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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

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

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Abstract

Advances in semiconductor-based power electronics and growing direct current loads in buildings have lead 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 10-21% when solar PV is distributed to all home appliances. When battery storage for excess solar energy is considered, these savings increase to 13-23%. 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 7-17% 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.

1 Introduction

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 [1]-[19]. The resulting research has led to the recent adoption of DC distribution systems in data centers and commercial lighting installations, among others [20][21]. 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 [12]. 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 [22] and 21% of all greenhouse gas emissions, 71% of which are a result of electricity use in homes [23]. Making up approximately 35% of all home energy consumption are appliances, electronics, and lighting, which can all operate on DC [13][24]. 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 [25][26]. 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 [2][4]. Building on these findings Thomas, Azevedo, and Morgan [14] 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 [20].

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 [13], 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 [15][17][19]. 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 [7] and the Emerge Alliance [27]. 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 [12]. Most recently, under a Department of Energy (DOE) initiative investigating DC power in residential and small commercial markets, Garbesi et al. [13] catalogued and characterized a range of existing and future appliances that are compatible with DC power. In a follow-up study [16], 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 study takes the final recommendation of the DOE report and models DC residential systems using a unique dataset with 15-minute interval data measured at the home-, circuit-, and appliance level in single-family homes in Austin, Texas. The use of actual monitored data allows us to accurately quantify the effect of highly variable energy consumption and solar generation patterns on DC-powered residences. The importance of this effect was highlighted in [16], which identified the use of simulated data as a limiting factor in that work. In addition to estimating the energy effects of direct-DC PV systems in the sampled homes, we provide a 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.

2 Material and Methods

2.1 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. 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 approximately 693 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. Gantt charts show the availability of data for each home in the sample across this timeline, as well as the number of circuits monitored per home. One of these charts is shown in Appendix A.

Average electricity consumption for households in Pecan Street's sample is approximately 85% of the local utility's average residential customer [29]. These households are therefore likely to provide a reasonable approximation of household electricity consumption around Austin, but not generally to Texas (as we show in Appendix B, where we compare Pecan Street households to typical Texas households using the Residential Energy Consumption Survey).

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 1 we provide information on the number of houses for which we have different levels of information. From the original 693 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 as explained in Appendix C.

Table 1. Data validation criteria for final simulations.

Validation criteria	Qty. of homes
Total homes in dataset	693
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

2.2 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 [24]. Table 2 summarizes these allocations.

Table 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 [30].

The annual energy consumption of each appliance class was calculated for the sample homes. The same allocation was applied to the most recent RECS data and was plotted for comparison in Figure 1. The data generally show similar proportions of energy use for the major appliance classes. In Appendix D we show these proportions normalized to annual energy consumption in each home. In Appendix E we show other information relevant to understand the sample data. These include survey and energy audit participation, and intervention records for every home in the study.

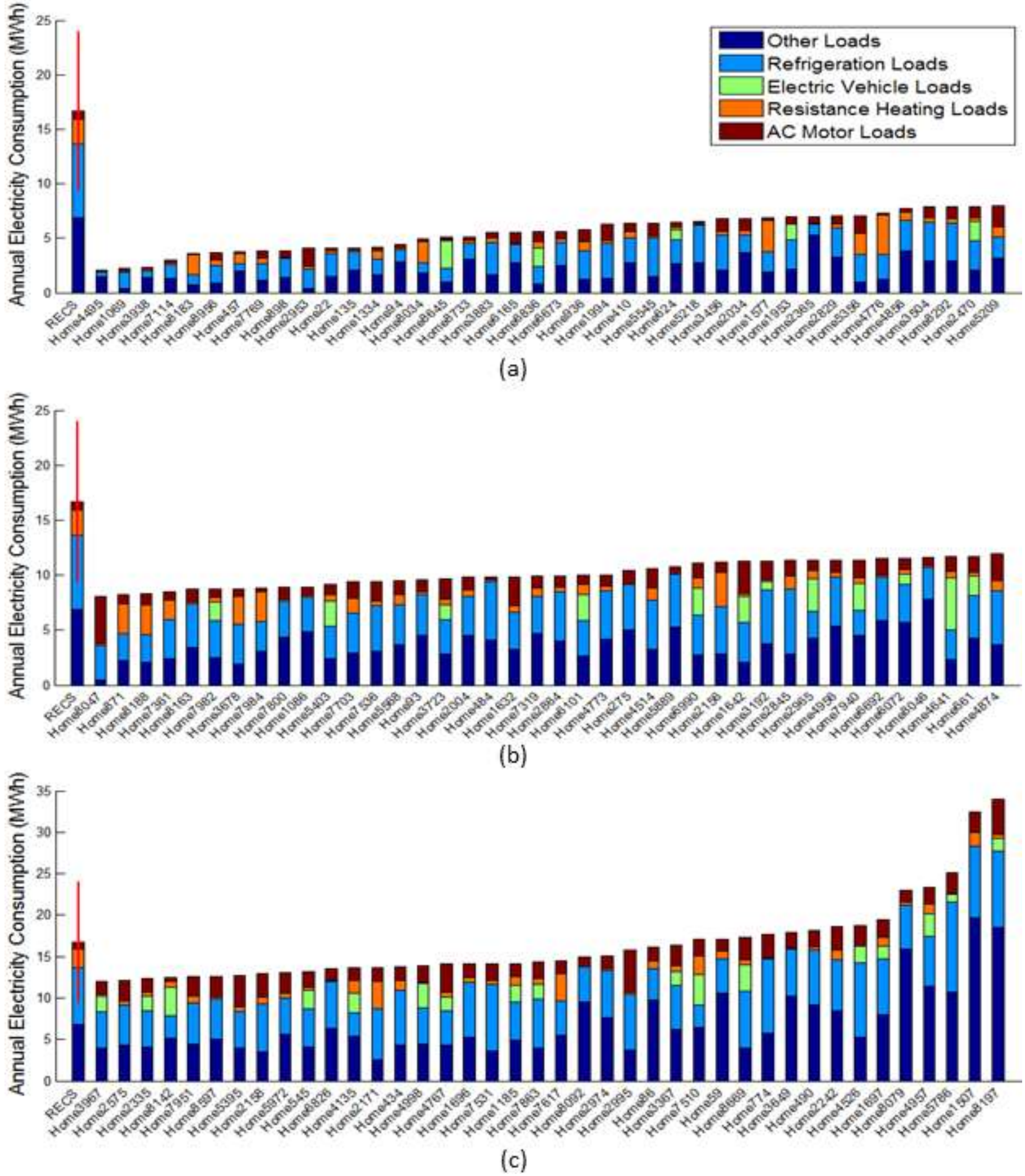

Figure 1. Annual energy consumption by appliance class. The first bar in each figure shows the mean electricity consumption by appliance class reported in RECS for single family homes in Texas with central air. Error bars show plus or minus one standard deviation from this mean. (a)-(c) show energy use breakdowns by appliance class for Pecan Street homes included in final simulations ordered by annual energy consumption and separated to show one third of total homes in each graph. Data: Pecan Street [28], RECS [24], and [30]

2.3 DC Compatible Appliances

Every major appliance in a modern home could be replaced by a more efficient device that can operate on DC [15]. 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 [15]. Garbesi at al. catalogued the manufacturers of many of these devices in [15]. 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 [10]. 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 [15]. 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 [31][32]. 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. EV chargers operate internally on DC, 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.

2.4 DC Home Configurations

For homes in our sample, we perform simulations for the scenarios shown in Table 3. Figure 2 shows schematic diagrams of these configurations.

Table 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 2(a) shows a home with no solar array and traditional AC circuits. Figure 2(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 2(c) is similar to that analyzed by Vossos et al. in [16]. 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 [16][29]. 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 2.3.

The remaining systems shown in Figure 2 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. Storage is not perfect, however, and both charging and discharging have associated efficiencies listed in Table 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 [33]. 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.

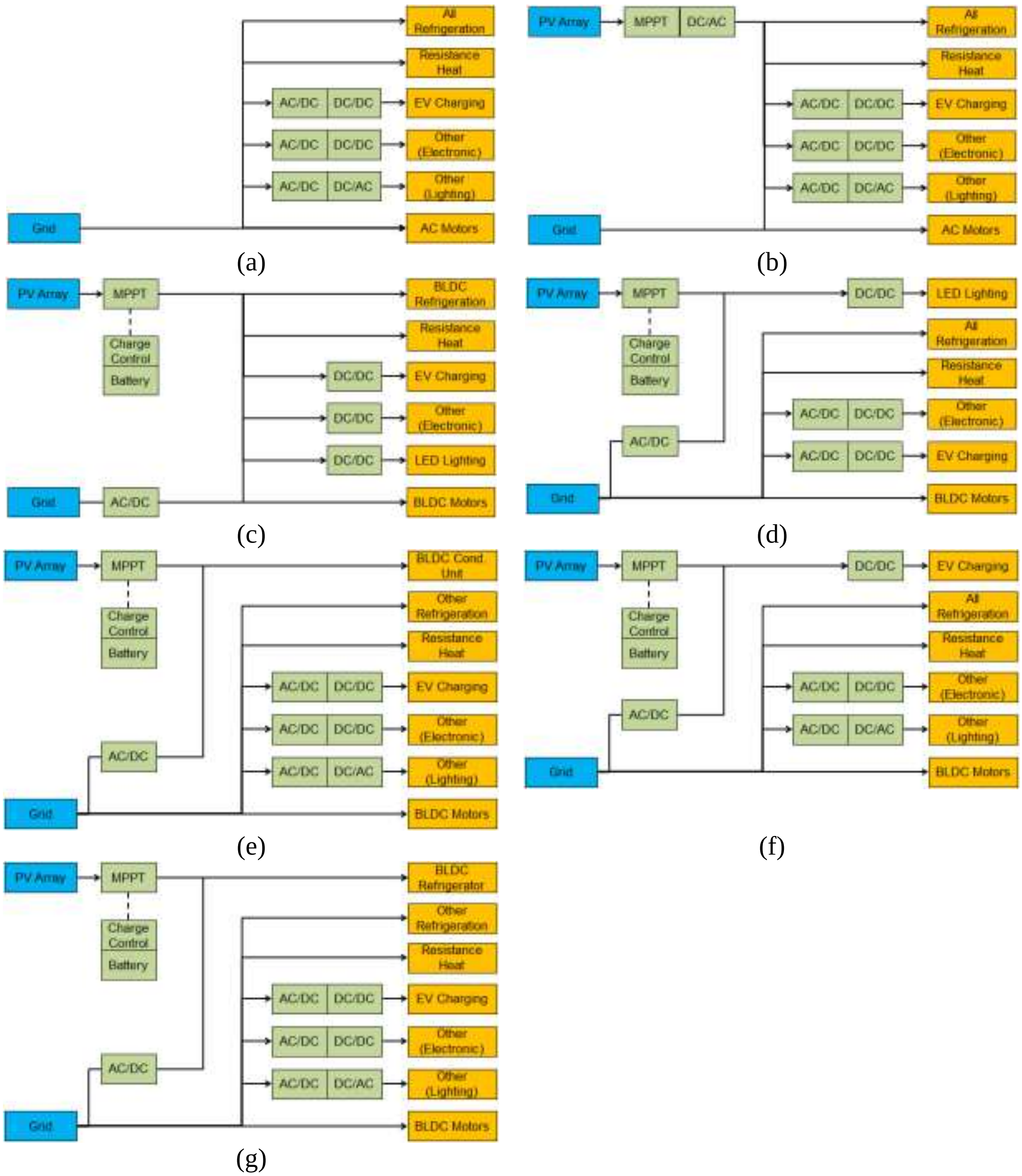

Figure 2. Schematic diagrams of simulated home configurations: (a) traditional home with AC distribution, without PV (b) traditional home with AC distribution and net-metered solar PV (c) home with DC distribution to all loads and net-metered PV with grid-rectified backup (d) home with DC distribution 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.

2.5 *Modeling Operations*

Each of the ten scenarios depicted in Figure 2(c) through Figure 2(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. 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 2(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.

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

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

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 [43]. 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. Details of these billing rates, solar crediting rates, and solar PV rebates can be found in Appendix F. 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. 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. Parameters and ranges used in Monte Carlo simulations.

	Min	Max	Unit	Source
Engineering Parameters				
Existing or New Inverter Efficiency	0.87	0.94		[4]
Existing or New Rectifier Efficiency	0.93	0.97		[5]
DC-DC Converter Efficiency	0.80	0.90		[14]
Battery Charge Efficiency	0.95	0.95		[35]
Battery Discharge Efficiency	0.95	0.95		[35]
Pecan Street Condenser Efficiency	7.6	13.5	EER	[28]
DC Condenser Efficiency	16	22	EER	[31]
BLDC Motor Efficiency Gain	0.05	0.15		[15]
CFL to LED Efficiency Gain	0.07	0.28		[36]
Circuit Breakers per Home	20	20		
Battery Storage Capacity	2	2	hours	[37]
Battery Minimum Charge	0.2	0.2		[16]
Economic Parameters				
PV Module Cost	750	910	$/kW-AC installed	[38]
PV Balance of System Cost	3,440	4,200	$/kW-AC installed	[38]
Inverter Cost	250	310	$/kW-AC installed	[38]
Rectifier Cost	250	310	$/kW-AC installed	
Bidirectional Inverter Cost	500	620	$/kW-AC installed	
AC Condensing Unit Cost	700	1,200	$/kW-AC installed	[39]
AC Supply Fan Cost	1,800	4,300	$/kW-AC installed	[39]
AC Refrigerator Cost	900	2,200	$/unit	[39]
AC Circuit Breaker Cost	40	50	$/unit	[40]
DC Condensing Unit Cost	2,400	2,400	$/kW-DC installed	[41]
DC Supply Fan Cost	3,400	4,700	$/kW-DC installed	[39]
DC Refrigerator Cost	1,700	2,700	$/unit	[44]
DC Circuit Breaker Cost	130	150	$/unit	[40]
Battery Cost	130	310	$/kWh storage	[40]
Discount Rate	0.05	0.10		
Austin Energy Parameters				
Austin Energy Solar Rebate	2,990	2,990	$/kW-AC installed	[29]
Electric Rate (see Appendix F)	Varies	Varies	$/kWh consumed	[29]
Solar Credit Rate	0.107	0.107	$/kWh generated	[29]
Lifetime Parameters				
PV Panel Lifetime	20	20	Years	[42]
Balance of System Lifetime	20	20	Years	
Inverter Lifetime	10	10	Years	[14]
Rectifier Lifetime	10	10	Years	
Bidirectional Inverter Lifetime	10	10	Years	
Battery Lifetime	10	10	Years	[14]
AC Appliance Lifetime	10	10	Years	
DC Appliance Lifetime	10	10	Years	
Circuit Breaker Life	20	20	Years	[14]
Simulation Parameter				
Number of runs	1,000	1,000		
Environmental Parameter				
ERCOT grid emission factor	1,218	1,218	$lbCO_2/MWh$	[45]

2.6 <u>Modeling Assumptions</u>

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.

3 Results

3.1 <u>Direct-DC Energy Savings</u>

Figure 3 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 10-21% (mean ±1 standard deviation) and increase to 13-23% with storage.

The majority of these savings are attributed to DC condensing units, which alone generate around 12% mean savings that increase to around 13% 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.

For results shown in terms of annual kWh saved per home, see Figure 9 in Appendix G. These show median savings of around 1,500 kWh/yr and 1,700 kWh/yr for whole-home DC simulations without and with storage, respectively. As in Figure 3, 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.

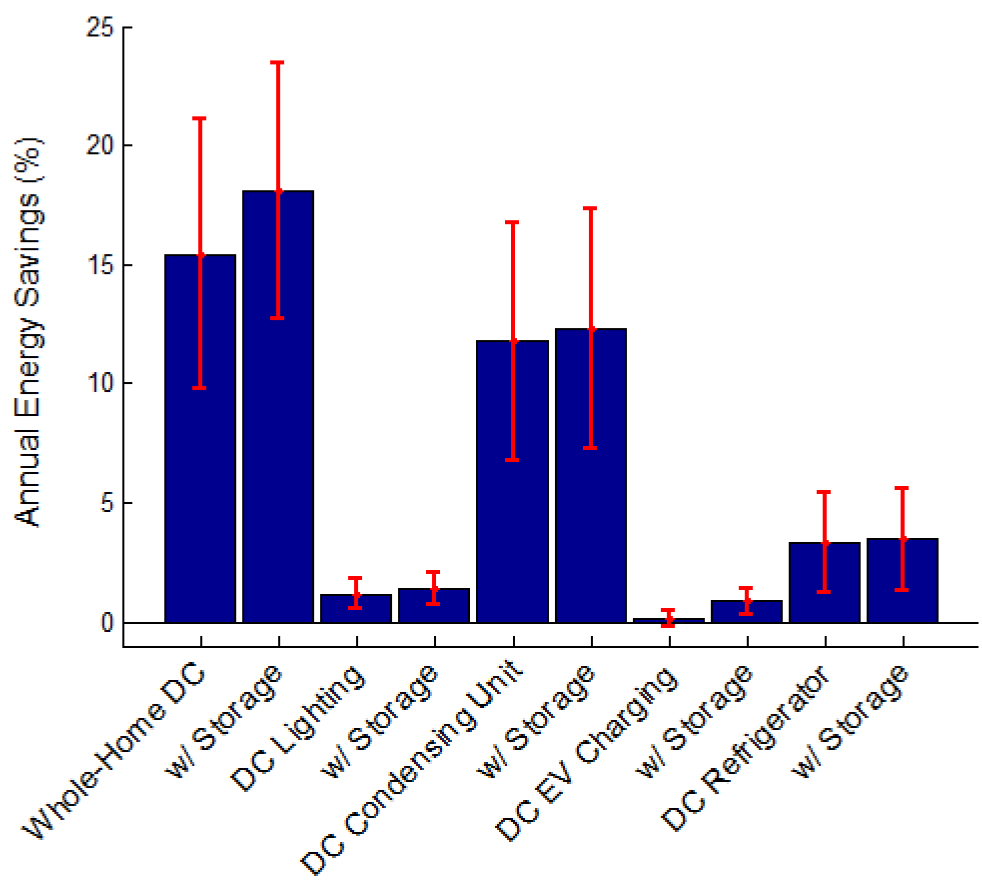

Figure 3. Annual energy savings for simulated direct-DC systems. Savings are reported as a percentage of baseline energy consumption of traditional AC homes. Simulation results correspond to the systems shown in Figure 2(c) through Figure 2(g). Error bars show plus or minus one standard deviation from the mean.

3.2 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 existing equipment prices. Using the energy savings results presented in Section 3.1, 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.

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 [40]. Of these components, only the cost of breakers is significant – on the order of $1,000 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 retail prices from existing vendors as shown in Table 4 [31][39][44]. 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 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%. For results shown without installation incentives applied, see Figure 10 in Appendix G.

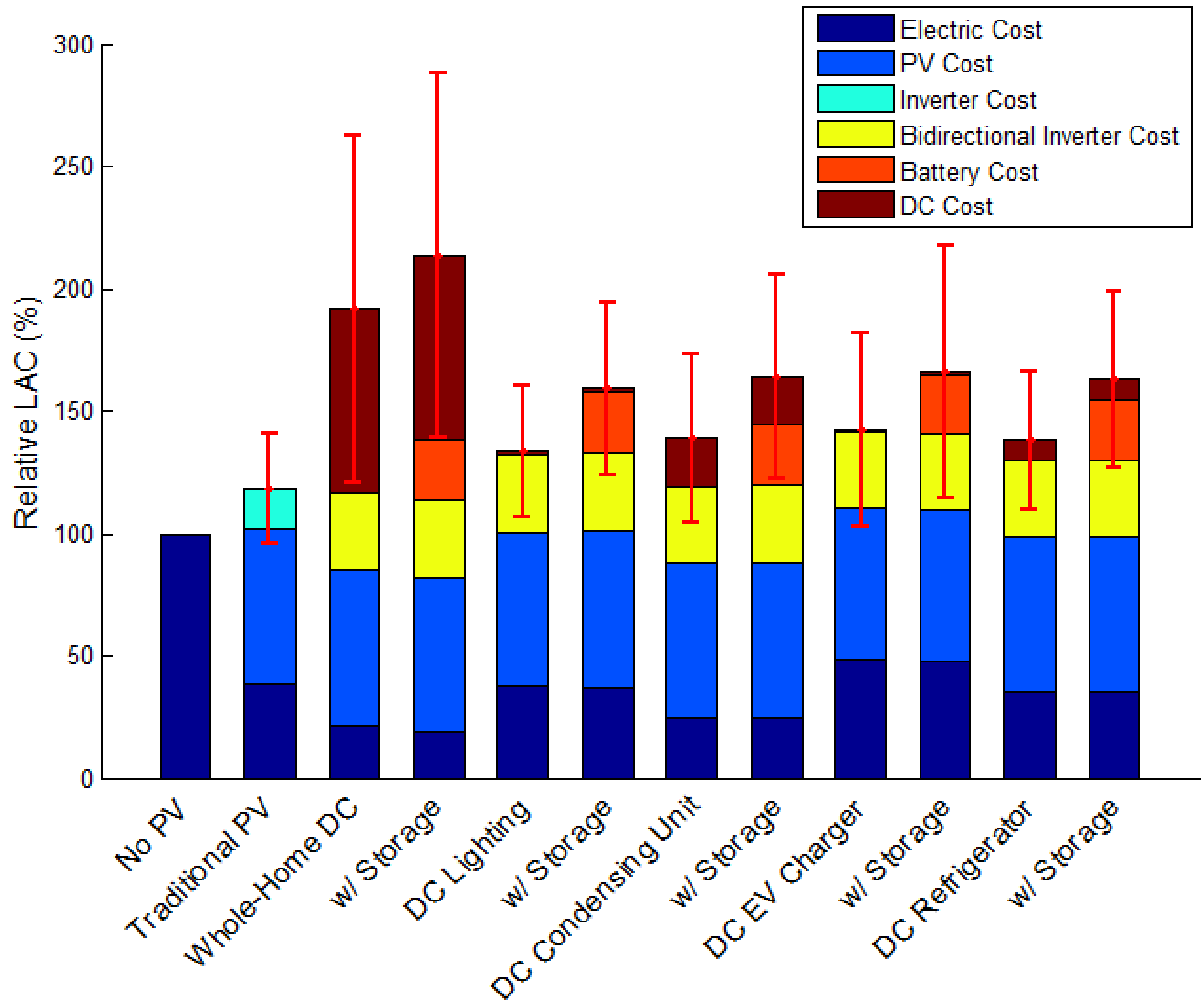

Figure 4. Levelized annual costs for the systems shown in Figure 2(a) through Figure 2(g). Results are shown as a percentage of a traditional (AC) home with no PV generation's annual electric bill. Discount rate was varied from 5-10%. Bars show the mean result for each simulation. Error bars show plus 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 $300) 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 5-73% without storage and 22-105% 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 11-68% without storage.

Cost Effectiveness of Savings: The overall cost effectiveness of each direct-DC configuration is plotted in Figure 5. 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. 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.

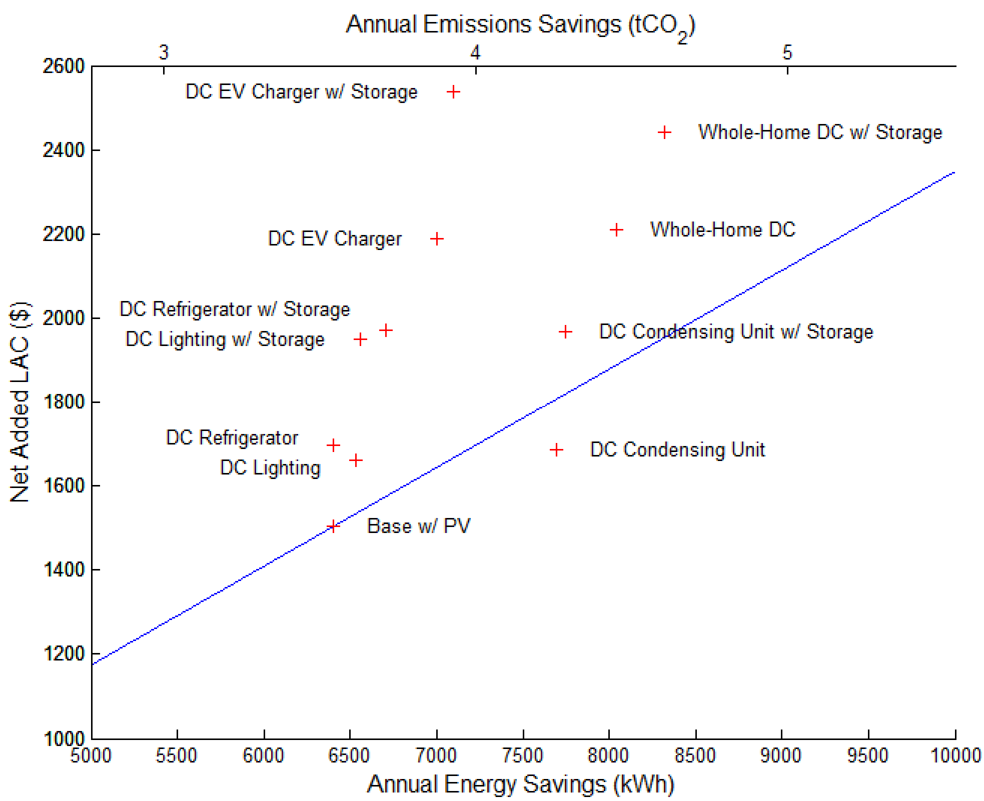

Figure 5. Average cost-effectiveness of savings associated with each simulated DC home configuration. Average annual energy and emissions savings are shown on the x-axes. The net cost added to a traditional AC home's LAC by implementing each scenario is shown on the y- axis. This cost includes the cost 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. 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. See Appendix G for details.

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. Results showing the cost-effectiveness of each scenario in terms of \$/kWh saved and \$/tCO_2 saved can be found in Appendix G Table 5.

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 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 7-17% while adding 18-78% 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. 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.

5 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 [12]. 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 [29]. 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 [29]. 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.

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