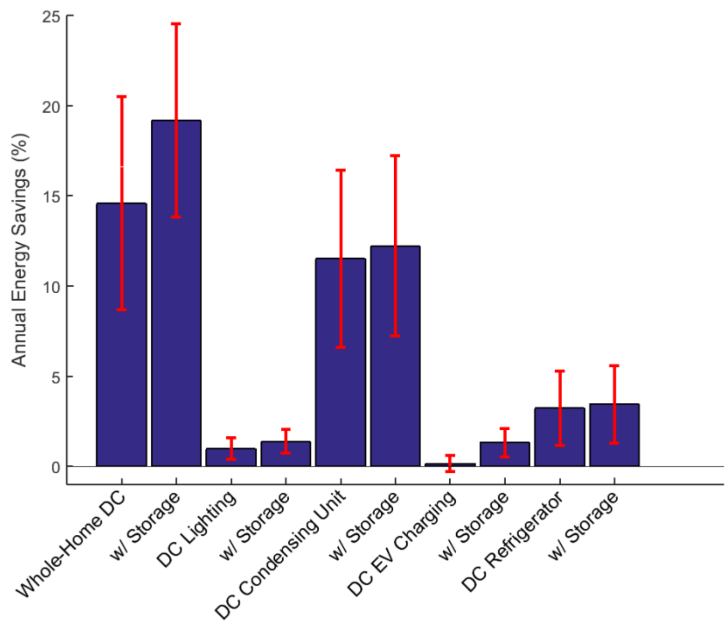



**Figure 4.2. Annual energy savings for simulated direct-DC systems. Savings are reported as a percentage of baseline energy consumption of traditional AC homes. Simulation results correspond to the systems shown in Figure 4.1(c) through Figure 4.1(g). Error bars show plus or minus one standard deviation from the mean.**

### 4.4.2 Direct-DC energy cost savings – present DC equipment market

In this section we consider the monetary costs and benefits associated with outfitting a new home with DC circuits, appliances, and devices at current equipment and electricity prices. Using the energy savings results presented above, we calculate new electricity bills and annual solar credits for every home and every simulation using Austin Energy's billing and solar crediting rate structures in 2016.

Assuming a 120VDC standard means the installation and physical wiring in a DC home would be nearly identical to that in a traditional 120VAC home, incurring no extra wiring cost. Traditional residential-size circuit breakers, switches, and wall outlets are readily available and are often compatible with DC, but are rated to operate at a lower voltage [87]. Of these components, only the cost of breakers is significant – on the order of several hundred dollars per home – so we account for only this added component cost in each home.

Of the five appliance classes, plus lighting, that are considered for conversion to direct-DC, we assign an added cost to refrigerators, air conditioning condensing units, and central air supply fans. These are the largest end users in the sampled homes and would have the greatest added cost in converting to DC. In calculating these costs, we use current retail prices from existing vendors as shown in Table 4.4 [86–89]. Remaining appliances and lights are assumed to have a negligible effect on the overall cost of implementing DC.

The final additional cost considered in the proposed DC home is a bidirectional inverter. Because these devices are still uncommon, we estimate their cost as the combined cost of a rectifier and an inverter.

Figure 4.3 shows the levelized annual cost of electricity for each scenario as a percentage of each home's baseline annual energy bill (denoted as 100%). When solar PV is considered, annual electric cost decreases as a result of Austin Energy solar crediting, but there is the additional levelized annual cost of the PV array (shown here with Austin Energy installation incentives applied) and a system inverter. This results in a net increase in LAC of around 18%.

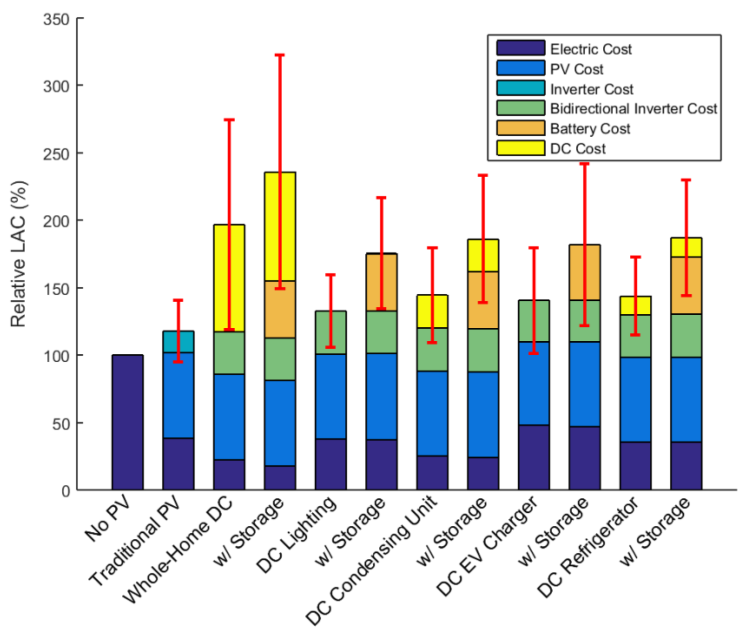



**Figure 4.3. Levelized annual costs for the systems shown in Figure 4.1(a) through Figure 4.1(g). Results are shown as a percentage of a traditional (AC) home with no PV generation's annual electric bill. Discount rate was varied from 5-10%. Bars show the mean result for each simulation. Error bars show plus or minus one standard deviation from the mean.**

**Whole-Home DC:** Both whole-home DC scenarios see LAC roughly double compared to a home without a PV array. On average, this means LAC increases from around $1,200 per home to over $2,300 per home. While solar credits from PV generation and savings from converting to DC reduce each home's annual electric bill by around $950 on average, the added cost of the solar array (average LAC $770 with applicable rebates), bidirectional inverter (average LAC $380), and DC appliances and components (average LAC $900) exceed these savings. In the whole-home case, as well as all others, the addition of battery storage results in a small reduction in energy costs while adding a substantial capital cost (average LAC $500) that is largely not recovered.

**DC Lighting:** DC lighting simulations see an increase in LAC due to the added cost of the bidirectional inverter and small energy savings. DC equipment costs are small as only one circuit must be fitted with a DC-specific breaker and the cost of converting to DC LEDs is negligible when annualized over the life of the lamps. Power electronics make up a small fraction of the cost of an LED, so we do not expect the removal of a single rectification stage to significantly reduce equipment costs.

**DC Condensing Unit:** While DC condensing units deliver substantial energy savings, the cost of these units surpass cost savings and results in a net increase in LAC of 9-80% without storage and 39-133% with storage. Existing units are intended for rugged, off-grid, often mobile applications and have features not required for a residential installation. Thus, while the costs used here are high, they are reflective of the best currently available technology to serve a home's cooling load with variable speed BLDC motors.

**DC Plug-in Electric Vehicle Charger:** Similar to the conversion of home lighting loads to DC, EV chargers see minimal energy cost savings. DC implementation costs are also small as only one DC circuit is installed and the only hardware change at the charger is the removal of a rectification stage. The net results of these changes are an increase in LAC primarily due to the cost of a bidirectional inverter and storage, when applicable.

**DC Refrigerator:** A conversion to direct-DC supply of a refrigerator sees energy costs decrease, but the added cost of a bidirectional inverter and DC-compatible refrigerator result in a net increase in LAC of 15-73% without storage.

**Cost Effectiveness of Savings:** The overall cost effectiveness of each direct-DC configuration is plotted in Figure 4.4. The x-axes show total annual savings in kWh and metric tons of $CO_2$ calculated using the local grid emission factor shown in Table 4.4. The y-axis shows the cost added to each home's LAC to implement each solution. Coordinates show the mean of all homes in each simulation. Wide ranges of energy consumption baselines and solar PV system capacities across homes in the sample result in large variances that make presenting results with confidence bounds meaningless. For reference, houses in the sample have annual $CO_2$ emissions ranging from 1.1 to 19 metric tons.

The mean result of solar PV installation in the sample was a net energy generation of around 6,200 kWh/yr per system that was offsetting grid generated electricity. This equates to an emissions reduction of around 3.4 $tCO_2$ per system per year. Without installation incentives, these systems add a levelized annual cost of around $1,400/yr per home. We use this level of cost-effective energy and emissions savings – observed as the slope of the line intersecting the solar PV marker ($0.23/kWh or $410/$tCO_2$) – to compare each DC simulation.

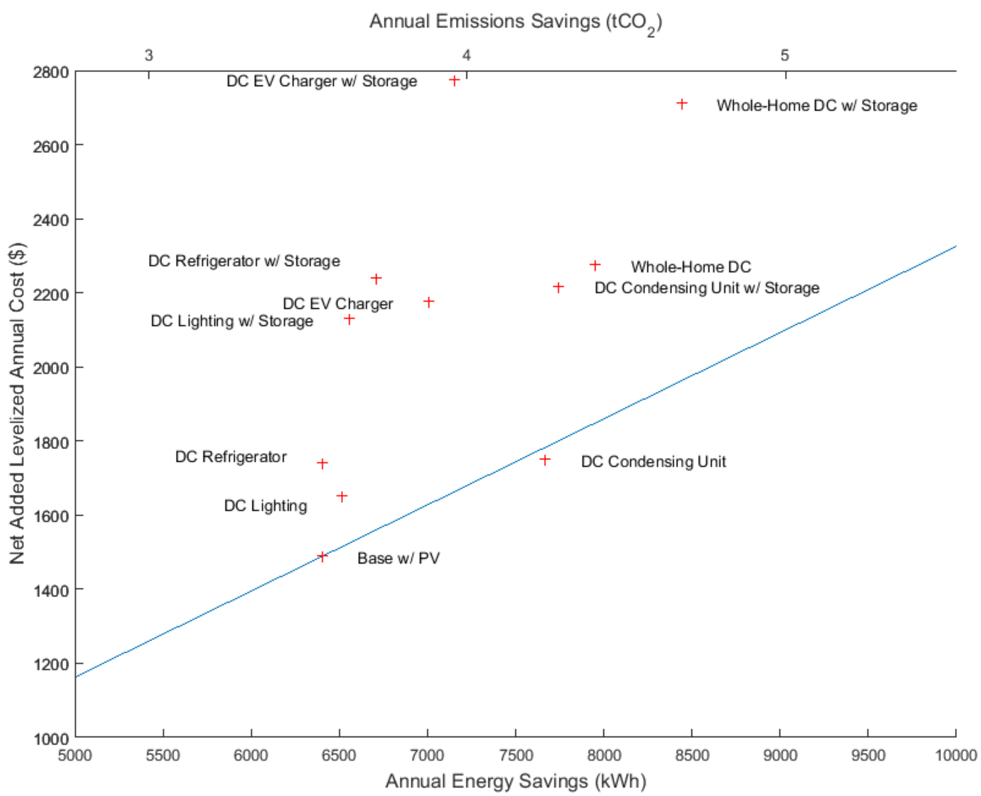



**Figure 4.4. Average cost-effectiveness of savings associated with each simulated DC home configuration. Average annual energy and emissions savings are shown on the x-axes. The net cost added to a traditional AC home's LAC by implementing each scenario is shown on the y- axis. This cost includes the cost of the PV system in every configuration. The blue line shows the cost-effectiveness (in $/kWh saved and $/$tCO_2$ saved) of installing a solar PV array without considering any utility incentives. All values shown are the mean of all homes in each sample.**

While all scenarios generate energy and emissions savings beyond what would be generated by solar PV alone, the added cost to achieve these savings is at a rate higher than implementing AC distributed solar PV alone in all cases but one. Solar PV arrays with direct-DC distribution to a condensing unit result in more emissions savings per dollar of added LAC than a traditional AC distributed PV array and condensing unit.

If over time the added costs of today's DC components and appliances were eliminated due to widespread deployment, the whole-home DC scenario without storage becomes cost-competitive with a home with a traditional AC-distributed solar PV array. The cost differential between a traditional system inverter and the DC system's bidirectional inverter is covered by the energy savings generated in this configuration. Because much of the energy savings and added DC system cost is a result of the central air condensing unit, the scenario where only this device is converted to DC is nearly cost competitive with traditional PV, showing only around a 4% higher LAC than a traditional PV array.

## 4.5 Conclusions

Results show that direct-DC distribution of solar PV power is a feasible means of generating energy and emissions savings in this sample of homes. However, at present costs only direct-DC-supplied variable speed brushless condensing units match the cost-effectiveness in achieving these savings of a traditional solar PV array. These systems were found to reduce homes' baseline energy consumption and emissions by 7-16%while adding 9-80% to each homes' baseline LAC. Note that because all simulated DC systems rely on solar PV arrays, these costs are included in LAC calculations. In none of the simulated configurations was the added cost of battery storage for excess solar PV energy justified by the energy and emissions savings it provided. This analysis, however, is limited by its reliance on current device and component efficiencies, lifespans, and market prices in 2016 for determining cost-effectiveness of savings. As these factors – especially costs – change in the near future, the economics of DC circuits in homes will change and deserve reconsideration. Given these findings, the continued growth of distributed solar PV generation, the increasing home electronic loads seen in recent years, and industry interest in direct-DC, it is likely that a very small number of such systems in homes may soon appear.

## 4.6 Policy Discussion and Recommendations

In light of these results, there is not a strong argument for an immediate large-scale deployment of direct-DC systems in any configuration other than DC condensing units at current component prices on the basis of reducing emissions. Given the cost-effectiveness of the savings these systems provide and the growing interest in direct-DC in homes, such systems may begin appearing in one-off system designs without universal standards in place as has been the case in direct-DC commercial lighting systems. Many aspects of such an installation would be without issue, but some significant barriers remain.

Under the National Electrical Code AC and DC systems under 600V are not explicitly differentiated, meaning a direct-DC home would pass existing building inspections [58]. From an electric utility provider's perspective, all of the proposed system changes occur downstream of traditional meters so grid connection would likely not pose a challenge. However, Austin Energy's solar rebate program specifies that rebates and generation credits are administered based on AC capacity and AC generation [41]. It is therefore unclear whether a direct-DC PV array would be eligible for up-front equipment rebates. Also given the qualification that solar generation is credited per AC kWh, which assumes a conversion loss, any solar-generated DC power that is consumed in the home and not inverted to AC and sold to the grid would be undervalued with this program. If direct-DC systems gain more widespread adoption, utilities would have to respond to fairly credit this generation. Similarly, Austin Energy and other rebate programs for energy efficient air conditioning condensing units rely on certifications from the Air-Conditioning, Heating, and Refrigeration Institute (AHRI) for performance guarantees [41]. The manufacturer of the DC condensing units used here in modeling energy performance and cost does not have this certification, and it is likely that none of the certified units operate on DC. Obtaining this certification would allow early adopters of direct-DC condensing units the same benefit available to homeowners purchasing less efficient traditional condensing units.

In addition to these relatively minor issues, major nontechnical barriers to residential DC implementation remain and will have to be addressed before these systems gain more widespread adoption. Fortunately, experience with DC systems in data centers and the commercial market is growing. This has created a small industry of professionals with experience designing, installing, maintaining, and inspecting these systems. This knowledge base would have to be transitioned to a broader audience of engineers, electricians, and building inspectors to ensure that not only are the systems themselves safe, but that the image of direct current circuits becomes less foreign over time. Direct current may very well have a place in the residential sector, and research and development should continue to explore other potential benefits that might make a stronger case for a more widespread transition to what now appears a promising technology.

# 5 Expert assessments on the future of direct current in buildings

## 5.1 Abstract

Increasing adoption of distributed generation, improving power electronics, and growing electronic loads in buildings have led researchers to propose increased use of direct current (DC) power distribution systems in buildings. As these systems have proven safe and reliable in other applications, they are now being considered for more widespread use in commercial and residential buildings. But nontechnical obstacles remain that have not been addressed in the technical engineering and economic analyses conducted thus far. In this paper, we report on an expert elicitation of 17 experts from industry, research organizations, academia, and the implementation or operation of DC systems to better understand the barriers to more widespread adoption of these systems.

Results show that the two biggest barriers are industry professionals such as electricians and engineers being unfamiliar with DC and a lack of a large and developed market for DC devices and components. To address these, experts proposed developing training programs for engineers and electricians, and developing pilot projects to prove the benefits of DC in niche applications where DC power distribution holds a clear advantage over AC. Experts also identified lasting and inherent benefits of DC that make these systems better suited to serve future building loads. These include their ability to interface with distributed generation and onsite DC generation sources such as solar photovoltaics, as well as their ability to communicate and supply power over a single distribution line. Finally, experts identified research priorities to better understand what appears to be a promising technological solution to efficiently, safely, and reliably power future buildings.

## 5.2 Background

Recent research on direct current circuits and devices has largely concluded that these systems have the potential to generate modest energy and cost savings in residential and commercial buildings by centralizing and reducing the number of power converters serving building loads and implementing efficient DC-internal end uses [60,62,92]. Supported by these findings, researchers, manufacturers, and industry groups are now turning their attention to demonstration projects and the development of products and standards to capitalize on what is seen as a new market for energy-efficient devices and services [70,93–95]. But investment in DC technologies may be premature. Widespread adoption of DC distribution systems will depend on a number of factors, only a fraction of which have been captured by the engineering and economic analyses conducted thus far.

In this paper, we explore the nontechnical barriers to more widespread adoption of DC circuits and devices in residential and commercial buildings. Many such barriers have been identified in previous studies, but not analyzed in detail. These include a lack of standards, small markets for DC devices and components, uncertain utility interaction, and public perceptions that DC is dangerous or foreign, among others [58–60,92]. Developing a better understanding of these barriers can serve to inform and direct future research and development activity to minimize or eliminate their impact on the deployment of DC.

Expert elicitation is a tool intended for instances where analytical methods are unable to handle some factors relevant to the research questions at hand. This makes the method well-suited to analyzing the trajectories of developing technologies, where ongoing research and development efforts are critical to future deployment.

These elicitations often aim to define subjective probability distributions of key uncertain parameters, often related to system costs, which can be used to compare a given technology to alternatives. For example, Curtright et al. used expert elicitations to assess future module costs of several solar photovoltaic (PV) technologies under varying policy scenarios [96]. This allowed for conclusions to be reached not only about the future cost-competitiveness of solar PV, but also about the effects of different policy interventions.

Such methods are not restricted to defining distributions for uncertain parameters. Rao et al. used expert elicitation to assess possible improvements in key parameters which determine the performance and cost-effectiveness of existing $CO_2$ capture technologies, thus allowing a comparison to more novel and unproven systems [97]. In addition to estimating 4 key defining parameters of these systems, the study also asked participants to classify 19 research objectives as high-, medium-, or low priority in minimizing the overall cost of $CO_2$ avoidance. The resulting rankings allow the most pressing research needs to be identified and compared to the focus of recent research in the field.

A more comprehensive expert elicitation was conducted jointly by CMU's Center for Climate and Energy Decision Making, the International Risk Governance Council, and the Paul Scherrer Institute to assess the feasibility of deploying small modular nuclear reactors (SMRs). At a two-day workshop attended by an international assembly of nuclear experts, a workbook format was used to elicit judgments on a wide range of topics [98,99]. This format included traditional methods of determining subjective probability distributions of important parameters, but also asked more open-ended questions and included a variety of exercises that help identify and address potential risks and non-technological barriers that would need to be overcome for SMRs to be widely deployed.

We adopt this format and apply it to better understanding the challenges and uncertainties facing increased adoption of DC circuits in residential and commercial buildings. In Section 5.3, we discuss these challenges as they have been identified in the existing literature. Section 5.4 discusses the experts and elicitation methods used. Section 5.5 presents the results of the elicitation, and Section 5.6 provides a discussion of these results and conclusions reached.

## 5.3 Literature Review

In this section the existing literature on nontechnical barriers to more widespread adoption of DC power systems in buildings and microgrids is reviewed and summarized.

### 5.3.1 Shock and electrocution risk

There is presently no scientific consensus as to whether alternating current (AC) or DC power is more harmful physiologically if contacted. Some argue that DC poses more risk, as a direct current shock could cause muscles in the forearms and hands to clench and lock the victim to the exposed conductor. Dalziel and Massoglia conducted a study in the 1940's and 1950's to test this by measuring the "let-go" currents and voltages of AC and DC power [100]. While the paper is still widely cited, the study design and testing method of simply administering electric shocks until study participants could no longer release an electrode prevent any reliable conclusions from being drawn.

Much of the preliminary work on developing standards for future DC systems has sought to minimize this risk and ensure future electrical code compliance. The Emerge Alliance Occupied Space Standard was developed with this in mind, resulting in a 24VDC standard which falls into the National Fire Protection Association's (NFPA) Class 2 circuit designation [58]. Class 2 circuits are considered intrinsically safe, providing "acceptable protection from electrical shock" [101]. Higher voltage circuits will not fall under this classification, and will need to be designed, installed, and inspected to ensure they pose no greater shock and electrocution risk than equivalent, existing AC circuits.

### 5.3.2 Fire risk

DC circuits are prone to arcing during switching or circuit breaking, as there is no natural passage through zero current to quench arcs as occurs in AC circuits [102]. Without appropriate arc quenching capabilities, DC circuits may therefore pose increased fire hazard over comparable AC circuits. Direct current circuit breakers are commercially available that provide one line of defense against potentially dangerous arc faults [102]. In AC circuits, Ground Fault Circuit Interrupters (GFCIs) provide a second level of defense. The intended purpose of these devices is to prevent electrical shocks to people during ground faults at much lower currents and powers than would be required to trip a circuit breaker [103]. The same functionality means that these devices simultaneously reduce fire risks caused by small arc faults. Unfortunately, GFCIs are only available to protect AC circuits. While technological solutions exist to provide similar protection in DC circuits, these devices are not yet commercially available. This lack of DC GFCIs could be seen as incrementally increasing the risk of DC circuits in buildings.

### 5.3.3 Public perceptions of DC

While it is unclear whether AC or DC circuits are more dangerous in the event of an electric shock and the fire hazard of DC circuits is likely only incrementally higher than in AC circuits, public perceptions of these risks will play a role in determining their adoption. Additionally, consumers' fundamental lack of familiarity with DC power systems may cause concern among the public about the safety, reliability, and costs of DC circuits and devices.

Similar concerns arose around the deployment of smart meters. Raimi and Carrico explored perceptions of smart grid technologies in response to a small but vocal minority view that smart meters posed health, privacy, and cost risks [104]. In that case, consumers ultimately have little control over widespread adoption of smart meters. But adoption of DC circuits will be voluntary, so public perceptions of these systems could affect their deployment.

### 5.3.4 Reduced reliability

Proponents of DC distribution systems argue that the reduction in power electronics required to serve DC native loads will actually make these devices more reliable, as their power supplies are simplified [47]. However, the power electronics and end-use appliance technologies proposed as replacements for our current AC devices are not currently manufactured at large scale. At the scale needed for widespread deployment, these would essentially be new products for many manufacturers and could potentially suffer the same reliability issues as new devices.

### 5.3.5 Engineers, electricians, inspectors, regulators, and others unfamiliar with DC

DC distribution systems in buildings are still uncommon, so very few professionals have experience with these systems. Simply overcoming this lack of information and experience to design, build, certify, and regulate these circuits will pose a challenge. Until these professions develop experience with DC, this lack of familiarity could magnify concerns surrounding the safety, reliability, and cost of their implementation and operation of these systems.

A lack of trained electricians was identified as a challenge to DC distribution systems and servers in data centers by Ton et al. [53]. The authors of that report called for the development of training programs for both work safety and recommissioning of these systems.

### 5.3.6 Uncertain utility interaction

There is no clear model for how a utility interacts with a DC building or microgrid. Technical analyses of these systems typically assume that a customer-owned bidirectional inverter will be installed downstream of the utility meter, and therefore should not pose any challenges to the existing utility-customer interface.

However, potential nontechnical barriers have been identified and discussed by Savage et al. in [58]. These include uncertainties surrounding net metering, utility ownership, and renewable electricity standards. Additional issues with existing utility agreements were identified in [92]. These issues were related to the wording of these agreements referring only to traditional AC systems, which would need to be modified if DC systems are more widely adopted.

One concern that utilities may have with widespread use of these systems relates to the power factors seen at building-level rectifiers or bidirectional inverters. At a smaller scale, power factor requirements are now included in ENERGYSTAR requirements for some electronic devices [105]. Similar requirements would be needed for the large rectifiers converting grid AC power to DC at the building level. Absent these requirements, power factor penalties might one day be needed for residential and commercial utility customers as they are now for industrial customers.

### 5.3.7 Power quality concerns

Several papers cite improvements in power quality as a potential benefit of DC power systems [60,106]. However, there is disagreement as to whether this would actually be the case. Whaite et al. reviewed examples of applications of DC architectures and found that power quality concerns in datacenters, homes, telecommunications systems, and renewable collector systems need to be better understood to properly design future DC systems [107].

### 5.3.8 Regulatory uncertainty

The National Fire Protection Association's National Electric Code (NEC) is the standard by which nearly every state and municipality in the US ensures safe electrical practices are followed [108]. The NEC does not currently distinguish between AC and DC for circuits carrying less than 600 volts [58]. While this means DC systems technically fall under the existing code, the lack of distinction and specific reference to DC could be cause for concern. Savage et al. argue that DC systems should be better specified in this code to avoid this concern.

### 5.3.9 Lack of standards

In addition to the NEC ensuring safe electrical practices, there are a number of other relevant standards that address other aspects of building electrical systems. Organizations such as the National Institute of Science and Technology (NIST), the American National Standards Institute (ANSI), the National Electrical Manufacturers Association (NEMA), and the Institute of Electrical and Electronics Engineers (IEEE) all maintain standards that govern aspects such as line voltages and tolerances, metering accuracy, and device safety. While many of these organizations have standards that apply to DC power systems in niche roles, most of these were never intended for widespread public adoption of DC circuits and devices.

The 24 VDC standard being promoted by the Emerge Alliance is the most advanced effort to establish a voltage standard for DC circuits in buildings [70]. However, this has not yet been formally adopted by government or other bodies [2]. Before DC power systems can be widely deployed, applicable standards will need to be developed and accepted to ensure the safe, reliable, and efficient operation of these systems.

#### 5.3.10 Diversification of buildings and appliances

Adoption of DC circuits in buildings will mean devices and services cannot be universally exchanged between buildings without specifying the circuit type. This increases uncertainty and complicates equipment purchasing decision-making and prospects for reselling equipment at a later date. A similar issue was identified in [53] that called for additional labeling to clarify whether a system is AC or DC for personnel working on and interacting with the system.

A counterargument is that universal adoption of DC would improve interoperability between countries and continents as specifying the grid frequency would no longer be an issue.

#### 5.3.11 Small markets for DC devices and components

While nearly all devices and components can be made to operate on DC, manufacturers will see a risk in serving what will initially be a small market of early adopters. As a result of this lack of economies of scale, prices for these components and devices are currently much higher than for equivalent AC devices [92]. Consumers might also see uncertainty in purchasing DC devices and components from companies that might abandon their DC product lines, or that might not exist if DC does not flourish in the near future. This creates a disincentive where, without outside intervention, both manufacturers and consumers will be skeptical of this new market and progress and adoption will be slow.

## 5.4 Methods

### 5.4.1 Identifying the experts

Experts in this study came from a variety of backgrounds. The majority came from research institutions such as universities, national labs, and industry research institutes. These participants were identified based on their recent publications on topics either directly or indirectly related to the deployment of DC circuits and devices in homes and commercial buildings. Industry experts came from companies that either currently manufacture devices or components for DC circuits or have expressed interest in this new market. Many of these industry experts were identified through their participation in an industry trade group called the Emerge Alliance. This is an open industry association dedicated to developing standards for the adoption of DC circuits in commercial and telecommunications applications [70]. Finally, practitioners such as electrical engineers, contractors, and project managers with experience in DC systems provided their hands-on expertise in dealing with these systems. These individuals were identified based on their experience in the design, construction, and operation of a DC microgrid located in Pittsburgh, PA [93]. The final set of experts included 17 individuals from industry (6), research organizations (5), academia (1), and the implementation or operation of DC systems (5).

### 5.4.2 Elicitation protocol

Following previous protocols [98,109], an online survey was designed to gather and record responses from the experts. Individuals were initially contacted by email, and the elicitation took place over the phone while the experts completed the online survey on their own computers. Responses were either entered into the online survey form or discussed over the phone and transcribed. A copy of the material and questions included in the online survey can be found in Appendix E.

The survey began with a brief introduction to the subject matter, format, and goals of our study. Experts were then asked to rank the applications most likely to adopt DC power systems in the near future. This was followed by two similar exercises which asked the experts to rank the positive characteristics that make the strongest case for more widespread use of DC, and the negative characteristics that pose the greatest challenge to that adoption.

Next, a hypothetical commercial office building was described to frame the next few questions. Experts were asked to estimate the costs of implementing DC and hybrid AC/DC circuits in this building now and in the future. Then voltage standards were elicited, with experts describing the most likely voltages and system architecture for the building. Finally, a series of open-ended questions were posed about long-term trends and their effects on adoption, potentially disruptive technologies, and research priorities to address in moving forward.

Experts' responses were recorded by the online survey tool, and audio recordings of the interviews were transcribed. All responses were sent to the experts to review both their short-form question responses and their transcribed discussion of more open-ended questions.

## 5.5 Results

### 5.5.1 Applications for DC

Experts were asked to rank the three applications which they thought are most likely to adopt DC power distribution in the future. Figure 5.1 shows these results. The four highest ranked applications were datacenters, developing world microgrids, commercial buildings with both AC and DC circuits, and electric vehicle charging stations.

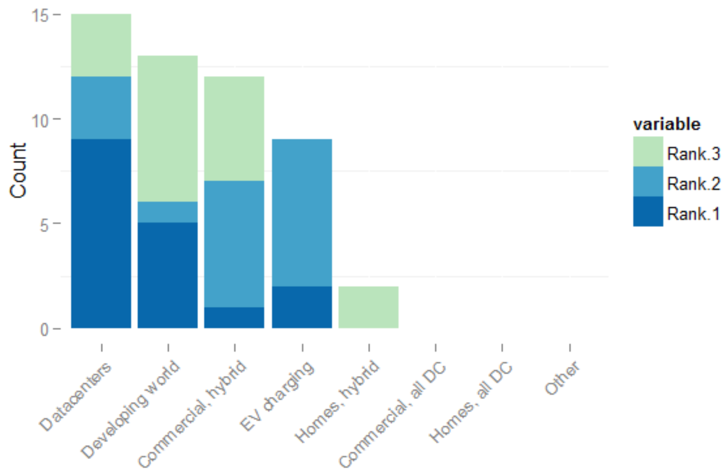



**Figure 5.1. Ranking results of applications most likely to adopt DC distribution systems**

### 5.5.2 Key characteristics of DC

Figure 5.2 shows experts' rankings of the characteristics of DC circuits that make the strongest case for more widespread use of DC in commercial and residential buildings.

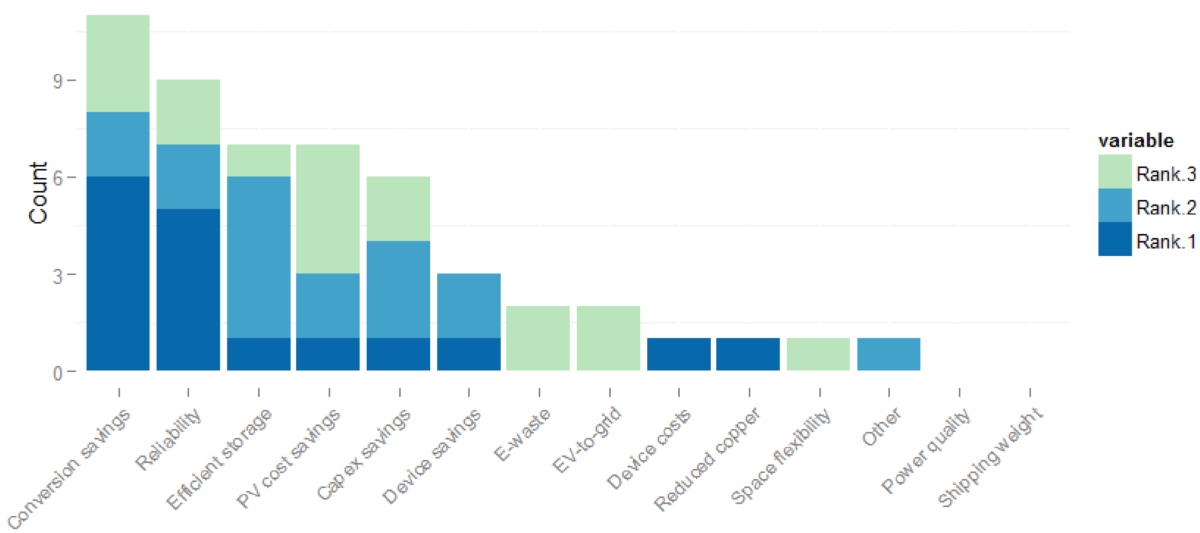



**Figure 5.2. Positive characteristics of direct current**

Energy savings from reduced power conversions was the most highly cited positive characteristic of DC systems. Many experts highlighted the fact that this was the biggest selling point being used in existing efforts to drive adoption of DC as the reason for their ranking. Others said that while energy savings make for a convenient talking point, these savings alone are not significant enough to drive adoption on a large scale.

Nearly as commonly cited were the potential reliability improvements offered by DC distribution systems and end uses. The reasons offered for this were largely twofold. First, the reduction in power conversion steps required to serve DC-internal end uses simplifies the failure-prone power supplies to these devices. Secondly, many experts mentioned the ease of integrating storage in DC systems and raised the potential for creating building-level microgrids to deal with grid outages. This was closely related to the next most commonly cited benefit that DC systems enable efficient energy storage with fewer conversion steps than an AC system. Discussion of these responses often described a future where on-site renewables, battery storage, and DC end uses were connected by a common DC bus. DC was seen as a solution to simplifying and reducing the costs of such systems. Similar discussions were provided as reasons for the next two most commonly cited benefits: solar PV and overall system capital cost savings.

Figure 5.3 shows experts' rankings of the characteristics of DC circuits that pose the greatest challenge to more widespread use of DC in commercial and residential buildings.

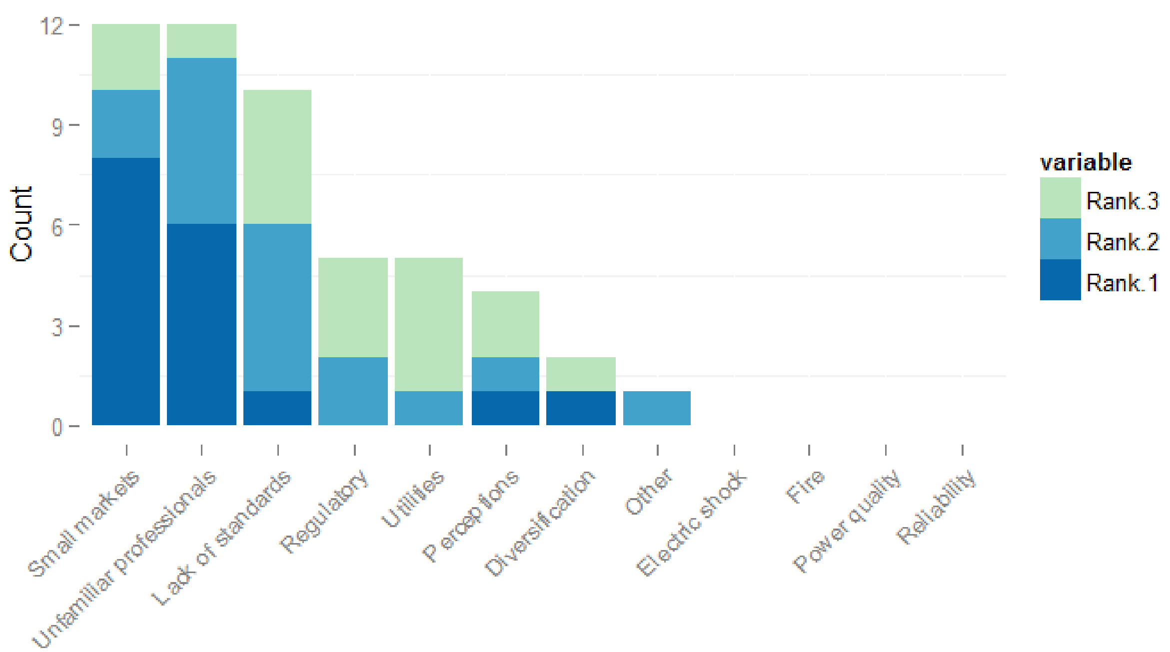



**Figure 5.3. Negative characteristics of direct current**

Lack of developed markets for DC devices and components was the most highly cited negative characteristic of DC systems. Many experts described this as a chicken-and-egg problem where manufacturers are hesitant to build devices and components for a small and uncertain market and consumers are therefore faced with high prices for the few devices that are available. Many of these devices and components are manufactured on a small scale to serve niche markets. These include mobile applications such as boats, trains, and RVs, as well as stationary applications such as data centers and telecommunications infrastructure. While the same technologies would transfer to buildings, existing manufacturers are not producing devices at the scale needed to serve a broad deployment of DC circuits outside of their existing markets.

Similarly ranked was the characteristic that engineers, electricians, building inspectors, regulators, and other industry professionals are unfamiliar with DC power systems. This prevents DC systems from being deployed as there are simply not many professionals familiar enough to recommend them at the early stages of a project. As a secondary effect, engineers and electricians will initially charge more to design and install these systems. These professions prefer to follow proven, standard design and installation heuristics. Departing from those standard practices requires extra time to ensure the systems are safe and reliable.

Finally, a lack of universally accepted standards was in over half of the experts' top three negative characteristics. Standards were seen foremost as a means of providing manufacturers with technical guidelines to which they can design and build devices. But standards also were mentioned as providing both consumers and manufacturers a measure of confidence that DC systems in buildings are a vetted and viable technology alternative.

### 5.5.3 DC distribution system costs

Experts were asked to estimate the overnight capital cost to outfit a standard commercial office building with DC circuits. To reduce variance in the responses experts were told to consider only the distribution system itself. The additional costs of building-level power electronics, appliances, and controls are not included here. These components would add a large capital cost that was intentionally excluded from this exercise. To serve as a reference point, experts were told that the cost for an equivalent AC system – providing 1000-amp service with panel boards and feeder lines – was $3.66 per square foot of floor area [110]. Figure 5.4 shows experts' estimated lower bound, upper bound, and best estimate costs for (a) an all DC building under current market conditions, (b) a hybrid system serving only lighting and computer workstations under current market conditions, and (c) an all DC building to be constructed 10 years in the future.

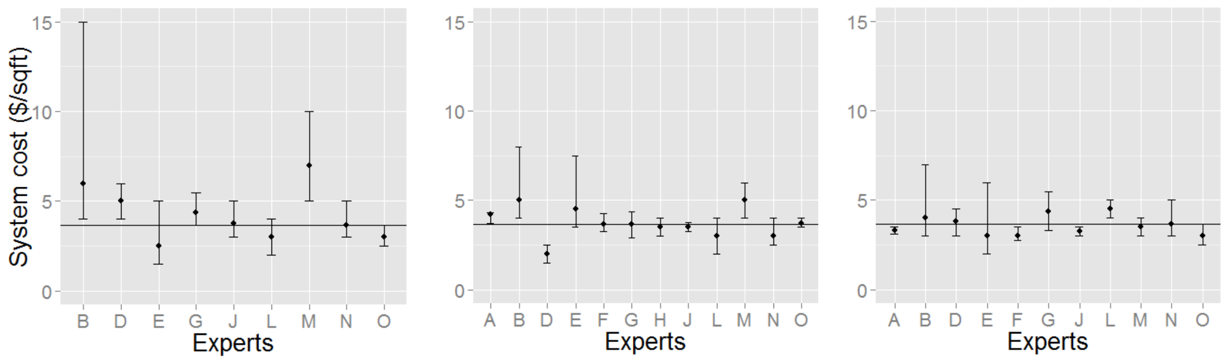



**Figure 5.4. Experts' estimated distribution system costs for (a) an all DC building under current market conditions, (b) a hybrid system serving only lighting and computer workstations under current market conditions, and (c) an all DC building 10 years in the future**

Only 9 of the 17 experts elected to estimate current system costs for an all DC system. Others either did not feel qualified to make an estimate or did not think an all DC system was feasible at this time. Most respondents estimated that DC systems would be – to varying degrees – more expensive than equivalent AC circuits.

Three additional experts thought a hybrid AC/DC building was now feasible, and were willing to provide cost estimates. Estimates here show that over half of experts believe such a system could reduce capital costs compared to the traditional AC system, while two others believe that the same system could be over twice the cost.

Finally, experts were asked to estimate costs for the all-DC system 10 years into the future assuming there has been no major outside intervention to prevent or impede the adoption of DC power systems. Most estimates show future all-DC system cost ranges that either include or are slightly below the current AC system cost.

The values provided here are only very rough estimates of the current and future costs of DC distribution systems in buildings. Many experts expressed very low confidence in their estimates. But these results do show that most experts believe that these systems at least have the potential to provide slight cost savings compared to a traditional AC distribution system. Alternatively, they could also be significantly more expensive over the next ten years.

### 5.5.4 Standards

Referencing the same hypothetical commercial office building, experts were asked to identify the voltage levels and current forms most likely to be seen in future buildings wired with DC circuits. Figure 5.5

shows experts' responses. The figure on the left shows the voltage levels and current forms chosen by each expert, and the figure on the right shows the number of times each combination was selected.

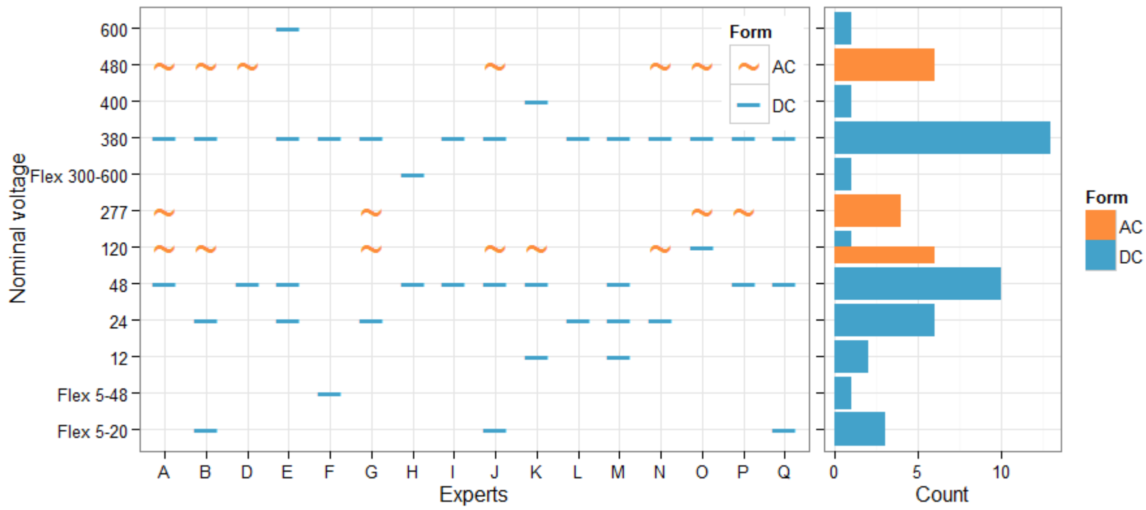



**Figure 5.5. Experts' expected voltage levels and current forms**

The two most common voltage levels chosen were 48VDC and 380VDC, followed by 24VDC, 120VAC, and 480VAC.

48VDC was described as a replacement for the 120AC standard. It would serve similarly sized loads and not suffer as much line loss as lower proposed replacement voltages. 48VDC also has the benefit of being considered a Class 2 voltage under the National Fire Protection Code, which allows for easier installation and interaction with these circuits. This increased safety and accessibility is part of the reason why Emerge Alliance proposed 24VDC for their occupied space standard. At such low voltages, untrained personnel can move and install fixtures and devices, meaning homeowners would be less dependent on electricians for this work.

380VDC was cited for larger loads, and convergence to this level was due to its promotion and existing use in data centers that would easily transition to other buildings and loads. 24VDC was described for serving smaller electronics and lighting, with industry promotion cited as the reason for convergence on this level. Maintaining a 120VAC distribution circuit was often mentioned to give the option to continue using existing devices in future hybrid buildings. And finally, 480VAC was chosen to serve large loads such as HVAC equipment where a DC alternative may not be readily available.

Five experts described flexible voltage circuits, most commonly at low voltage levels to serve small loads. Similar to the USB Power Delivery specification, these circuits were described as having the ability to provide various DC voltages to devices that communicate their required voltage to the circuit. Thus, these types of circuits are capable of serving electronic devices with varying voltage levels on a common circuit.

Next, the experts were asked if they had any concerns about the systems they described as most likely to be adopted. If they identified any such issues, they were asked to describe the system architecture that should be adopted. There were two common responses to this question: that the 24VDC standard that industry appears to be converging toward is too low to serve any loads but small electronics, and that higher voltages would have benefits when onsite generation is available. 24VDC was seen as generating too much line loss compared to 48VDC that would be similarly safe. 48VDC also has the benefit of having been used in the telecom industry for decades, meaning that expertise and some componentry already exist and have been proven safe and reliable. For higher voltages, experts cited 760VDC to 1000VDC distribution buses for collecting power from solar arrays. These would be stepped down before being distributed throughout the microgrid at the voltages identified above.

### 5.5.5 Long-term viability

As the experts identified above, one of the primary benefits cited of DC circuits in buildings is the energy savings generated by reducing the number of power conversions required to serve DC-internal end uses. However, as power electronic conversions become more efficient, the savings generated by eliminating those conversions will diminish over time. Of the 17 experts interviewed, 8 said that this trend will not change the outlook of DC systems in the future and 6 said that it could. Most experts cited other positive characteristics of DC systems as being the real drivers of future adoption.

Another trend relevant to adoption of DC relates to raw material supplies. Central in most analyses of DC circuits in buildings is an assumption that efficient DC appliances will be adopted. Many such appliances replace traditional electric motors with permanent magnet motors. Beginning in 2011, due to a combination of increased demand from electric vehicles and Chinese production quotas, magnetic material prices increased rapidly for several years before falling back to close to their original price. Experts were asked how the outlook of DC systems would change if a similar price fluctuation increased magnetic material prices by 20%. Nearly half of experts were unsure, and only one expert expected this to significantly change the outlook of DC systems in the future.

### 5.5.6 Disruptive technologies

Next, experts were asked to describe any technologies that could potentially change – positively or negatively – the trajectory of DC power distribution, DC microgrids, or DC appliances in buildings.

Responses showed optimism about developments in related technologies that would positively influence adoption of DC.

Most commonly cited was increased adoption of battery storage – either as a dedicated system or as part of vehicle-to-grid storage architectures – and pairing that storage with increasingly affordable and accessible solar PV arrays. Experts thought that as more homes and buildings began installing these systems to reduce their reliance on grid power, the better the case became to distribute generated power to the batteries and internal loads as DC. Thus, any developments that would increase adoption of batteries, EVs, or distributed generation sources producing DC would also positively influence adoption of DC.

Also commonly cited were advances in digital power delivery or combined communication and power delivery systems like Power over Ethernet (POE). Such systems allow end uses to be controlled and powered over a common line, while simultaneously allowing end uses to communicate back to a central hub. This kind of power delivery inherently operates over DC lines, often at low voltages, so these systems deliver the same reliability, space flexibility, easy installation, and low shock risk benefits. As existing trends continue to increase the automation, connectivity, control, and overall intelligence of buildings, the case for distributing power as DC will only improve.

### 5.5.7 Research priorities

Finally, we asked the experts to reflect on their roles, their knowledge of the state of the industry and technology, and the questions we posed during the rest of the elicitation and identify what they consider to be the top research priorities going forward. Table 5.1 summarizes these responses.

**Table 5.1. Summary of research priorities**

| Research objective | Mentions (Qty) |
|---|---|
| Understanding use cases where DC has a clear advantage over AC | 6 |
| Developing devices and components for DC systems | 5 |
| Integrating communication and power delivery | 4 |
| Building demonstration projects | 3 |
| Better understanding energy and cost savings potential | 3 |
| Better understanding power quality issues | 2 |
| Better understanding the potential for implementing DC as a retrofit | 1 |
| Better understanding transactive power potential of DC | 1 |
| Better understanding resilience benefits of DC | 1 |
| Training and educating professionals | 1 |
| Better understanding power scavenging | 1 |
| Developing voltage, metering, safety, and other standards | 1 |
| Better understanding electromagnetic emissions in DC buildings | 1 |

## 5.6 Discussion

This study presents 17 experts' judgments on the barriers and opportunities to more widespread use of direct current power systems in buildings. While there are major hurdles that need to be overcome to see these systems more widely deployed, there are fundamental advantages that make these systems better suited than our existing AC building infrastructure to meet the needs of future buildings.

One main focus of research into the prospect of DC circuits in buildings to this point has focused on the potential energy savings generated by centralizing and reducing the number of power conversions required to supply building loads. While experts thought this was a major determinant of the minor success of these systems so far, the long-term viability of DC power systems is less dependent on energy savings than existing literature would suggest. While there are fairly clear and significant energy savings to be generated, experts were not confident that these savings alone are enough to drive adoption.

Instead, experts cited a number of other known benefits of DC as promoting adoption. These are related to ongoing trends that are already driving adoption of other technologies such as increasing attention to resilience, increasing electronic loads, and increasing demand for centralized control of end uses. The direction and strength of these trends makes for a clear argument that DC power systems are better suited to serve the increasingly DC-internal loads in modern buildings.

Finally, the biggest challenges to DC were identified as being the small markets for these systems and professionals unfamiliar with them. To address these, experts proposed training engineers and electricians on DC systems, and identifying niche use cases where DC power distribution holds a clear advantage over AC and building pilot projects to further prove the technology is safe and reliable.

# 6 Conclusions and Policy Discussion

Device-level energy use data has the potential to drive adoption of energy efficiency technologies by providing decision-makers a better understanding of how buildings consume energy and how that consumption can be reduced. This dissertation provides insight into the sources of these data and demonstrates how they can be used to guide policy and investment decision-making.

## 6.1 Value of device-level energy use data

The number of studies and the investments being made to build a device-level accounting of where energy is used in US homes speaks to the value of that information. Direct metering methods, NILM methods, and statistical methods for disaggregation are all means of reaching the same end – shrinking the information gap that has been identified as slowing efficient technology adoption.

As these types of data become more available, their value as a decision support tool deserves more attention. Researchers, consumers, manufacturers, utilities, and policymakers can all advance their interests and promote better-informed energy use by utilizing these data. But access to the data alone will not drive results. Continued efforts are needed to ensure that these data are used to inform decisions. In this dissertation, we demonstrate the value that these data can provide and develop methods to translate them into meaningful, actionable information.

At the most basic level, disaggregate energy use data can simply inform stakeholders of how much, where, and when energy is being consumed. With this understanding, consumers would be able to make behavioral and investment decisions to more effectively reduce their energy bills. Manufacturers would be better positioned to develop and market efficient appliances and devices. Utilities and grid operators could incorporate these data to better forecast loads. And policymakers and utility program designers could use this information to better target energy efficiency, demand response (DR), and demand side management (DSM) initiatives that deliver sustainable, cost-effective, and verifiable results.

The same data can also be used to validate existing methods and tools for understanding energy use in buildings. In Chapter 2, I compared disaggregated end-use data from the Pecan Street project to modeled device-level energy use estimates from the EIA's RECS and revealed large, but somewhat expected differences between the two datasets. In addition to this simple validation, I propose a method by which the EIA could cost-effectively incorporate the Pecan Street data into their study to increase confidence in their model estimates. In Chapter 3, I examined another application where the Pecan Street data can be used to validate an existing tool – in this case the DOE's EnergyPlus building simulation package. After modeling the Pecan Street homes, I again find large differences between modeled and measured energy consumption. While additional input data to these models would undoubtedly improve the performance of the models, the Pecan Street data enable a detailed comparison that provide important context for the use of EnergyPlus in the residential sector.

The last application I explored for using device level data was simulating an efficiency intervention. Device-level data from actual, occupied homes captures variation in home appliance stocks, physical home characteristics, occupant behaviors, and other factors that make for a relatively diverse population to evaluate interventions. This makes results more reliable than the alternative method of using generic load profiles and energy consumption values to base savings estimates.

In addition to broadly demonstrating the value of device-level data in these applications, specific conclusions and recommendations can be made about the specific technology and policy issues addressed.

## 6.2 EnergyPlus for building code analysis and verification

Results from Chapter 3 have implications for two policy-related uses of EnergyPlus in the residential sector.

First, the DOE's Building Energy Codes Program should consider the inaccuracies found in our results and in previous research as their work continues to use EnergyPlus as a tool for evaluating changes to future energy codes. The current method of simulating slight changes to building codes likely provides a reasonable estimate of the savings from those changes. But the fact that simulations typically do not accurately predict actual energy consumption once homes are occupied means that these simulations should not be used to predict actual realized energy savings in future homes.

Secondly, the EnergyPlus-based tool currently being developed by RESNET needs to be thoroughly validated before being deployed to verify energy code compliance in new residences. This validation should compare the estimated performance of the building using the tool to actual measured performance at the device level. This should be done with hourly or sub-hourly data, as my results show that even in cases where annual energy consumption is very accurately estimated, measures comparing time-series data show very poor calibration. ASHRAE's Guideline 14 provides rules for determining a calibrated model that could be used for this purpose.

Residential building energy code compliance would ideally be verified through demonstrated energy performance, but this is not feasible for a number of reasons. Compared to the current prescriptive, component-based compliance pathways, the use of simulated performance for compliance verification seems like a step in the right direction. Similar uses of simulation software packages for compliance have been used by building certification programs for commercial buildings. In an analysis of the accuracy of the simulations used in the LEED certification process, it was found that simulations generally predict average energy use over a group of buildings, but not specific buildings [22]. In other words, simulations overestimate and underestimate actual consumption by roughly the same amounts across populations. If the same holds true in the residential sector, there will be homes that consume far more energy than their design simulation predicts. At this point there are too few studies investigating the accuracy of EnergyPlus in homes to draw much more specific conclusions. More work is needed to better understand this future use of simulation tools, and Chapter 3 from this dissertation can serve as a valuable guide.

## 6.3 Direct current power in buildings

Lastly, Chapters 4 and 5 provide insight into a potential transition to direct current power distribution systems in homes and commercial buildings. The energy and cost savings estimated in Chapter 4 do not alone make a strong argument for deploying direct-DC systems in homes. In some configurations, these systems would generate emissions reductions roughly as cost-effectively as a traditional solar PV array. But a number of nontechnical barriers need to be addressed by policymakers before these systems are anything more than one-off installations.

In Chapter 5, experts from a range of backgrounds identified the biggest of these barriers as being the small markets for these systems and industry professionals unfamiliar with them. Many experts described the lack of an established market as a chicken-and-egg problem where manufacturers are hesitant to build devices and components for a small and uncertain market and consumers are therefore faced with high prices for the few devices that are available. Having engineers, electricians, building inspectors, regulators, and others unfamiliar with DC power systems compounds this problem, making these systems unlikely to be implemented or cost-effective without outside intervention.

To address these barriers, experts proposed identifying niche use cases where DC power distribution holds a clear advantage over AC and building pilot projects to further prove the technology is safe and reliable. Cell towers and military installments were given as examples of applications which would be ideal for piloting DC systems. These applications have large electronics loads, rely heavily on the availability of backup power, and are often already supplied with distributed generation sources like solar PV. In parallel with these pilot projects, training programs for engineers and electricians will make DC systems less foreign, thereby speeding adoption and reducing the added cost penalty that these professions would otherwise impose. Finally, a lack of universally accepted standards was seen as another major barrier. While the 24 VDC standard being promoted by the Emerge Alliance is gaining recognition, it has not yet been formally adopted by government or other bodies. To see wider adoption of DC systems this, and other standards, will need to be formally adopted by organizations such as NIST, ANSI, NEMA, and IEEE to ensure the safe, reliable, and efficient operation of these systems.

Despite these considerable barriers, there are a number of known advantages of DC systems that make a strong case for their more widespread adoption. Increasing use of solar PV with storage, growing concerns over grid reliability, growing electronics loads, and demands for increased control over end uses all favor building-level direct current power distribution. The direction and strength of these and other trends makes for a clear argument that DC power systems are better suited to serve future buildings, and investment in better understanding and deploying these systems is indeed worthwhile.

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# A. Chapter 1 Supplemental Information

## Pecan Street intervention summary

**Table A.1. Summary of intervention participation**

| | Quantity | % of Total |
|---|---|---|
| Pecan Street households | 1,089 | 100% |
| Intervention 1 – Outside Greater Austin | 371 | 34% |
| Intervention 2 – Baseline | 201 | 18% |
| Intervention 3 – CCET Control | 63 | 6% |
| Intervention 4 – CCET Portal | 44 | 4% |
| Intervention 5 – CCET Pricing | 62 | 6% |
| Intervention 6 – CCET Text | 49 | 4% |
| Intervention 7 – CCET Appliance | 46 | 4% |
| Intervention 8 – Energy Internet | 635 | 58% |
| Intervention 9 – LG Appliance | 15 | 1% |
| Intervention 10 – Tablets | 177 | 16% |
| Intervention 11 – Energy Audits | 240 | 22% |

Intervention 1 indicates that the home is located in Texas but is outside of the Greater Austin area.

Intervention 2 was a study in which energy use in each home in the study was monitored for one year and then summarized. At the end of that year, this summary was provided to the homeowner and another year of data was monitored to determine if energy use changed.

Intervention 3 indicates the home was part of a control group for the CCET trial. This was a study which made home energy use data available to homeowners via an online portal and established an experimental time-of-use pricing scheme.

Intervention 4 indicates that homeowners only had access to the CCET home energy reporting portal. While these participants were made aware of how the experimental pricing scheme would affect them, they did not receive any actual financial incentive.

Intervention 5 indicates that homeowners both had access to the CCET online energy portal and received financial incentives in accordance with the experimental pricing scheme established to reduce peak demand.

Intervention 6 indicates that homeowners in the CCET trial received text messages asking them to reduce their energy consumption on peak days.

Intervention 7 was similar to Intervention 6, but text messages provided information on which appliances should be curtailed.

Intervention 8 indicates participation in the energy internet demonstration program. Most of these homes are in Austin’s Mueller neighborhood.

Intervention 9 was a program that delivered new LG washers, dryers, and some refrigerators to participating homeowners.

Intervention 10 is a program that gives tablets to residents of low-income apartment complexes to provide access to their online energy portal.

Intervention 11 is a program that provides energy audits to homeowners in the sample at no cost. Audits were conducted in two phases. In the first phase, audits were conducted by an outside contractor. In the second phase, a different set of homes were audited by trained Pecan Street personnel.

# B. Chapter 2 Supplemental Information

## Estimated submetering costs

Table B.1 below shows appliances monitored in the Pecan Street dataset which consumed more than 100 kWh/yr. Monitoring these (10) appliances would ensure that the majority of energy use is monitored in the majority of homes.

**Table B.1. Monitored appliances with electricity consumption greater than 100 kWh/yr**

| Appliance | Annual Energy Consumption (kWh) |
|---|---|
| Air conditioner condensing unit (apartment / home) | 1,300 / 3,000 |
| Clothes dryer | 500 |
| Electric vehicle charger | 2,000 |
| Freezer | 300 |
| Furnace Fan | 900 |
| Oven | 140 |
| Pool Pump | 4,600 |
| Electric Range | 170 |
| Refrigerator (apartment / home) | 400 / 700 |
| Water heater (apartment / home) | 900 / 1,500 |

Not every housing unit has each of the appliances shown above, while other housing units may have more than one of some of these appliances. For cost approximation purposes, we assume that these two roughly cancel out and 10 appliances per home will be monitored. Table B.2 shows a rough breakdown of the costs associated with monitoring these appliances in an individual housing unit.

**Table B.2. Monitoring cost estimate**

| | Unit Price | Unit Quantity | Total Cost |
|---|---|---|---|
| **Material Costs** | | | |
| eGauge Main Units | $386/ea. | 1/residence | $386/residence |
| 100 amp CTs | $15/ea. | 10/residence | $150/residence |
| **Installation Costs** | | | |
| Electrician labor | $100/hr | 8 hours/residence | $800/residence |
| **Data Management Costs** | | | |
| Data management | $1,500/residence | - | $1,500/residence |
| **Total Cost** | | | **$2,800/residence** |

Costs shown are approximate.

**Whole-residence consumption by income bracket**

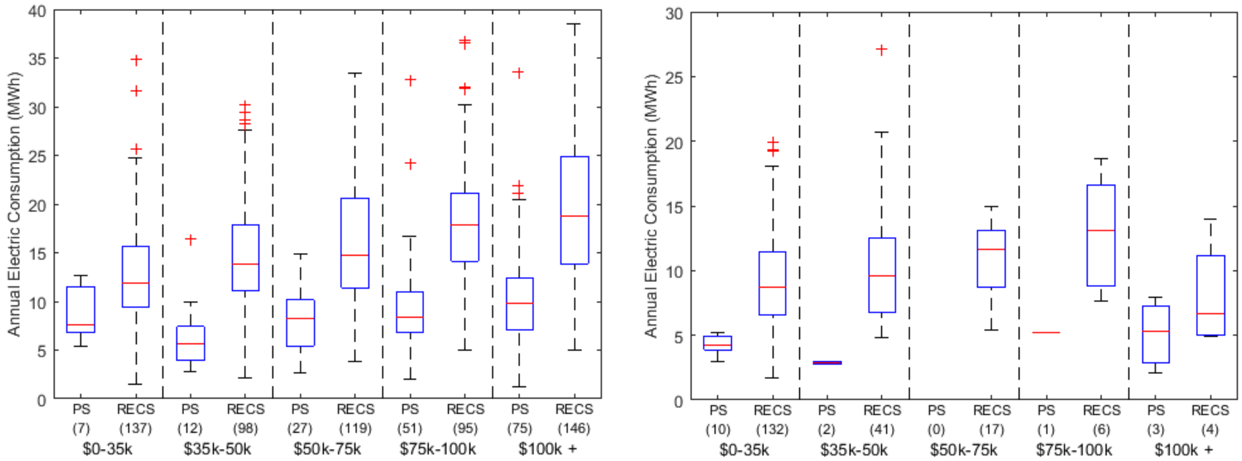



**Figure B.1. Whole-residence electric consumption for homes (left) and apartments (right) by income bracket. Note that not all homes report income level, so sample sizes are smaller than previously shown. Box plots show the median, 25% quartile, 75% quartile, maximum, minimum, and outliers. For each appliance, the left box shows Pecan Street data and the right box shows RECS data. The source and number of data points represented in each plot is shown below each box.**

## C. Chapter 3 Supplemental Information

### Residential energy code adoption

In the residential sector, building energy codes are adopted at either the state or local level through either legislative action by the government or regulatory action by an authorized agency. In practice, many codes are adopted through a combination of these frameworks. Examples include the following:

- Statewide, uniform adoption of a code by legislative action
- Statewide adoption by a board which was established by legislative action
- Statewide adoption of a minimum code, with local governments adding amendments or opting for more stringent codes

Most state and local codes specify an existing model code such as the International Energy Conservation Code (IECC) or the ANSI/ASHRAE/IES Standard 90.1. These underlying codes can then be modified or amended to create more or less stringent custom codes [111].

New or revised codes are adopted every few years and often follow regular updates to the underlying IECC or ASHRAE model code. While the exact timing of these updates is not consistent, as of 2016 the majority of statewide adoptions use the 2009 or 2012 versions of the model codes [112].

### Residential energy code content

Residential building energy codes are less comprehensive than commercial building codes, but generally cover the building envelope, space conditioning equipment, water heating equipment, and lighting.

Building envelope requirements set insulation levels, fenestration levels, and solar heat gain coefficients for ceilings, walls, windows, floors, and foundations. This section of the code provides minimum values for these criteria by climate zone, methods for necessary calculations, and installation instructions for installers.

Space conditioning equipment requirements are a combination of equipment efficiency, control, installation, and other requirements. Equipment efficiency standards and sizing rules are typically set outside of the energy code, so the governing regulation is simply referenced for these requirements. Remaining requirements specify necessary technologies, leakage rates, and other relevant factors that must be met for a building to meet the code.

Water heating equipment requirements specify the necessary controls, insulation, and pipe sizes that need to be followed for the system to meet the code.

Lighting requirements simply set a percentage of the total lamps in a residence that must be high efficacy.

## Residential energy code compliance pathways

Compliance with an energy code is achieved by one of two pathways. In the prescriptive pathway, a building's design materials, systems, and installations are simply chosen so as to satisfy the minimum requirements laid out in the code. Some allowances are made such that less efficient components in one area are exchanged with more efficient components in another, but these are minimal. The second compliance pathway is the performance, or simulation, path. To comply under this pathway, certain mandatory prescriptive efficiencies are still adhered to, but the remainder of the building is left to the designer. Compliance with the code requires a simulation of the building to show that the overall energy cost of the building is less than that of a standard reference building. This pathway allows for more flexibility in the design process, but requires the additional steps of building a detailed simulation model of the designed home.

## Additional condensing unit results

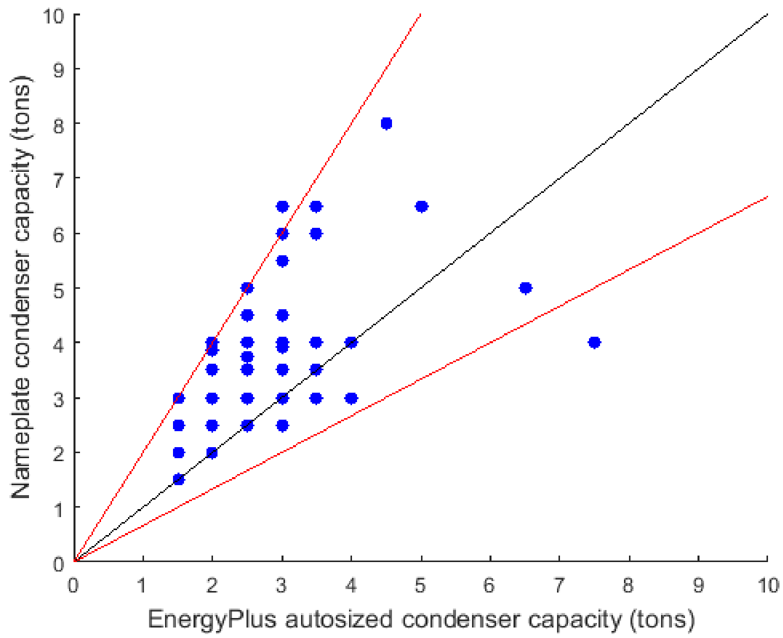
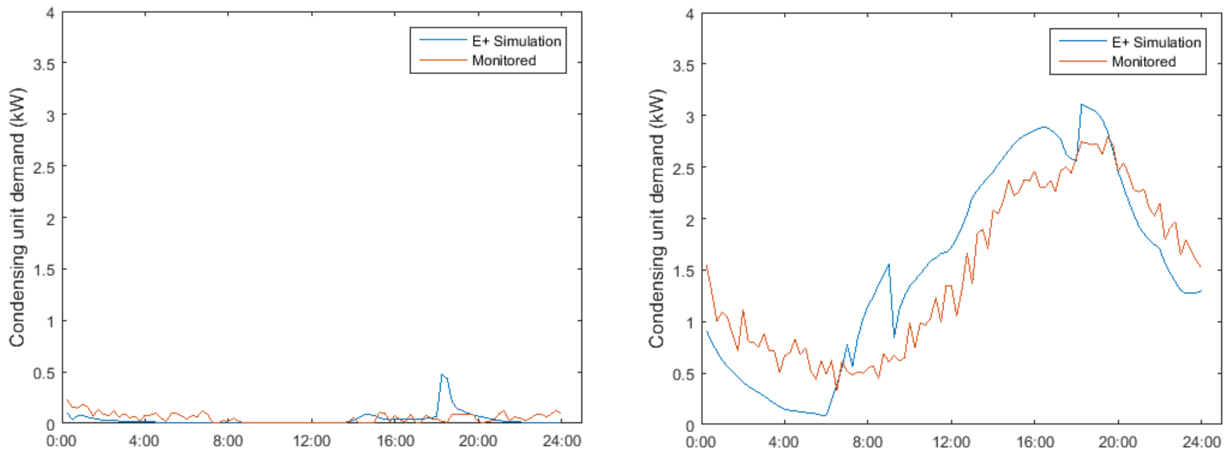
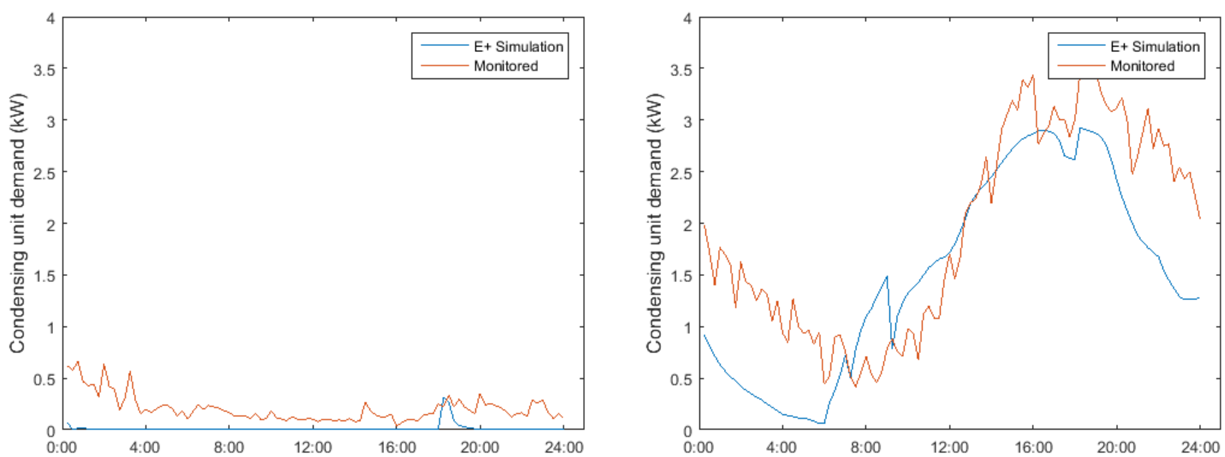



**Figure C.1. Scatterplot of autosized condenser capacities rounded up to the nearest half-ton on the x-axis and nameplate capacities on the y-axis. The black diagonal shows perfect agreement, while red diagonals show ±50% error bounds.**




(a) (b)

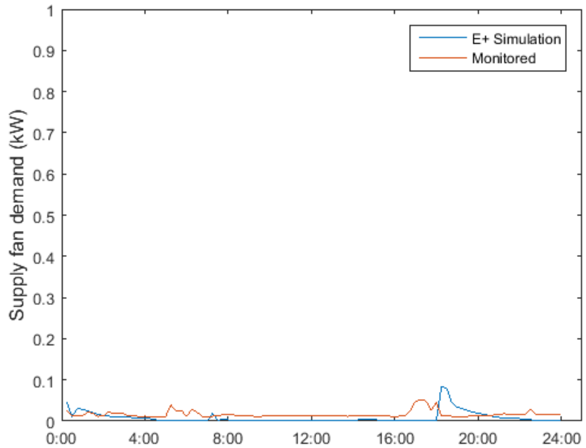
**Figure C.2. Average condensing unit demand for homes where EnergyPlus overestimated annual condensing unit energy consumption by <50%. (a) Shows average condensing unit demand for a day with negligible heating or cooling energy. (b) Shows average condensing unit demand for a peak cooling day.**



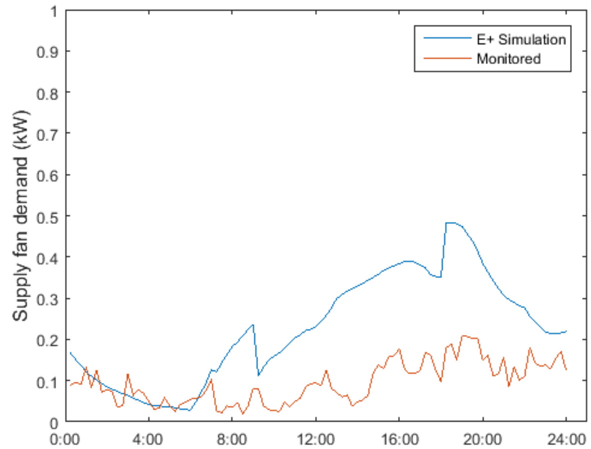

(a) (b)

**Figure C.3. Average condensing unit demand for homes where EnergyPlus underestimated annual condensing unit energy consumption. (a) Shows average condensing unit demand for a day with negligible heating or cooling energy. (b) Shows average condensing unit demand for a peak cooling day.**

## Additional central air supply fan results

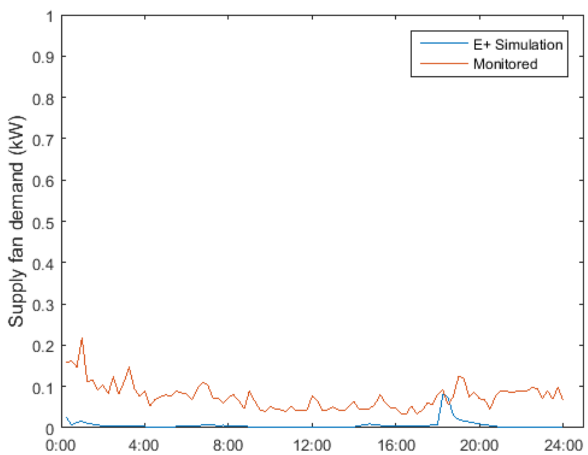



(a)

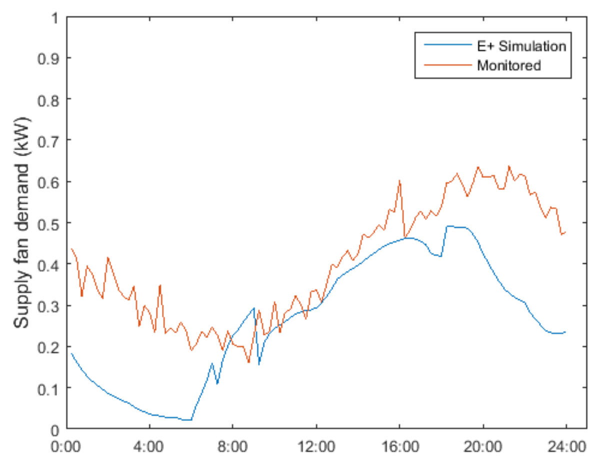



(b)

**Figure C.4. Average central air supply fan demand for homes where EnergyPlus overestimated annual central air supply fan energy consumption by >50%. (a) Shows average demand for a day with negligible heating or cooling energy. (b) Shows average demand for a peak cooling day.**

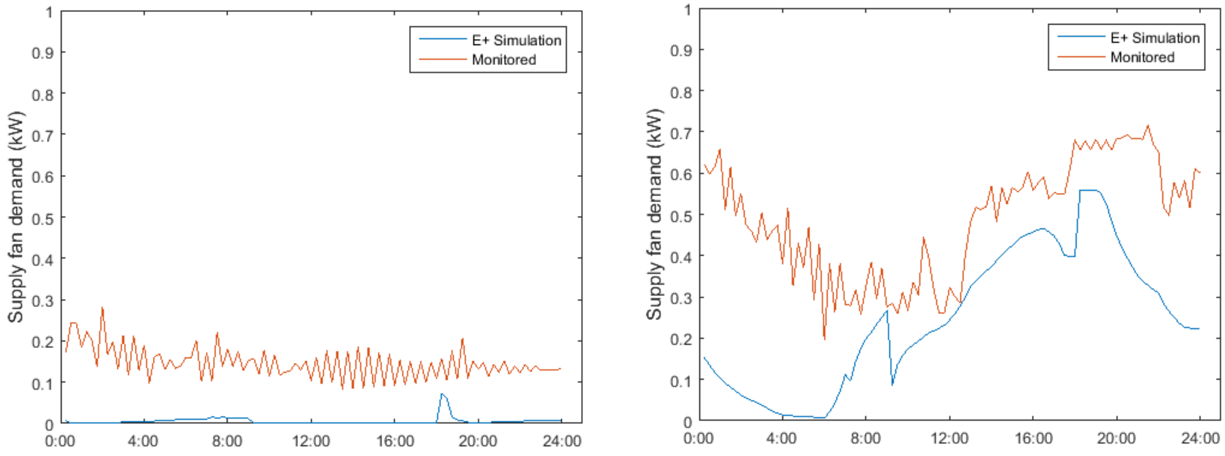



(a)




(b)

**Figure C.5. Average central air supply fan demand for homes where EnergyPlus underestimated annual central air supply fan energy consumption by <50%. (a) Shows average demand for a day with negligible heating or cooling energy. (b) Shows average demand for a peak cooling day.**




(a)

(b)

**Figure C.6. Average central air supply fan demand for homes where EnergyPlus underestimated annual central air supply fan energy consumption by >50%. (a) Shows average demand for a day with negligible heating or cooling energy. (b) Shows average demand for a peak cooling day.**

# D. Chapter 4 Supplemental Information

## Assumption of a 120VDC standard

The assumption of a voltage standard around 120 VDC is based on [61] which examined potential DC voltages for residential microgrids based on line power losses, voltage losses, and the thermal limits of typical residential wiring. The paper breaks home loads into 5 classes based on their typical power demands and physical distribution of each load type within a home. Based on acceptable line losses, a voltage is recommended for each load class. Despite the large number of 12 and 24 VDC appliances already available for other markets, the authors find that the losses associated with distributing power throughout a home at such a low voltage to anything but “extra-low power devices” results in excessive line losses. Instead, the lowest recommended voltage was 48 VDC for small loads such as those found in living rooms, bedrooms, and bathrooms. Meanwhile the few large loads are found to be best served by 120 VDC and slightly larger AWG 6-8 wiring. This meets the International Electrotechnical Commission’s definition of extra-low voltage, indicating low risk of electrical shock. Given the few loads that are to be served by this voltage-wire combination, the added cost of the larger wiring is negligible. A higher 240 VDC is also considered to serve a home air conditioner and is found to marginally decrease line losses. Higher voltages such as EPRI and LBNL’s 380 VDC datacenter and telecom standard are also mentioned, but are found to provide negligible line loss savings while introducing safety concerns. Ultimately, the authors call 120 VDC a promising standard for the industry based on its safety and efficiency. For these reasons, and the parallels that such a standard would allow between future DC systems and today’s AC systems, we chose this as the standard for this analysis.

## Storage sizing heuristic

Storage capacity for each home was calculated as two hours of full PV array output, so a 5 kW array would have a 10 kWh battery. This was based on a DNV Kema report for NYSERDA that examined residential PV system battery storage capacities for serving internal home loads during outage events [84]. That report recommended a minimum 10 kWh of storage capacity, and cited a standard PV array of 5 kW. Several commercially available PV + storage systems were presented that either exactly or nearly matched this design heuristic. Because battery capacity was not a specific focus of this paper, this standard was held constant through all simulations.

## Solar PV proxy method

As explained in Section 2.1 of the main manuscript, homes were selected for final simulations that report data for whole-home electricity use, air conditioner condensing unit use, central air supply fan use, and refrigerator use for over one year with less than one week of missing data.

This leaves 120 homes, with only 45 reporting solar PV generation. In order to include the 75 remaining homes in the final analysis we select a typical PV system from another home and apply that generation profile as a proxy. Of the 693 homes monitored, 166 report solar generation and whole-home use for over one year with less than one week of missing data. To identify a suitable PV array, we first estimate the rated capacity of each system as the peak 1-hour average generation monitored over the entire monitoring period. Figure D.1 shows a histogram of these calculated solar PV array capacities. The average system capacity calculated using this method is around 5.1 kW.

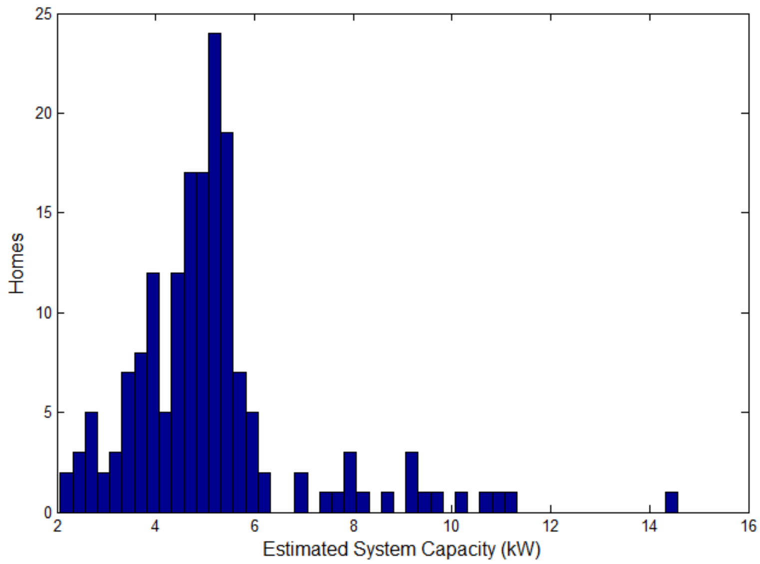



**Figure D.1. Estimated solar PV array capacities. These values are calculated as the peak 1-hour average generation reported over the entire monitoring period**

Next, we sort these solar PV arrays by the quantity of data available. Because the appliance use profiles used in our final simulations are distributed across Pecan Street's entire monitoring period, we choose a solar generation profile that covers as much of this time period as possible to increase the likelihood of having overlapping data. Table D.1 shows the length of data available and the estimated system capacity for the five solar arrays with the longest monitoring periods.

**Table D.1. Solar data availability for the five solar arrays with the longest monitoring periods**

| Home ID | Qty. of Data Available (Years) | % of Pecan Street Monitoring Period | Estimated System Capacity (kW) |
|---|---|---|---|
| Home 585 | 2.7 | 99% | 4.0 |
| Home 744 | 2.6 | 96% | 4.1 |
| Home 8084 | 2.6 | 94% | 7.9 |
| Home 4336 | 2.6 | 94% | 2.8 |
| Home 4031 | 2.6 | 93% | 5.5 |

The solar generation data reported for Home 4031 covers approximately 93% of the period for which monitored data is available (January 2012 through October 2014). The calculated capacity of this system is around 5.5 kW, slightly larger than the 5.1 kW average. To ensure that this system operates similarly to other arrays, we plot calculated system capacity and annual solar energy generation in Figure D.2.

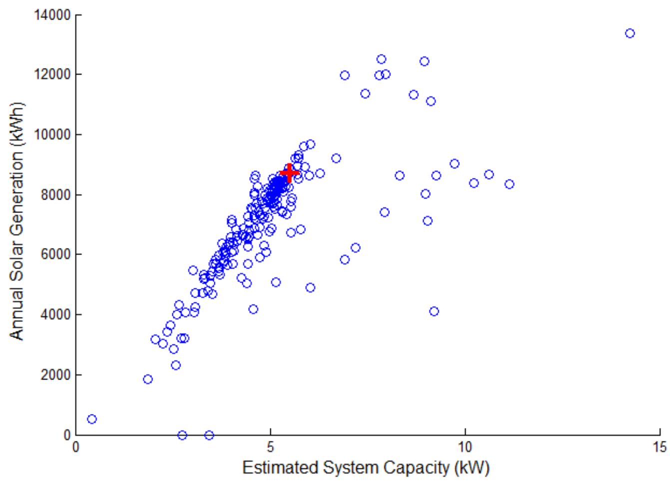



**Figure D.2. Estimated solar PV array capacity versus annual solar generation. Home 4031 is shown in red.**

This figure shows the majority of homes' annual solar generation is a linear function of its system capacity. The solar array monitored at Home 4031, shown in red, follows this relationship closely indicating that it operates similarly to the remaining homes in the sample. Based on these factors, this generation profile was chosen to serve as a proxy for homes for which solar PV generation data is unavailable. In applying this profile to these 75 homes, we use the timestamps available on both the solar data and the home load data to align the two data sets for final simulations.

In order to account for varying home sizes, this solar generation profile was scaled based on each home's annual energy consumption. Figure D.3 shows the fraction of each home's annual energy consumption that is met by PV generation.

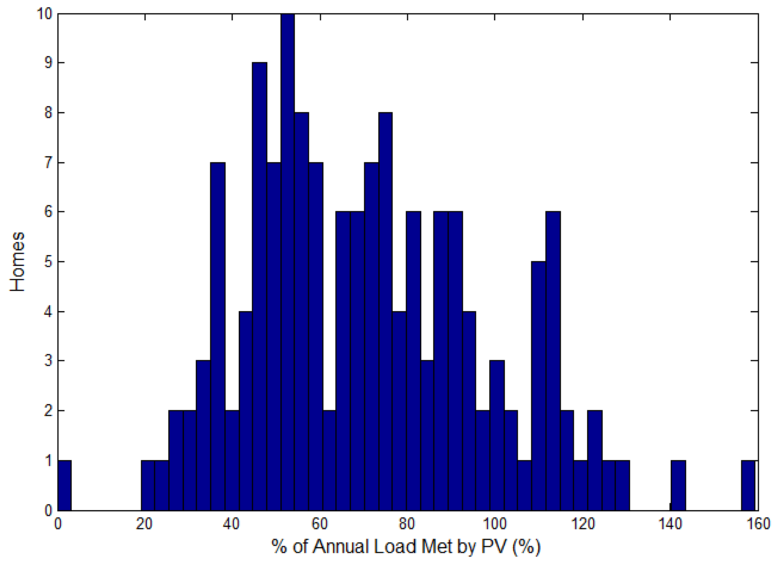



**Figure D.3. Fraction of home load met by PV.**

The average solar array generates enough energy to meet around 69% of the annual consumption of the home on which the array is installed. We use this value to scale Home 4031's solar profile to the 75 homes for which solar data was unavailable. For example, a home which consumes 10,000 kWh/yr will have a proxy solar profile with twice the annual energy output of a home which consumes only 5,000 kWh/yr. In both cases, annual solar generation will be equal to 69% of annual home consumption.

## Normalized appliance class bar charts

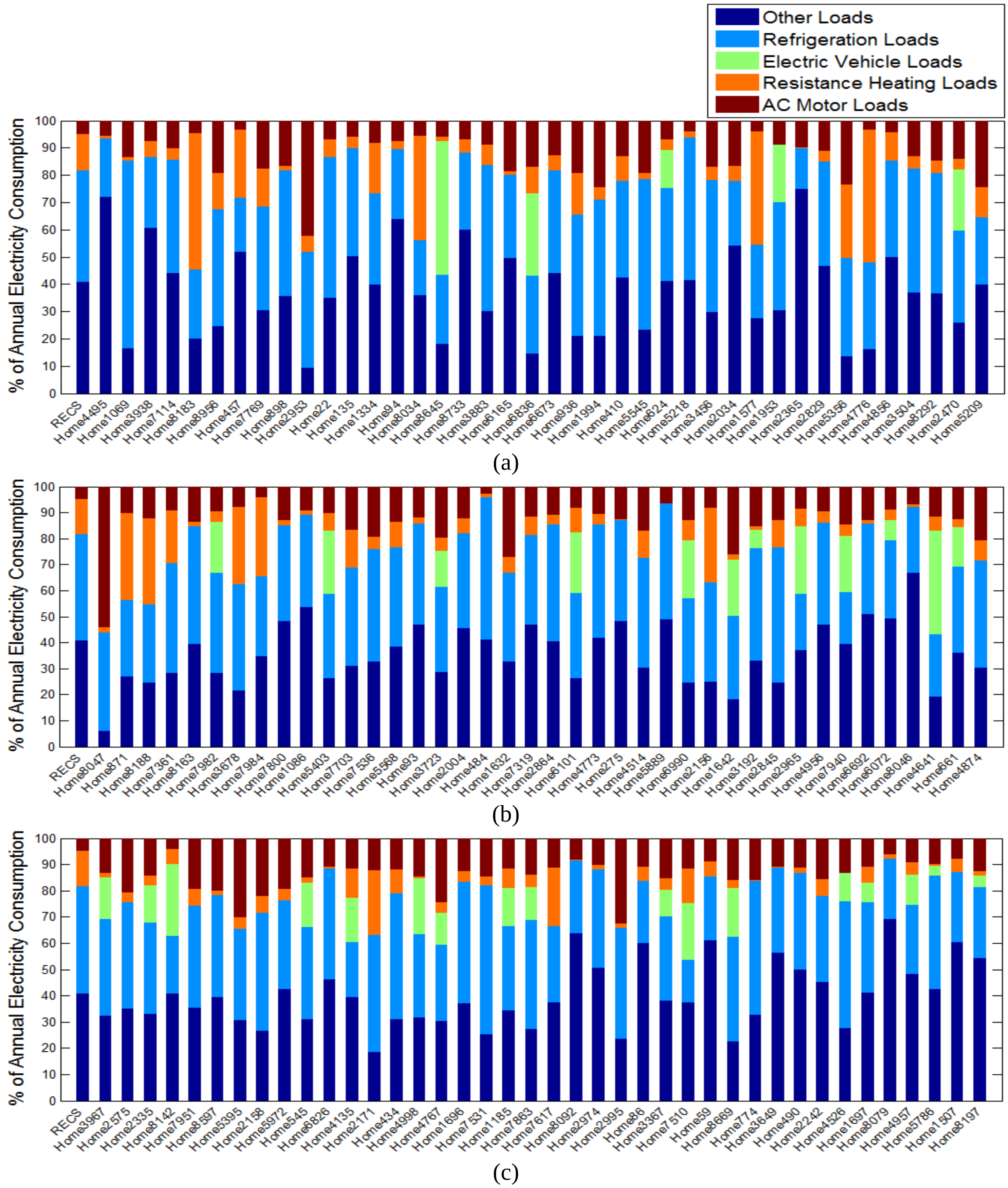



**Figure D.4. Annual energy consumption by appliance class normalized to whole-home energy consumption. The first bar in each figure shows the mean electricity consumption by appliance class reported in RECS for single family homes in Texas with central air. (a)-(c) show energy use breakdowns by appliance class for Pecan Street homes included in final simulations ordered by annual energy consumption.**

### Austin Energy billing rate, solar credit rate, and solar rebate structures

Table D.2 shows Austin Energy's residential billing rate structure used to calculate baseline energy costs and savings for the homes in this study. Winter rates are applied from October through May. Summer rates are applied from June through September. See reference [41] for more details.

**Table D.2. Austin Energy residential electricity billing components. Winter rates are applied from October through May. Summer rates are applied from June through September. Table is taken directly from [41].**

| Billing Components | % of Bills | Inside Residential |
|---|---|---|
| **Customer Charge – ($ per month)** | | $ 10.00 |
| **Energy Charge – Summer - (per kWh)** | | |
| Tier 1: 0 – 500 kWh | *15% of bills* | $ 0.033 |
| Tier 2: 501 – 1000 kWh | *26% of bills* | $ 0.080 |
| Tier 3: 1001 – 1500 kWh | *25% of bills* | $ 0.091 |
| Tier 4: 1501 – 2500 kWh | *25% of bills* | $ 0.110 |
| Tier 5: > 2500 kWh | *9% of bills* | $ 0.114 |
| **Energy Charge – Winter - (per kWh)** | | |
| Tier 1: 0 – 500 kWh | *40% of bills* | $ 0.018 |
| Tier 2: 501 – 1000 kWh | *37% of bills* | $ 0.056 |
| Tier 3: 1001 – 1500 kWh | *14% of bills* | $ 0.072 |
| Tier 4: 1501 – 2500 kWh | *7% of bills* | $ 0.084 |
| Tier 5: > 2500 kWh | *2% of bills* | $ 0.096 |
| **Power Supply Adjustment - (per kWh)** | | $ 0.03945 |
| **Community Benefit Charges - (per kWh)** | | |
| Customer Assistance Program | | $ 0.00172 |
| Service Area Street Lighting | | $ 0.00093 |
| Energy Efficiency Programs | | $ 0.00400 |
| **Regulatory Charge - (per kWh)** | | $ 0.0083 |

In homes with solar PV arrays, these rates are applied to total home consumption regardless of the home's net load on the grid. Solar energy generation is then rebated at a flat $0.107 per alternating current kWh, measured downstream of the system inverter, which is credited to the home's monthly bill. Figure D.5 shows the resulting marginal billing and solar crediting rates.

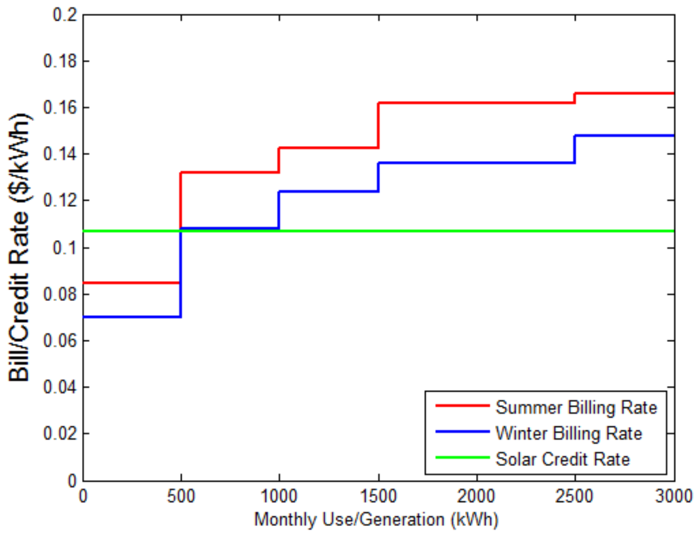



**Figure D.5. Austin Energy billing rates and solar credit rate.**

Austin Energy provides rebates to residential customers for the installation of solar PV arrays. In 2012, the most recent year for which data is available, these rebates averaged $2,990 per kW of installed AC system capacity.

**Table D.3. Recent Austin Energy Solar Rebate Program summary. Table is taken directly from** [41]**.**

| Solar Rebate Program | FY 2010 | FY 2011 | FY 2012 |
|---|---|---|---|
| **Residential (Capacity Based Incentive)** | | | |
| Rebate Dollars | $3,216,535.05 | $4,711,101.25 | $5,721,412.02 |
| # Rebates | 213 | 328 | 458 |
| kW-AC | 793.26 | 1,352.65 | 1,913.26 |
| Avg. Rebate per customer | $15,101.10 | $14,363.11 | $12,492.17 |
| Avg. System Size kW-AC | 3.72 | 4.12 | 4.18 |
| $/kW-AC | $4,054.81 | $3,482.86 | $2,990.41 |

## E. Chapter 5 Supplemental Information

**Complete expert elicitation protocol**

# Expert elicitation on direct current in buildings

## Elicitation Protocol

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**Introduction**

Recent research on DC microgrids in buildings has largely concluded that these systems have the potential to generate modest energy and cost savings in residential and commercial buildings by centralizing and reducing the number of power converters serving building loads and implementing efficient DC-internal end uses.

Supported by these findings, researchers, manufacturers, and industry groups are now turning their attention to demonstration projects and the development of products and standards so as to capitalize on what is seen as a new market for energy-efficient devices and services. But investment in DC technologies may be premature. Widespread adoption of DC microgrids will depend on a number of factors, only a fraction of which have been captured by the technical engineering and economic analyses conducted thus far.

Expert elicitation is a tool intended for instances where analytical methods are unable to address some factors relevant to the research questions at hand. This makes the method well-suited to analyzing the trajectories of developing technologies, where ongoing research and development efforts are critical to future deployment. These elicitations typically aim to define subjective probability distributions of certain key parameters, often related to system costs, which can be used to compare the technology to alternatives.

The goal of this elicitation is to identify and describe the nontechnical aspects of a wider adoption of DC microgrids in residential and commercial buildings in the US. Many such barriers and opportunities have been identified in previous studies, but not analyzed in detail. Others will likely be identified as a result of this work. By better understanding these issues, our results will serve primarily to direct further research to issues identified as critical to a transition to DC in buildings.

**Notes on expert elicitation**

Attached you will find a series of worksheets intended to elicit your expert judgments on a variety of topics regarding a transition to direct current circuits and end uses in the buildings sector. The topics to be addressed come largely from the existing literature where they are mainly mentioned briefly, but not discussed in detail.

Participants are asked to draw upon their expertise and judgment when answering the questions as individual experts. In other words, we are not asking you to represent the organization you are affiliated with. Each participant will be assigned a number that will be used in place of names when we report results for each expert.

**Notes on heuristics and bias**

Expert elicitation is an inherently subjective method for gathering information. The questions that you will be asked to answer do not have right or wrong answers. Instead, they will require you to reflect on your experience and expertise to provide us with an answer that you think best reflects reality. Research shows that as you answer these questions, you will be unconsciously relying on cognitive heuristics that could lead to biased results. Two of the most common heuristics are the availability heuristic and the anchoring and adjustment heuristic.

The availability heuristic describes how people assess probabilities and frequencies by how easily they can recall a similar instance. For example, if it rained last night you might provide a biased estimate to the question "What is the probability it will be raining at this time next week?"

The anchoring and adjustment heuristic describes how people will often respond to an estimation task by thinking of a single value and adjusting their estimates up and down from that *anchor*. In doing so, they typically do not adjust sufficiently from their single value estimate.

Finally, as a result of these heuristics and a number of other factors, both laypeople and experts are prone to overconfidence in estimation tasks. The following questions are designed to minimize the effects that these heuristics have on results. But we also ask you to consider these effects as you respond to the exercises in this workbook.

**Calibration Exercise**

| | Minimum | Maximum |
|---|---|---|
| 1. Commercial buildings account for roughly what percentage of US electricity consumption? | | |
| 2. What is roughly the average age of all office buildings in the US? | | |
| 3. What is the average square footage of all office buildings in the US? | | |

**Potential Applications**

Through research and existing installations, DC distribution circuits have been implemented or proposed for data centers, homes, commercial interiors, exterior lighting, electric vehicle charging, and HVAC applications, among others.

Here we will investigate the suitability of DC circuits to serve each of these applications.

Below is a list of applications where DC circuits are either already in use or have been proposed as a means of supplying power to end uses.

In the second column, rank the three applications which you think are most likely to adopt DC circuits in the future (with the application listed first being the one you believe most likely to adopt DC).

| Application | Rank |
|---|---|
| Data centers | |
| Commercial buildings – hybrid AC and DC circuits | |
| Commercial buildings – DC circuits only | |
| Homes – hybrid AC and DC circuits | |
| Homes – DC circuits only | |
| Electric vehicle charging | |
| Developing world microgrids for locations that currently have no electricity | |
| Other (please list): | |
| Other (please list): | |

**Key Characteristics of DC Circuits**

In this section we will explore the characteristics of DC circuits that promote and impede their more widespread adoption.

**Positive Characteristics**

Below is a list of positive characteristics that have been ascribed to DC circuits. Next to each characteristic is a short description of the expected benefit.

In the third column, rank the three characteristics which you think make the strongest case for more widespread use of DC circuits <u>in residential and commercial buildings</u>.

| Positive Characteristics | Description | Rank |
|---|---|---|
| Improved reliability | DC power delivery systems reduce the number of power conversions required to serve DC-internal end uses. Reducing the number of conversions and the waste heat they generate could potentially improve the reliability of devices that rely on these conversions. | |
| Energy savings – reduced power conversion losses | Electronic loads are the fastest growing load segment in modern buildings. Energy savings are generated by DC distribution systems both directly by eliminating inefficient conversions serving these loads and indirectly by the reduced heat load from eliminating those conversions. Solar PV, small wind turbines, and fuel cells all inherently generate DC power. DC distribution systems eliminate conversion losses between generated DC and the distribution network. | |
| Energy savings – more efficient end uses | Nearly all residential and small commercial appliances can be made more efficient by switching to DC-compatible technologies. | |
| Increased space flexibility | The low-voltage DC distribution system promoted by the EMerge Alliance allows spaces to be repurposed and reconfigured safely without requiring an electrician. In data centers, reductions in power conversions significantly reduce the floor space occupied by power supply equipment. | |
| Capital cost savings | Due to simplified power supplies, DC distribution systems and loads have the potential to reduce upfront capital costs. | |
| PV array cost savings | When connected to a DC distribution system, the inverters that convert generated DC to AC can be replaced with simpler, less expensive DC-DC converter. This can reduce the capital cost of a complete PV system by 7-20%. | |
| Reduced copper use | In higher-voltage DC systems, smaller conductors can be used. This reduces the amount of copper required and can improve the overall environmental footprint of the system. | |
| Enables more efficient energy storage | Batteries connected to a DC distribution network avoid conversion losses both in charging and discharging cycles. These circuits are also simplified as there is no phase-matching required to connect to the grid. | |
| Enables vehicle-to-grid storage architectures | DC distribution systems simplify and increase the efficiency of connecting plug-in electric vehicles (PEVs) to the grid. Further, DC microgrids incorporating PEVs as storage can serve as distributed grid storage. | |
| Reduces device costs as a result of less power electronics | Reducing the power electronics required in appliances has the potential to reduce the cost of these devices. | |

| | | |
|---|---|---|
| Reduces electronic waste as a result of less power electronics | Reducing the power electronics required in appliances has the potential to reduce the electronic waste associated with these devices. | |
| Reduces electronics shipping weight as a result of less power electronics | Reducing the power electronics required in appliances has the potential to reduce the shipping weight of these devices. | |
| Improved power quality | The nature of power quality concerns are different in DC systems than in AC systems [107]. While it is not clear which type of system is preferable, some research claims that DC circuits and the associated solid state power electronics improve power quality. | |
| Other (please list): | Please describe: | |
| Other (please list): | Please describe: | |
| | | |

Please explain briefly why you chose the three characteristics above.

**Characteristic you ranked #1:** ________________________________________________

________________________________________________________________

________________________________________________________________

________________________________________________________________

**Characteristic you ranked #2:** ________________________________________________

________________________________________________________________

________________________________________________________________

________________________________________________________________

**Characteristic you ranked #3:** ________________________________________________

________________________________________________________________

________________________________________________________________

________________________________________________________________

**Negative Characteristics**

Below is a list of negative characteristics that have been ascribed to DC circuits. Next to each characteristic is a short description.

In the third column, rank the three characteristics which you think pose the greatest challenge to more widespread use of DC circuits in residential and commercial buildings.

| Negative Characteristics | Description | Rank |
|---|---|---|
| Fire risk | DC power does not pass through 0V like an AC current. This makes breaking a DC circuit more difficult than an AC circuit. Without appropriate arc quenching circuit breakers, DC circuits may pose increased fire hazard over AC circuits. | |
| Electric shock and electrocution risk | There is no unanimous opinion as to whether AC or DC current is more dangerous physiologically. Some argue that DC poses more risk, as a direct current shock could cause muscles in the forearms and hands to clench shut and lock the victim to the exposed conductor. | |
| Reduced reliability | The power electronics and end-use appliance technologies proposed as replacements for our current AC devices are not currently manufactured at large scale. At the scale needed for widespread deployment, these would essentially be new products for many manufacturers and could suffer the same reliability problems as new devices. | |
| Negative public perceptions of DC | A lack of familiarity may cause concern among the public about the safety, reliability, and cost of DC circuits and devices. | |
| Engineers, electricians, building inspectors, regulators, and others unfamiliar with DC | These parties have had little interaction with DC circuits in any application. Simply overcoming this lack of information and experience to design, build, certify, and regulate these circuits will pose a challenge. | |
| Uncertain utility interaction | There is no clear model for how a utility interacts with a DC building or microgrid. Potential problems arise around ratemaking, feed-in tariffs, and ownership roles. | |
| Power quality concerns | Ongoing research is looking into the effects that DC distribution systems would have on harmonic currents, inrush currents, fault currents, and grounding. | |
| Regulatory barriers | The National Electric Code does not distinguish between AC and DC for circuits carrying less than 600 volts. While this means DC systems technically fall under the existing code, the lack of distinction and specific reference to DC could be cause for concern. | |
| Lack of universally accepted standards | The 24 VDC standard being promoted by the Emerge Alliance is the most advanced effort to establish a voltage standard for DC circuits in occupied spaces. However, this has not yet been formally adopted by government or other bodies such as the National Institute of Science and Technology (NIST), the American National Standards Institute (ANSI), the National Electrical Manufacturers Association (NEMA), or others. | |
| Diversification of buildings and appliances | Adoption of DC circuits in buildings will mean devices and services cannot be universally exchanged between buildings without specifying the circuit type. | |
| Small markets for DC devices and system components | While nearly all devices and components can be made to operate on DC, device manufacturers might not be interested in servicing what will initially be a small market of early adopters. Prices for these components and devices are currently much higher than for equivalent AC devices as | |

| | | |
|---|---|---|
| | a result of this lack of economies of scale. | |
| Other (please list): | Please describe below. | |
| Other (please list): | Please describe below. | |

Please explain briefly why you chose the three characteristics above.

**Characteristic you ranked #1:** ____________________________________________

____________________________________________

____________________________________________

____________________________________________

**Characteristic you ranked #2:** ____________________________________________

____________________________________________

____________________________________________

____________________________________________

**Characteristic you ranked #3:** ____________________________________________

____________________________________________

____________________________________________

____________________________________________

**Reference Building Description**

The next few exercises are going to focus on the potential use of DC circuits in a hypothetical commercial building to be constructed in the near future. In order to frame these questions, we describe below a commercial building for you to consider as you answer the questions posed in the following sections.

| | |
|---|---|
| Principal building activity | The building's occupants offer professional services, with most workers seated at desks working on computers. Approximately 50% of floor space is dedicated to cubicles, 10% to conference rooms, and 10% to private offices. The remaining area is a mix of restrooms, public areas, mechanical rooms, and a small data center serving the building's occupants. |
| Construction | This is to be a rectangular, standalone building. Exterior walls are brick veneer with concrete masonry backup and a flat roof. |
| Occupants and occupancy | The building will be occupied by roughly 160 people. The office's work hours are 8am to 5pm, but the building will be open from around 6am to 7pm Monday through Saturday. |
| Location | The building is to be located in an office park in Pittsburgh, PA. |
| Size | The building has four floors with a combined area of 68,000 square feet. |
| Interior equipment | Interior equipment is typical of a professional office. Each occupant has a computer workstation with a laptop and standalone monitor. Overhead lighting is throughout the building. Kitchen areas throughout the building are outfitted with microwaves and refrigerators. Conference rooms have overhead projectors. Natural gas fired water heaters provide domestic hot water. |
| Space conditioning | Central cooling is provided by a chiller plant which distributes chilled water to rooftop units through insulated piping. Rooftop units are natural gas fired. |
| Expected utility bills | Similarly sized office buildings in the region have an average annual electricity bill of around $150,000/yr and a natural gas bill of around $15,000 per year. |

**System Costs**

The costs of implementing DC distribution are going to play an important role in determining whether these systems are adopted. In this section we will explore some of the key costs associated with a transition to DC circuits in buildings.

**Question 1. Electrical system cost – all DC system.** The total overnight capital cost to provide electrical service to a building similar to the one described is around \$3.66 per square foot of floor area (around \$250k total) for traditional AC, 1000 amp service, panel boards, and feeder lines. What range of costs, in \$/sqft, would you expect to outfit this building with equivalent DC circuits to supply all interior loads? Include a lower and upper bound and best estimate.

If you are certain that the equivalent DC circuits would cost exactly the same, your estimate would be \$3.66/sqft for the best estimate, lower and upper bound.

| \$__________/sqft. | \$__________/sqft. | \$__________/sqft. |
|---|---|---|
| Estimated cost (lower bound) | Estimated cost (most likely) | Estimated cost (upper bound) |

**Question 2. Electrical system cost – hybrid AC and DC system.** The total overnight capital cost to provide electrical service to a building similar to the one described is around \$3.66 per square foot of floor area (around \$250k total) for traditional AC, 1000 amp service, panel boards, and feeder lines. What range of costs, in \$/sqft, would you expect to outfit this building with equivalent DC circuits to supply only lighting and computer workstations? Assume the remainder of the building's loads are wired with traditional AC circuits. Include a lower and upper bound.

| \$__________/sqft. | \$__________/sqft. | \$__________/sqft. |
|---|---|---|
| Estimated cost (lower bound) | Estimated cost (most likely) | Estimated cost (upper bound) |

**Question 3. Lighting cost – DC lighting array.** The total overnight capital cost to provide high efficiency fluorescent lighting and branch wiring for switches and plugs in a building similar to the one described is around \$11.73 per square foot of floor area (around \$800k total). What range of costs, in \$/sqft, would you expect to outfit this building with equivalent lighting via DC-powered LEDs? Include a lower and upper bound.

| \$__________/sqft. | \$__________/sqft. | \$__________/sqft. |
|---|---|---|
| Estimated cost (lower bound) | Estimated cost (most likely) | Estimated cost (upper bound) |

**Question 4. Future electrical system cost – all DC system.** All costs discussed up to this point have focused on current prices, which are based on current market demand. If DC systems become more widely adopted, these prices might change.

Under a business-as-usual case, with no major intervention, what do you estimate the cost to provide all-DC service will be in 10 years?

Remember, the total overnight capital cost to provide electrical service to a building similar to the one described is around $3.66 per square foot of floor area (around $250k total) for traditional AC, 1000 amp service, panel boards, and feeder lines. What range of costs, in $/sqft, would you expect to outfit this building with equivalent DC circuits to supply all interior loads in 2027? Include a lower and upper bound and best estimate.

Provide your estimate in current dollars. So if you are certain that the equivalent DC circuits would cost exactly the same as AC circuits cost now, your estimate would be $3.66/sqft for the best estimate, lower and upper bound.

| $__________/sqft. | $__________/sqft. | $__________/sqft. |
|---|---|---|
| Estimated cost (lower bound) | Estimated cost (most likely) | Estimated cost (upper bound) |

**Voltage, Metering, and System Design Standards**

Voltage standards and system design standards are needed before DC circuits and microgrids can be widely deployed. In this section we will explore these proposed standards and their potential for future deployment.

**Question 1. Voltage standards and system architecture.** A number of voltage levels have been proposed for serving the various loads in commercial buildings. Much of the attention in this space has focused on the voltage levels of circuits to serve small loads such as computers and lighting arrays. Some of the voltage levels mentioned in the literature to serve these types of loads are 12 VDC, 24VDC, 48 VDC, and 120VDC. For larger loads, voltage levels of 380 VDC, 400 VDC and 500 VDC have all been cited in analyses of DC circuits in data centers.

For each voltage level (low, medium, and high) please write down the voltage level and current form you think <u>will most likely be adopted</u> in the commercial sector in the left box. In the right box, describe the types of loads and applications you think this voltage level will serve in commercial buildings.

Examples of loads / applications: Computers, miscellaneous plug loads, efficient lighting arrays, kitchen appliances, data center, HVAC equipment, PV distribution, battery storage, uninterruptible power supply, etc.

Note that DC buildings will likely have multiple voltage levels to serve different loads and applications, much as today's commercial buildings might have 120VAC, 277VAC, and 480VAC service. If you believe DC buildings will only utilize two voltage levels, you only need to fill out two voltage levels below.

| | |
|---|---|
| Low voltage level (list one or more) | Types of loads / applications |
| _______VDC / VAC | |
| Medium voltage level (list one or more) | Types of loads / applications |
| _______ VDC / VAC | |
| High voltage level (list one or more) | Types of loads / applications |
| _______ VDC / VAC | |

Please explain briefly why you chose the standard(s) above.

**Low voltage level:** ___________________________________________________________________

___________________________________________________________________________

___________________________________________________________________________

___________________________________________________________________________

**Medium voltage level:** ______________________________________________________________

___________________________________________________________________________

___________________________________________________________________________

___________________________________________________________________________

**High voltage level:** ________________________________________________________________

___________________________________________________________________________

___________________________________________________________________________

___________________________________________________________________________

**Question 2. Voltage standards and system architecture.** Above we asked you to describe the current forms and voltages of the system that is <u>most likely to be adopted</u>. You may see benefits of another system architecture, such as a higher or lower voltage level than current standards appear to be converging towards. Do you see any issues with the system described above, and if so, what changes would you make? Describe the system that <u>should be adopted</u>.

Please explain.

___________________________________________________________________________

___________________________________________________________________________

___________________________________________________________________________

___________________________________________________________________________

**Long-Term Viability**

Several trends in electric end uses, power electronics, and renewables have been cited by researchers as arguments against the long-term suitability of DC circuits to serve commercial and residential buildings. Here we will investigate some of these trends and explore their expected effects on the future of DC-powered buildings.

**Question 1. Diminishing energy savings.** One of the most commonly cited benefits of DC circuits and microgrids is their ability to generate energy savings by reducing the number of AC-DC and DC-AC power conversions required to serve loads. However, as these power electronic conversions become more efficient the energy savings generated by eliminating these conversions will diminish over time. How does this affect the outlook of DC circuits in the future?

- ☐ This will change the outlook of these systems.
- ☐ This could change the outlook of these systems.
- ☐ This will not change the outlook of these systems.
- ☐ I am unsure.

Please explain your stance.

______________________________________________________________________

______________________________________________________________________

______________________________________________________________________

______________________________________________________________________

**Question 2. Magnetic materials.** Central in many analyses of DC circuits in buildings is an assumption that efficient DC appliances will be adopted. Many such appliances replace traditional induction motors with permanent magnet motors. Beginning in 2011, due to a combination of increased demand and Chinese production quotas, magnetic material prices increased rapidly for several years. Broad adoption of permanent magnet-based appliances could create another increase in demand. If prices of these magnetic materials increased by 20%, how would this affect the outlook of DC circuits in the future?

- ☐ This will change the outlook of these systems.
- ☐ This could change the outlook of these systems.
- ☐ This will not change the outlook of these systems.
- ☐ I am unsure.

Please explain your stance.

______________________________________________________________________

______________________________________________________________________

______________________________________________________________________

______________________________________________________________________

**Question 3. Disruptive technologies.** Are there any technologies that could potentially change – positively or negatively – the trajectory of DC power distribution, DC microgrids, or DC appliances in buildings?

**Research Priorities**

What do you see as the most pressing research priority to increase adoption of DC circuits in buildings?

**Demographic survey**

Below we will collect some basic demographic information from all experts. This information will be used to frame our findings and highlight the experience of our experts.

| | |
|---|---|
| Year you first worked in your current – or other relevant – industry | |
| Highest level of education | |
| Degree(s) | |

| | How many years of experience do you have in each of the following fields? | In which field is your current position? |
|---|---|---|
| Auditing, financial, accounting | | |
| Government relations, marketing, PR | | |
| Human resources, legal | | |
| Technical services, operations, R&D | | |
| Management, project management | | |
| Supply chain logistics | | |
| Utilities | | |
| Other (please list) | | |