

1    **How much electricity can we save by using direct current circuits in homes?**  
2    **Understanding the potential for electricity savings and assessing feasibility of**  
3            **a transition towards DC powered buildings**

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26 **Abstract**

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

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

36 Results show site energy savings between 10-21% when solar PV is distributed to all home  
37 appliances. When battery storage for excess solar energy is considered, these savings increase to  
38 13-23%. At present DC equipment prices, converting all equipment to DC causes levelized  
39 annual costs of electricity to homeowners to roughly double. However, by converting only  
40 homes' air conditioning condensing units to DC, the costs of direct-DC are greatly reduced and  
41 home site energy savings of 7-17% are generated.

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

52

## 53 **1 Introduction**

54 Direct current power distribution systems and microgrids have become the topic of substantial  
55 research due to their potential to reduce power conversion losses, improve power quality,  
56 increase system reliability, reduce system costs, and facilitate a transition to inherently more  
57 efficient DC-based devices in buildings [1]-[19]. The resulting research has led to the recent  
58 adoption of DC distribution systems in data centers and commercial lighting installations, among  
59 others [20][21]. As these systems have been proven in niche applications, a discussion has  
60 emerged as to whether more buildings should be wired with DC circuits in addition to – or in  
61 place of – AC. Around 50% of the energy presently used in buildings is either consumed as DC  
62 in electronic loads or passes through a transient DC state as a means of motor control, resulting  
63 in significant losses when grid distributed AC is rectified using inefficient, distributed power  
64 supplies [12]. When a source of DC generated electricity such as a solar PV array is available,  
65 dedicated DC circuits reduce the usual losses that occur both in the inversion from generated DC  
66 to grid AC, as well as the rectification back to DC at the end load.

67 The residential sector is seen as a potential candidate for a transition to DC. Residential buildings  
68 currently account for about 22% of all energy consumption in the US [22] and 21% of all  
69 greenhouse gas emissions, 71% of which are a result of electricity use in homes [23]. Making up  
70 approximately 35% of all home energy consumption are appliances, electronics, and lighting,  
71 which can all operate on DC [13][24]. Lastly, sharply declining module costs, the federal solar  
72 investment tax credit, utility net energy metering programs, and renewable portfolio standards  
73 have together resulted in consistent growth in residential PV installations that is not expected to  
74 slow [25][26]. Together these factors have made home DC microgrids the topic of substantial  
75 research which has detailed several aspects of these systems.

76 Earlier studies looked at this opportunity in the commercial sector and found that the reduction  
77 of power conversions associated with DC circuits had the potential to reduce conversion losses,  
78 reduce lifecycle PV system costs, and improve the reliability of power electronic-dependent  
79 systems [2][4]. Building on these findings Thomas, Azevedo, and Morgan [14] analyzed direct-  
80 DC LED lighting in a modeled 48,000 ft<sup>2</sup> office building. Analyzing several configurations of  
81 AC and DC lighting circuits, the authors estimate that DC lighting circuits could reduce capital  
82 costs by 4-21% and levelized annual costs by 2-21% compared to an equivalent grid-connected

83 AC photovoltaic LED system. Indeed, such systems with centralized AC-to-DC conversion are  
84 now being installed in commercial applications by companies such as Redwood Systems [20].

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

88 Feasibility of DC in homes is now well established as presented in [13], which concluded that all  
89 major home appliances and end uses were compatible with direct current. Technical analyses of  
90 DC circuits in homes cover a range of issues including voltage levels, system architectures, and  
91 potential applications [15][17][19]. A broad consensus on a future DC system voltage has yet to  
92 be reached, but proposed levels have been presented by Lawrence Berkeley National Laboratory  
93 [7] and the Emerge Alliance [27]. Lastly, a number of studies have now estimated the potential  
94 energy savings associated with DC systems in homes. A study by Savage et al. looked at  
95 centralizing the conversion from grid AC to DC from distributed “wall warts” to a central home-  
96 level rectifier. This study estimated 25% energy savings across the US residential sector [12].

97 Most recently, under a Department of Energy (DOE) initiative investigating DC power in  
98 residential and small commercial markets, Garbesi et al. [13] catalogued and characterized a  
99 range of existing and future appliances that are compatible with DC power. In a follow-up study  
100 [16], the same group estimated the energy savings associated with a direct-DC home with PV  
101 using simulated home loads and solar generation profiles in 14 cities across the US. This study  
102 estimated a 5% electric savings in direct-DC homes without storage for generated solar energy  
103 and 14% savings with storage. In the summary report filed for that initiative, the authors identify  
104 four areas for continuing research in direct-DC power systems: developing direct-DC products,  
105 developing standards and test procedures, building demonstration projects, and improving  
106 techniques for modeling energy savings.

107 This study takes the final recommendation of the DOE report and models DC residential systems  
108 using a unique dataset with 15-minute interval data measured at the home-, circuit-, and  
109 appliance level in single-family homes in Austin, Texas. The use of actual monitored data allows  
110 us to accurately quantify the effect of highly variable energy consumption and solar generation  
111 patterns on DC-powered residences. The importance of this effect was highlighted in [16], which  
112 identified the use of simulated data as a limiting factor in that work. In addition to estimating the

113 energy effects of direct-DC PV systems in the sampled homes, we provide a first in-depth  
114 analysis of the economic feasibility of such systems using levelized annual cost of electricity to  
115 the customer and the cost-effectiveness for avoided CO<sub>2</sub> emissions. The method established for  
116 this analysis uses Monte Carlo simulation to account for uncertainty in the engineering,  
117 economic, and other inputs to the model. Additionally, we investigate utility billing and incentive  
118 programs, appliance and component markets, and building codes to determine their effects on  
119 increased use of DC power in the residential sector.

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

## 123 **2 Material and Methods**

### 124 *2.1 Appliance-Level Energy Use Data*

125 Appliance-level and home-level energy consumption data, as well as solar PV generation data  
126 used in the analysis were obtained from Pecan Street Research Institute's Dataport. Pecan Street  
127 Inc. is a 501(c)(3) not-for-profit corporation and research institute headquartered at The  
128 University of Texas at Austin. Volunteer homeowners in and around Austin elect to join the  
129 study and work with Pecan Street to decide which circuits and appliances to monitor. The  
130 resulting dataset includes records for approximately 693 homes, with data available for up to 28  
131 circuits per home at one-minute intervals. The first homes in this sample begin reporting data in  
132 January 2012, and installations are ongoing. Gantt charts show the availability of data for each  
133 home in the sample across this timeline, as well as the number of circuits monitored per home.  
134 One of these charts is shown in Appendix A.

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

140 For final whole-home simulations in our analysis, we select homes which had total electricity use  
141 and at least air conditioner condensing unit use, central air supply fan use, and refrigerator use

142 monitored for over one year with less than one week of missing data. In Table 1 we provide  
 143 information on the number of houses for which we have different levels of information. From the  
 144 original 693 homes, 279 have over one year of whole-home use data. Of these only 120 had  
 145 monitored the appliances listed above. Of these remaining 120 homes, 40 had data for an electric  
 146 vehicle charger and 45 had data for a solar PV array. For houses without PV, we use a proxy  
 147 monitored PV generation profile as explained in Appendix C.

148 **Table 1. Data validation criteria for final simulations.**

Validation criteria	Qty. of homes
Total homes in dataset	693
Homes with $\geq 1$ year of whole-home use monitored	279 <sup>a</sup>
+ Whole-home, AC condensing unit, central air supply fan, and refrigerator use monitored	120 <sup>a</sup>
+ Electric vehicle charger monitored	40 <sup>a</sup>

<sup>a</sup> Counts include only datasets with less than one week of data missing

149 **2.2 *Appliance Class Allocations***

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

154 Each appliance class in an individual home can include monitored data from 0, 1, or multiple  
 155 appliances depending on the home’s specific monitoring configuration. The difference between  
 156 the sum of monitored loads in each home and the home’s total metered use was assigned to  
 157 ‘Other Loads’ which we attribute to electronics, lighting, kitchen appliances, and plug loads.  
 158 These devices were not consistently monitored but are known to contribute substantially to total  
 159 home load [24]. Table 2 summarizes these allocations.

160 **Table 2. Appliance class allocation.**

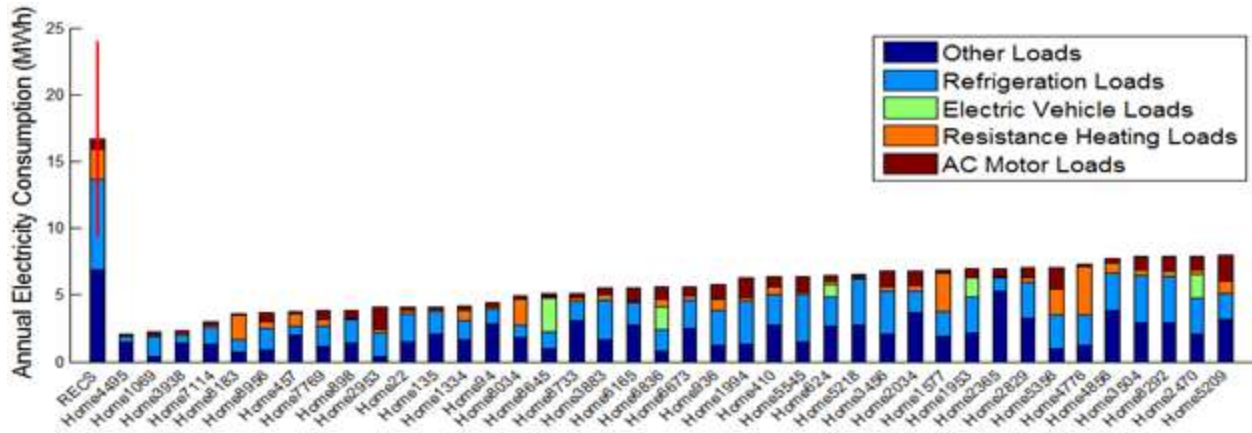
Refrigeration Loads	AC Motor Loads	Electric Vehicle Loads	Resistance Heating Loads	Other Loads
HVAC condensing unit, freezer, refrigerator, wine cooler	Kitchen disposal, clothes washer, central air supply fan, gas clothes dryer, vent hood fan	Electric vehicle charging	Oven, range, electric clothes dryer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

<sup>a</sup> 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.

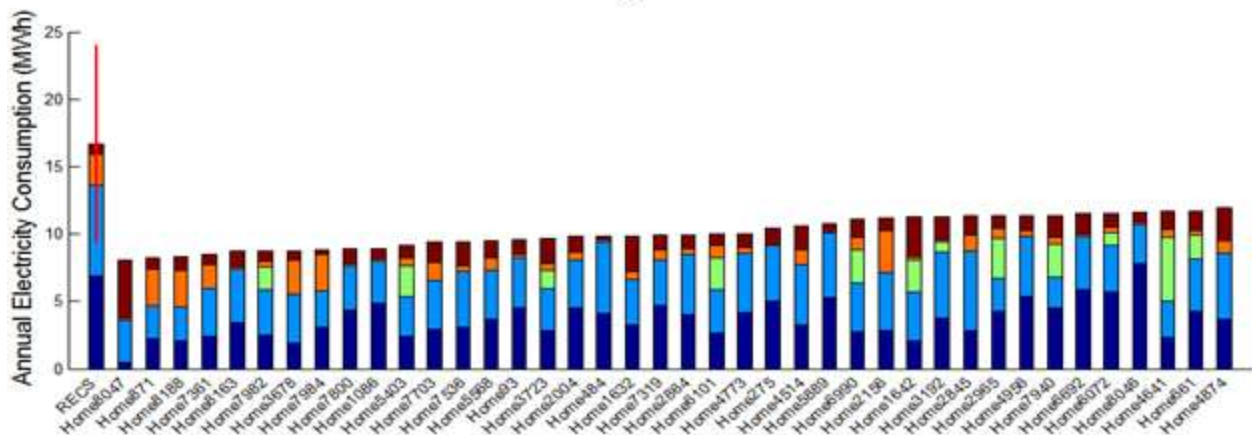
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<sup>b</sup> Dishwasher energy consumption is similarly comprised of resistance heating and AC motor load. We assign 30% of total energy consumption to AC Motor Loads and 70% to Resistance Heating based on [30].

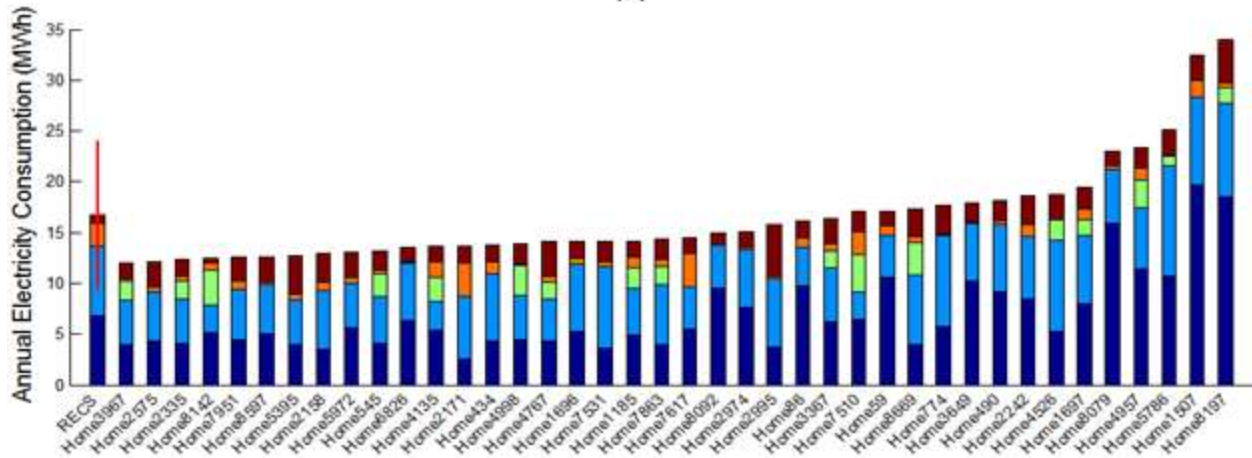
161 The annual energy consumption of each appliance class was calculated for the sample homes.  
162 The same allocation was applied to the most recent RECS data and was plotted for comparison in  
163 Figure 1. The data generally show similar proportions of energy use for the major appliance  
164 classes.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



(a)



(b)



(c)

168

169  
170  
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174

**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]**



### 175 2.3 DC Compatible Appliances

176 Every major appliance in a modern home could be replaced by a more efficient device that can  
177 operate on DC [15]. Most of these devices are currently intended for off-grid applications, where  
178 high equivalent electricity prices incentivize high efficiencies. While prices for such equipment  
179 are now prohibitively expensive for widespread residential use, their fundamental designs and  
180 capacities are suitable for the residential sector [15]. Garbesi et al. catalogued the manufacturers  
181 of many of these devices in [15]. For example, the motors currently found in home appliances  
182 are primarily a mix of AC induction motors for larger loads and universal motors for smaller  
183 loads [10]. Brushless DC permanent magnet (BLDC) motors are inherently more efficient than  
184 both types of motors, with savings estimated at 5-15% for constant speed applications [15]. In  
185 variable speed configurations, BLDC motors operate even more efficiently and generate  
186 substantial savings when compared to AC motors.

187 In air conditioner condensing unit applications, existing variable speed refrigerant compressors  
188 driven by BLDC motors achieve cooling efficiencies nearly twice the minimum requirement for  
189 Energy Star certification [31][32]. By comparing the energy efficiency ratios (EERs) of these  
190 units to those recorded in Pecan Street's energy audit records, we establish an efficiency  
191 improvement for converting a traditional condensing unit to a BLDC equivalent. Because the  
192 same vapor-compression cycle is used in refrigerators, freezers, and wine coolers, we apply the  
193 same efficiency improvement to the entire refrigeration load appliance class.

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

197 Of the 120 homes included in our final simulations, 40 have plug-in electric vehicles (PEVs)  
198 with home chargers. EV chargers operate internally on DC, requiring rectification of the existing  
199 AC supply and a subsequent DC-DC voltage transformation. In a DC home, this power supply  
200 would be simplified to a sole DC-DC converter, eliminating rectification losses.

201 Remaining loads in the monitored data are assumed to be comprised of lighting and consumer  
202 electronics. All modern consumer electronics operate internally on DC and therefore require  
203 variants of switched-mode power supplies to generate their necessary DC voltage. Similar to EV

204 charging circuits, these consist of a rectification stage typically followed by a DC-DC voltage  
 205 transformation. A DC circuit would eliminate the losses associated with the initial rectification.  
 206 Based on Pecan Street survey results, compact fluorescent lamps (CFLs) are the most common  
 207 primary lighting technology in the sampled homes. One DC alternative is to use light emitting  
 208 diodes (LEDs), which are the chosen technology for direct-DC lighting microgrids in the  
 209 commercial sector. We use DOE lighting efficacy values to determine the efficiency  
 210 improvement associated with converting the existing homes' lighting to LED.

211 *2.4 DC Home Configurations*

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

214 **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

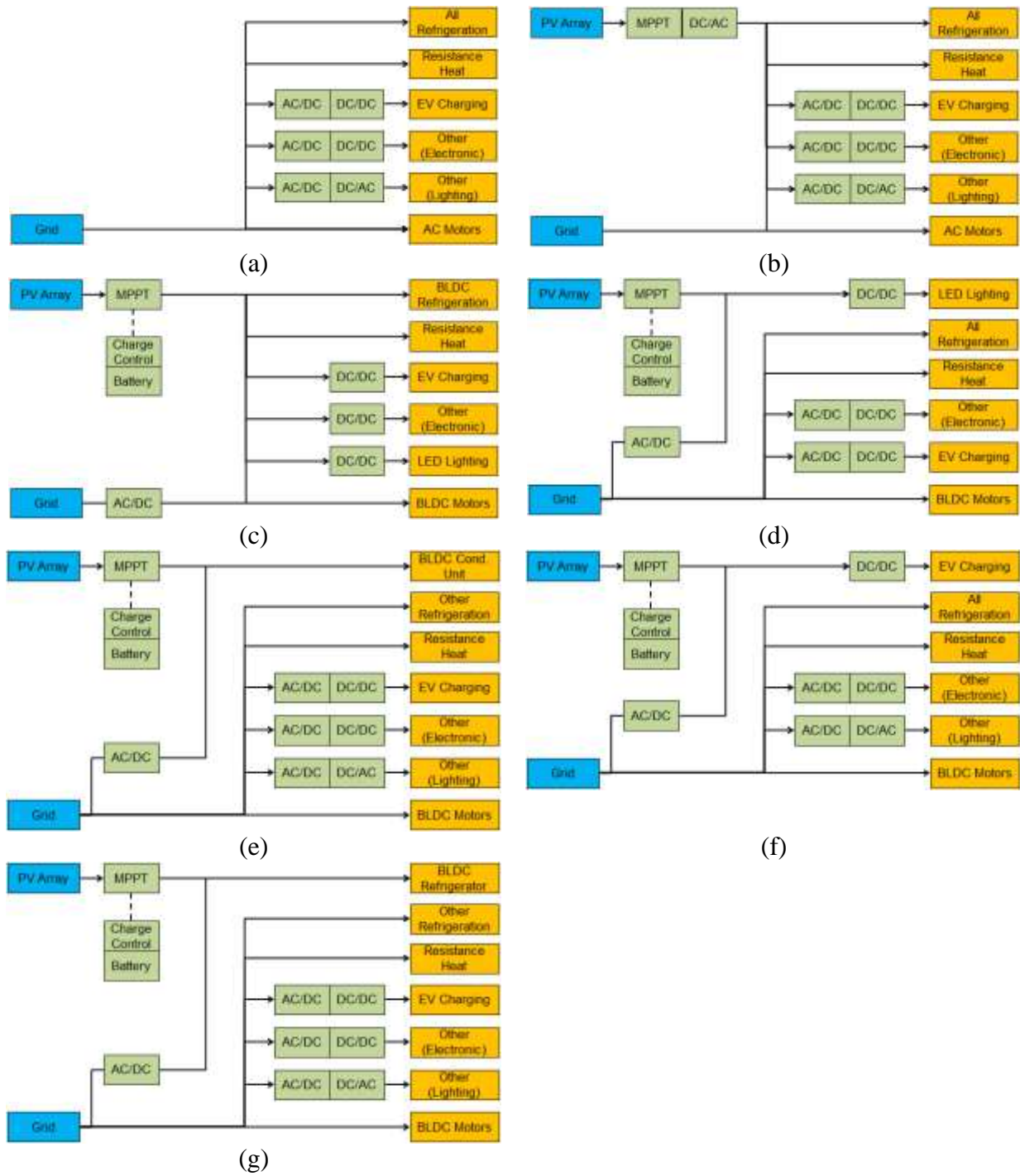
215  
 216 Figure 2(a) shows a home with no solar array and traditional AC circuits. Figure 2(b) shows a  
 217 home with a net-metered PV array connected to traditional AC circuits. All of the homes in the  
 218 sample dataset are represented by one of these two configurations. These will therefore serve as  
 219 baselines for the analysis as their exact consumption and solar generation were monitored.  
 220 The system shown in Figure 2(c) is similar to that analyzed by Vossos et al. in [16]. This  
 221 configuration features a solar PV connected DC circuit supplying all home loads with and  
 222 without battery storage (depicted by dashed line). When solar power is available, either as direct  
 223 feed-in from the array or as stored energy, savings are generated as the initial inversion from  
 224 generated DC to AC for distribution and the rectification back to DC required for electronic and  
 225 EV charging loads are eliminated. When solar power is not available or is insufficient in meeting  
 226 the home's load, grid power is rectified in a central home bi-directional inverter to meet the  
 227 balance. When solar power exceeds the home's load, this device acts as a traditional inverter and

228 allows excess power to be sold to the grid under existing net metering agreements [16][29]. In  
229 both the case of net energy exporting and purchasing, no energy or cost savings are generated on  
230 the exported or purchased energy, as this configuration is equivalent to the base PV scenario. In  
231 addition to generating savings by eliminating conversion stages, the simulations for these  
232 configurations assume the transition to more efficient DC compatible loads discussed in Section  
233 2.3.

234 The remaining systems shown in Figure 2 simulate direct-DC circuits supplying individual  
235 appliances or appliance classes. Given that the transition to DC circuits in the commercial market  
236 began with a single type of load – lighting – we simulate four appliances with substantial  
237 contributions to home energy consumption and energy savings potential to determine if a similar  
238 opportunity exists in homes. This strategy may be the most cost-effective if a large proportion of  
239 potential whole home energy savings from DC conversion can be generated by a single  
240 appliance.

241 Each of these four appliances was simulated with and without storage for each house  
242 individually. Storage allows solar power generated during the day that exceeds the instantaneous  
243 load to be stored and consumed later. This avoids the conversion losses associated with inverting  
244 the excess power to sell to the grid and rectifying grid power to meet unmet demand at night.  
245 Storage is not perfect, however, and both charging and discharging have associated efficiencies  
246 listed in Table 4.

247 Lighting data was not consistently available, as lighting and plug loads are often on common  
248 circuits. Lighting energy allocations are therefore based on the DOE’s Residential Lighting  
249 Usage Estimate Tool, a companion to a report released in 2012 [33]. By comparing the annual  
250 lighting energy consumption values in this tool to the unaccounted “Other Use” in the RECS  
251 data, we estimate 25% of “Other Use” is due to lighting.



252

253 **Figure 2. Schematic diagrams of simulated home configurations: (a) traditional home with AC distribution,**  
 254 **without PV (b) traditional home with AC distribution and net-metered solar PV (c) home with DC**  
 255 **distribution to all loads and net-metered PV with grid-rectified backup (d) home with DC distribution to a**  
 256 **lighting circuit and net-metered PV with grid-rectified backup (e) home with DC distribution to a condensing**  
 257 **unit and net-metered PV with grid-rectified backup (f) home with DC distribution to a PEV charger and net-**  
 258 **metered PV with grid-rectified backup (g) home with DC distribution to a refrigerator and net-metered PV**  
 259 **with grid-rectified backup.**

260 *2.5 Modeling Operations*

261 Each of the ten scenarios depicted in Figure 2(c) through Figure 2(g) (five scenarios with and  
 262 without storage) simulates 1,000 iterations of every home in the final sample. Each simulation  
 263 selects a unique combination of the parameters listed in Table 4. These 1,000 combinations of  
 264 parameters are then applied to each home in the simulation. This results in 1,000 annual energy  
 265 consumption profiles, bills, and levelized annual costs (LACs) for each home. Each simulated  
 266 scenario uses all (120) homes with complete data, except for EV simulations. Only (40) homes in  
 267 the sample had monitored data available for electric vehicles, so the simulations depicted in  
 268 Figure 2(f) use this smaller sample of homes. Note all simulations are applied to 15-minute  
 269 interval profiles for the most recent year of data available for each home, resulting in 35,040  
 270 readings for 1 year.

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

$$273 \quad NewDCLoad_{j,t} = \frac{MonitoredLoad_j \cdot \eta_{existing,powersupply} \cdot \eta_{existing,enduse}}{\eta_{new,powersupply} \cdot \eta_{new,enduse}} \quad (1)$$

$$t = 1, \dots, 35,040$$

274 Each home's available DC solar generation profile is calculated as eliminating the losses  
 275 associated with an inverter.

$$276 \quad NewPV_t = \frac{MonitoredGeneration}{\eta_{existing,inverter}} \quad (2)$$

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

$$283 \quad MetbyPV_t = \min(NewPV, \sum NewDCLoads) \quad (3)$$

$$284 \quad GridRectified_t = \frac{(\sum NewDCLoads) - MetbyPV}{\eta_{new,rectifier}} \quad (4)$$

285 
$$NewHomeLoad_t = MetbyPV + GridRectified \quad (5)$$

286 With annual electric consumption calculated, LAC is used to evaluate the economic feasibility of  
 287 each proposed scenario. Only new home applications are considered, as an AC-to-DC retrofit  
 288 would have a large capital cost – on the order of \$6,000 to \$10,000 – that would not soon be  
 289 recovered by even the largest energy cost savings realized here [43]. LAC takes into account  
 290 varying lifetimes of system components as well as the time value of money. Capital costs for  
 291 each major system component  $k$  include equipment and installation costs, as well as applicable  
 292 Austin Energy rebates. Electric costs and solar energy credits are calculated using Austin  
 293 Energy’s tiered rate structure for residential customers. Details of these billing rates, solar  
 294 crediting rates, and solar PV rebates can be found in Appendix F. CRF, the capital recovery  
 295 factor, is used to annualize a capital expenditure over the lifetime of  $n$  equipment capital  
 296 investments with discount rate  $i$ .

297 
$$LAC_l = NetAnnualElectricCost_l + \sum_{m=1}^n [AddedCapitalCost_m \times CRF_m] \quad (6)$$

298 
$$CRF_m = \frac{i}{1 - (1+i)^{-lifetime_l}} \quad (7)$$

299 To account for the uncertainty in prices and efficiencies of the proposed systems, ranges of  
 300 possible values were established for all uncertain engineering and economic parameters, shown  
 301 in Table 4. Monte Carlo simulations draw from uniform distributions between these ranges to  
 302 calculate energy savings, electric cost savings, and LACs. Uniform distributions were used as  
 303 data for better defining distributions was not readily available. Similarly, correlation between  
 304 variables (e.g. between component efficiencies, lifetimes, and costs) is not considered here for  
 305 the same reason.

306

**Table 4. Parameters and ranges used in Monte Carlo simulations.**

	Min	Max	Unit	Source
<b>Engineering Parameters</b>				
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]
<b>Economic Parameters</b>				
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		
<b>Austin Energy Parameters</b>				
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]
<b>Lifetime Parameters</b>				
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]
<b>Simulation Parameter</b>				
Number of runs	1,000	1,000		
<b>Environmental Parameter</b>				
ERCOT grid emission factor	1,218	1,218	lbCO <sub>2</sub> /MWh	[45]

310 *2.6 Modeling Assumptions*

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

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

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

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

333 **3 Results**

334 *3.1 Direct-DC Energy Savings*

335 Figure 3 shows the resulting site electricity savings of the ten simulated scenarios as a percentage  
336 of each home’s baseline consumption. Average savings in whole-home DC simulations are  
337 between 10-21% (mean  $\pm$ 1 standard deviation) and increase to 13-23% with storage.

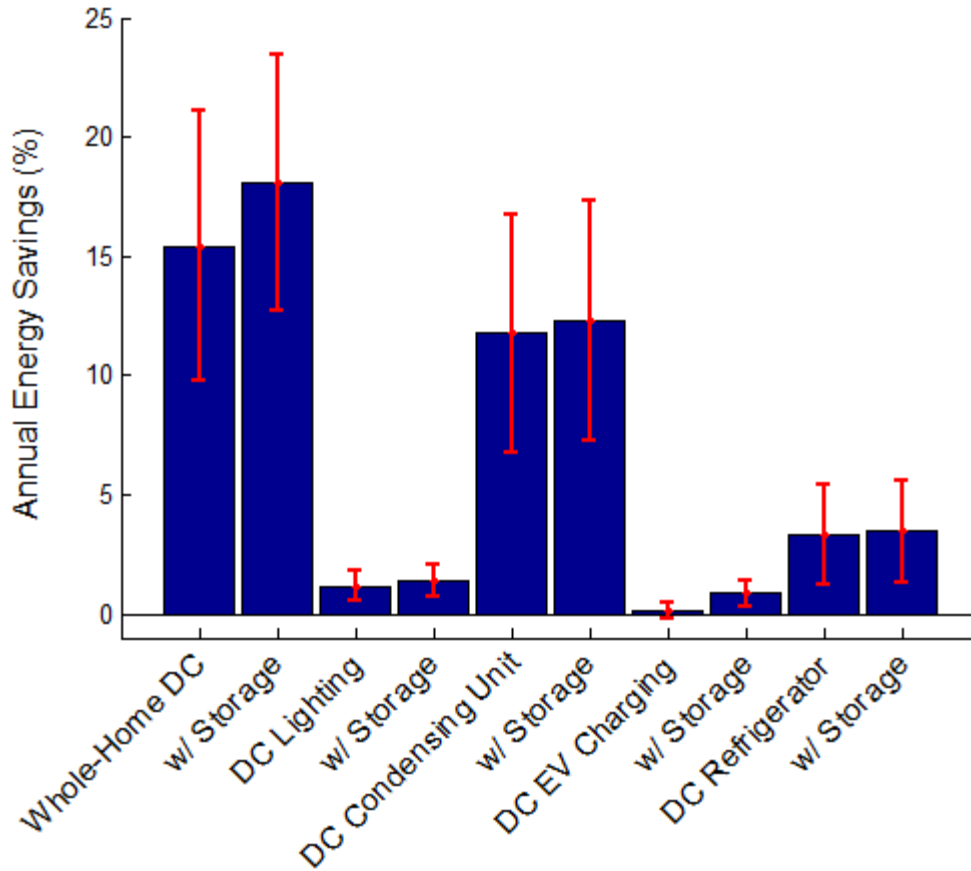


338 The majority of these savings are attributed to DC condensing units, which alone generate  
339 around 12% mean savings that increase to around 13% with storage. These savings are a result of  
340 the large fraction of home energy consumption that these devices contribute, the efficiency gains  
341 associated with BLDC units, and load profiles that align well with solar output.

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

347 The relatively flat load profiles, substantial energy consumption, and the same efficiency  
348 improvements seen in air conditioning condensing units result in whole-home savings of around  
349 1-6% when refrigerators are converted to DC.

350 For results shown in terms of annual kWh saved per home, see Figure 9 in Appendix G. These  
351 show median savings of around 1,500 kWh/yr and 1,700 kWh/yr for whole-home DC  
352 simulations without and with storage, respectively. As in Figure 3, the majority of these savings  
353 come from air conditioning condensing units, which alone generate median savings of around  
354 1,100 kWh/yr and 1,200 kWh/yr without and with storage, respectively.



355  
 356 **Figure 3. Annual energy savings for simulated direct-DC systems. Savings are reported as a percentage of**  
 357 **baseline energy consumption of traditional AC homes. Simulation results correspond to the systems shown in**  
 358 **Figure 2(c) through Figure 2(g). Error bars show plus or minus one standard deviation from the mean.**

359  
 360 *3.2 Direct-DC Energy Cost Savings – Present DC Equipment Market*

361 In this section we consider the monetary costs and benefits associated with outfitting a new home  
 362 with DC circuits, appliances, and devices at existing equipment prices. Using the energy savings  
 363 results presented in Section 3.1, we calculate new electricity bills and annual solar credits for  
 364 every home and every simulation using Austin Energy’s billing and solar crediting rate  
 365 structures.

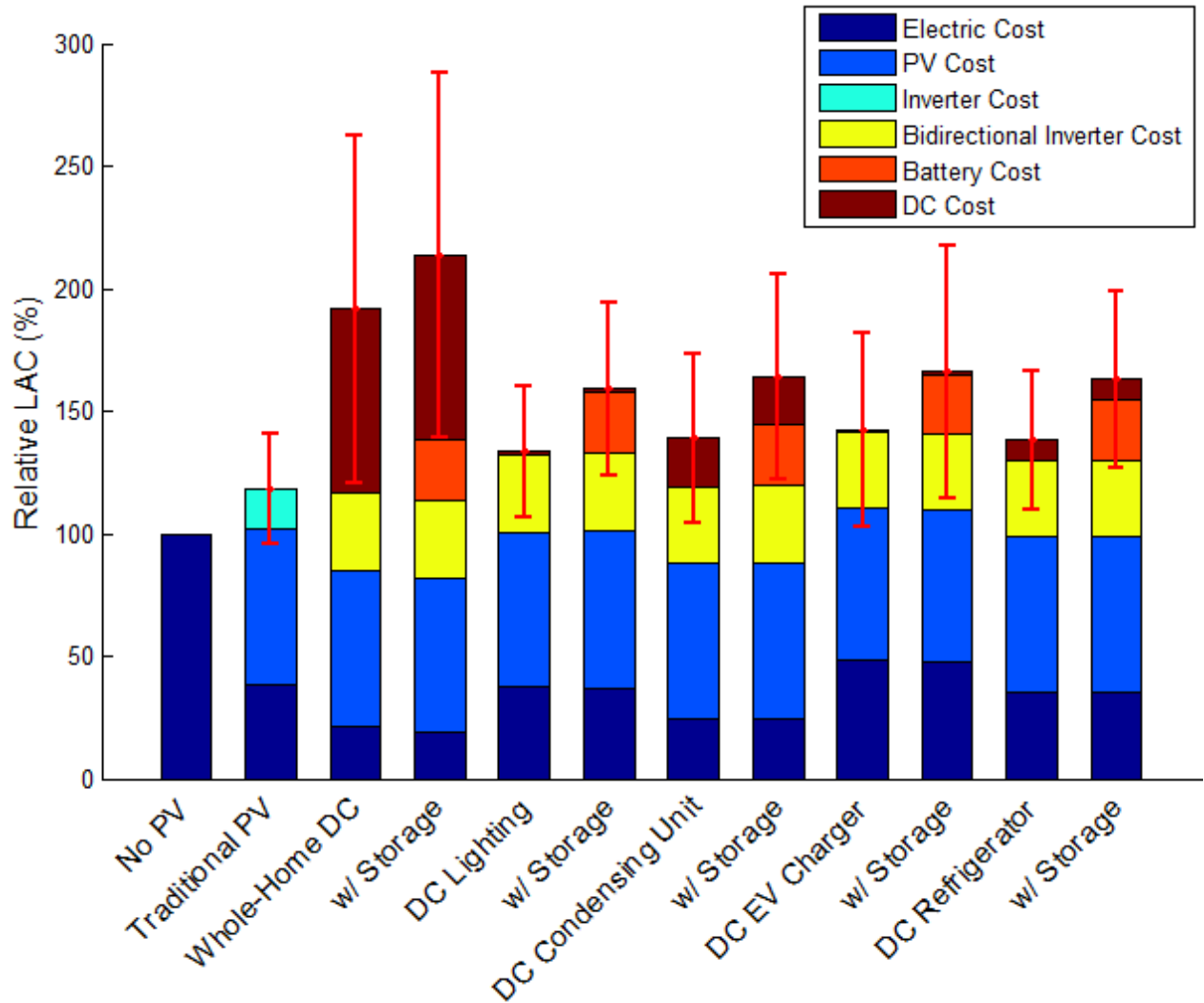
366 Assuming a 120VDC standard means the installation and physical wiring in a DC home would  
 367 be nearly identical to that in a traditional 120VAC home, incurring no extra wiring cost.  
 368 Traditional residential-size circuit breakers, switches, and wall outlets are readily available and  
 369 are often compatible with DC, but are rated to operate at a lower voltage [40]. Of these

370 components, only the cost of breakers is significant – on the order of \$1,000 per home – so we  
371 account for only this added component cost in each home.

372 Of the five appliance classes, plus lighting, that are considered for conversion to direct-DC, we  
373 assign an added cost to refrigerators, air conditioning condensing units, and central air supply  
374 fans. These are the largest end users in the sampled homes and would have the greatest added  
375 cost in converting to DC. In calculating these costs, we use retail prices from existing vendors as  
376 shown in Table 4 [31][39][44]. Remaining appliances and lights are assumed to have a negligible  
377 effect on the overall cost of implementing DC.

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

381 Figure 4 shows the levelized annual cost of electricity for each scenario as a percentage of each  
382 home's baseline annual energy bill (denoted as 100%). When solar PV is considered, annual  
383 electric cost decreases as a result of Austin Energy solar crediting, but there is the additional  
384 levelized annual cost of the PV array (shown here with Austin Energy installation incentives  
385 applied) and a system inverter. This results in a net increase in LAC of around 18%. For results  
386 shown without installation incentives applied, see Figure 10 in Appendix G.



387  
 388 **Figure 4. Levelized annual costs for the systems shown in Figure 2(a) through Figure 2(g). Results are shown**  
 389 **as a percentage of a traditional (AC) home with no PV generation’s annual electric bill. Discount rate was**  
 390 **varied from 5-10%. Bars show the mean result for each simulation. Error bars show plus or minus one**  
 391 **standard deviation from the mean.**

392  
 393 **Whole-Home DC:** Both whole-home DC scenarios see LAC roughly double compared to a  
 394 home without a PV array. On average, this means LAC increases from around \$1,200 per home  
 395 to over \$2,300 per home. While solar credits from PV generation and savings from converting to  
 396 DC reduce each home’s annual electric bill by around \$950 on average, the added cost of the  
 397 solar array (average LAC \$770 with applicable rebates), bidirectional inverter (average LAC  
 398 \$380), and DC appliances and components (average LAC \$900) exceed these savings. In the  
 399 whole-home case, as well as all others, the addition of battery storage results in a small reduction

400 in energy costs while adding a substantial capital cost (average LAC \$300) that is largely not  
401 recovered.

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

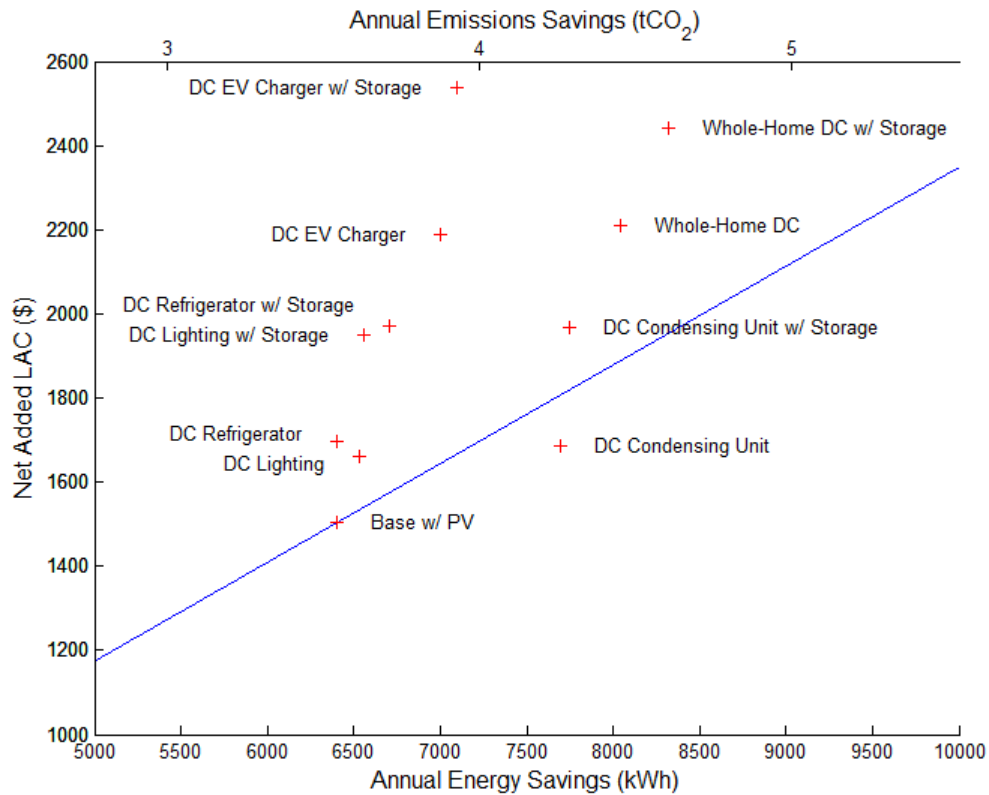
408 **DC Condensing Unit:** While DC condensing units deliver substantial energy savings, the cost of  
409 these units surpass cost savings and results in a net increase in LAC of 5-73% without storage  
410 and 22-105% with storage. Existing units are intended for rugged, off-grid, often mobile  
411 applications and have features not required for a residential installation. Thus, while the costs  
412 used here are high, they are reflective of the best currently available technology to serve a  
413 home's cooling load with variable speed BLDC motors.

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

419 **DC Refrigerator:** A conversion to direct-DC supply of a refrigerator sees energy costs decrease,  
420 but the added cost of a bidirectional inverter and DC-compatible refrigerator result in a net  
421 increase in LAC of 11-68% without storage.

422 **Cost Effectiveness of Savings:** The overall cost effectiveness of each direct-DC configuration is  
423 plotted in Figure 5. The x-axes show total annual savings in kWh and metric tons of CO<sub>2</sub>  
424 calculated using the local grid emission factor shown in Table 4. The y-axis shows the cost  
425 added to each home's LAC to implement each solution. Coordinates show the mean of all homes  
426 in each simulation. Wide ranges of energy consumption baselines and solar PV system capacities  
427 across homes in the sample result in large variances that make presenting results with confidence  
428 bounds meaningless. For reference, houses in the sample have annual CO<sub>2</sub> emissions ranging  
429 from 1.1 to 19 metric tons.

430 The mean result of solar PV installation in the sample was a net energy generation of around  
 431 6,200 kWh/yr per system that was offsetting grid generated electricity. This equates to an  
 432 emissions reduction of around 3.4 tCO<sub>2</sub> per system per year. Without installation incentives,  
 433 these systems add a levelized annual cost of around \$1,400/yr per home. We use this level of  
 434 cost-effective energy and emissions savings – observed as the slope of the line intersecting the  
 435 solar PV marker (\$0.23/kWh or \$410/tCO<sub>2</sub>) – to compare each DC simulation.



436

437 **Figure 5. Average cost-effectiveness of savings associated with each simulated DC home configuration.**  
 438 Average annual energy and emissions savings are shown on the x-axes. The net cost added to a traditional AC  
 439 home’s LAC by implementing each scenario is shown on the y- axis. This cost includes the cost of the PV  
 440 system in every configuration. The blue line shows the cost-effectiveness (in \$/kWh saved and \$/tCO<sub>2</sub> saved)  
 441 of installing a solar PV array without considering any utility incentives. All values shown are the mean of all  
 442 homes in each sample. Wide ranges of energy consumption baselines and solar PV system capacities across  
 443 homes in the sample result in large variances that make presenting results with confidence bounds  
 444 meaningless. See Appendix G for details.

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

449 distributed PV array and condensing unit. Results showing the cost-effectiveness of each  
450 scenario in terms of \$/kWh saved and \$/tCO<sub>2</sub> saved can be found in Appendix G Table 5.

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

#### 459 **4 Conclusions**

460 Results show that direct-DC distribution of solar PV power is a feasible means of generating  
461 energy and emissions savings in this sample of homes. However, at present costs only direct-DC-  
462 supplied variable speed brushless condensing units match the cost-effectiveness in achieving  
463 these savings of a traditional solar PV array. These systems were found to reduce homes'  
464 baseline energy consumption and emissions by 7-17% while adding 18-78% to each homes'  
465 baseline LAC. Note that because all simulated DC systems rely on solar PV arrays, these costs  
466 are included in LAC calculations. In none of the simulated configurations was the added cost of  
467 battery storage for excess solar PV energy justified by the energy and emissions savings it  
468 provided. Given these findings, the continued growth of distributed solar PV generation, the  
469 increasing home electronic loads seen in recent years, and industry interest in direct-DC, it is  
470 likely that a very small number of such systems in homes may soon appear.

#### 471 **5 Policy Discussion and Recommendations**

472 In light of these results, there is not a strong argument for an immediate large-scale deployment  
473 of direct-DC systems in any configuration other than DC condensing units at current component  
474 prices on the basis of reducing emissions. Given the cost-effectiveness of the savings these  
475 systems provide and the growing interest in direct-DC in homes, such systems may begin  
476 appearing in one-off system designs without universal standards in place as has been the case in

477 direct-DC commercial lighting systems. Many aspects of such an installation would be without  
478 issue, but some significant barriers remain.

479 Under the National Electrical Code AC and DC systems under 600V are not explicitly  
480 differentiated, meaning a direct-DC home would pass existing building inspections [12]. From an  
481 electric utility provider's perspective, all of the proposed system changes occur downstream of  
482 traditional meters so grid connection would likely not pose a challenge. However, Austin  
483 Energy's solar rebate program specifies that rebates and generation credits are administered  
484 based on AC capacity and AC generation [29]. It is therefore unclear whether a direct-DC PV  
485 array would be eligible for up-front equipment rebates. Also given the qualification that solar  
486 generation is credited per AC kWh, which assumes a conversion loss, any solar-generated DC  
487 power that is consumed in the home and not inverted to AC and sold to the grid would be  
488 undervalued with this program. If direct-DC systems gain more widespread adoption, utilities  
489 would have to respond to fairly credit this generation. Similarly, Austin Energy and other rebate  
490 programs for energy efficient air conditioning condensing units rely on certifications from the  
491 Air-Conditioning, Heating, and Refrigeration Institute (AHRI) for performance guarantees [29].  
492 The manufacturer of the DC condensing units used here in modeling energy performance and  
493 cost does not have this certification, and it is likely that none of the certified units operate on DC.  
494 Obtaining this certification would allow early adopters of direct-DC condensing units the same  
495 benefit available to homeowners purchasing less efficient traditional condensing units.

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

506



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