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Optimizing Energy Savings from Direct-DC in U.S. Residential Buildings

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DISCLAIMER

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Glossary of terms, acronyms, and abbreviations

AC	alternating current
BDCPM	brushless DC permanent magnet motor
EV	electric vehicle
Btu	British thermal unit
CEC	California Energy Commission
CFL	compact fluorescent lamp
DC	direct current
DC-based	technology that relies fundamentally on the use of DC power
DC-compatible	technology that can be operated on DC, though DC is not required
DC-internal	refers to appliances and equipment in which main power throughputs are converted from AC to DC internally (examples include brushless DC motors, electronic lights, and televisions)
direct-DC	the direct use of DC power from DC-generating power sources by appliances and equipment without converting to AC first
DOE	United States Department of Energy
EIA	United States Energy Information Administration
grid	The AC power grid consisting of the transmission and distribution lines that deliver power generated at centralized power plants to distributed loads and that accept excess power generated by net-metered distributed loads.
IEEE	Institute of Electrical and Electronics Engineers
inverter	a device that converts DC to AC
kW	kilowatt
LED	light-emitting diode
microgrid	A group of interconnected loads and distributed energy resources within clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid. A microgrid can connect and disconnect from the grid to enable it to operate in both grid-connected or island mode.
MPPT	maximum power point tracker: a high efficiency DC-to-DC converter
MW	megawatt
NEDO	New Energy and Industrial Technology Development Organization
NEMS	National Energy Modeling System
PHEV	plug-in hybrid electric vehicle
PV	photovoltaic

rectifier	a device that converts AC to DC
V_{ac}	AC voltage
V_{dc}	DC voltage
W	Watt (SI unit of power equal to one joule per second)
Wh	Watt hour

Executive Summary

An increasing number of energy efficient appliances operate on direct current (DC) internally, offering the potential to use DC from renewable energy systems directly and avoiding the losses inherent in converting power to alternating current (AC) and back. This paper investigates that potential for net-metered residences with on-site photovoltaics (PV) by modeling the net power draw of the 'direct-DC house' with respect to today's typical configuration, assuming identical DC-internal loads.

Power draws were modeled for houses in 14 U.S. cities, using hourly, simulated PV-system output and residential loads. The latter were adjusted to reflect a 33% load reduction, representative of the most efficient DC-internal technology, based on an analysis of 32 electricity end-uses. The model tested the effect of climate, electric vehicle (EV) loads, electricity storage, and load shifting on electricity savings; a sensitivity analysis was conducted to determine how future changes in the efficiencies of power system components might affect savings potential.

Based on this work, we estimate that net-metered PV residences could save 5% of their total electricity load for houses without storage and 14% for houses with storage. Based on residential PV penetration projections for year 2035 obtained from the National Energy Modeling System (2.7% for the reference case and 11.2% for the extended policy case), direct-DC could save the nation 10 trillion Btu (without storage) or 40 trillion Btu (with storage). Shifting the cooling load by two hours earlier in the day (pre-cooling) has negligible benefits for energy savings. Direct-DC provides no energy savings benefits for EV charging, to the extent that charging occurs at night. However, if charging occurred during the day, for example with employees charging while at work, the benefits would be large. Direct-DC energy savings are sensitive to power system and appliance conversion efficiencies but are not significantly influenced by climate.

While direct-DC for residential applications will most likely arise as a spin-off of developments in the commercial sector—because of lower barriers to market entry and larger energy benefits resulting from the higher coincidence between load and insolation—this paper demonstrates that there are substantial benefits in the residential sector as well. Among residential applications, space cooling derives the largest energy savings from being delivered by a direct-DC system. It is the largest load for the average residence on a national basis and is particularly so in high-load regions. It is also the load with highest solar coincidence.

1 . Introduction

A convergence of factors are driving recent interest in using direct current (DC) from solar electric systems in its DC form to power electricity loads in buildings, rather than converting it to alternating current (AC) first as is current practice. The new millennium has witnessed sustained and rapid growth in the adoption of rooftop solar electric systems and increased interest in advanced solar technology, as concerns about climate change have intensified. Net-metered photovoltaic (PV) power systems, which have dominated on-site renewable energy supply in the building sector, are a DC power source, as are batteries, which are the dominant energy storage technology used with such systems. An increasing fraction of the most efficient electric appliances operate internally on DC [1, 2]. This suggests that energy savings could be obtained by *directly* coupling DC power sources with DC appliances, thus avoiding DC-AC-DC power conversions. Recent demonstrations with commercial data centers have shown that significant energy savings can be achieved with DC power distribution delivered directly to DC loads, rather than utilizing AC power.

While the direct use of DC has been extensively studied in the commercial building sector and is being recommended as a key strategy for improved reliability and increased energy savings in such environments [3, 4], residential applications have received relatively little attention and differ considerably from these commercial applications. Most importantly, residential loads have poorer coincidence with PV system output than commercial loads and are likely to be less predictable. These issues would appear to make the residential sector a poorer candidate for direct-DC than the commercial sector. Acknowledging these barriers, this study assesses the relative energy savings of 'direct-DC' power for residential buildings.

1.1 Historical Review

The current electric distribution system is based on centralized production, high voltage transmission, and low voltage power delivery of AC. Each U.S. home connected to the electric grid is supplied with 120 or 240 Volts of AC at 60 Hz. However, the first power systems, designed by Thomas Edison in the late 19th century, operated with DC. Edison's idea for electricity distribution was to develop small-scale power plants that would deliver power in small areas. A short while after the introduction of the DC distribution system, its AC counterpart was developed by George Westinghouse. AC was superior to DC mainly because it enabled central generation and efficient long-distance power transmission. Transmission losses over long distances were intolerably high at the low voltages required by appliances. Westinghouse's invention of a low-cost AC transformer allowed power to be transmitted at high voltage and then transformed to low voltage for use in buildings. In addition, AC induction motors were more reliable and efficient than DC motors of the era because the latter used brushes, which required frequent maintenance and replacement. No comparable technologies existed for DC power at the time. [5]

1.2 Renewed Interest in Direct-DC

Today, DC power can be efficiently transformed to high and low voltage levels while brushless DC motors have also become available, eliminating the inherent advantages of AC over DC and renewing the debate of AC versus DC. This section discusses the combination of factors that are driving the resurgence of interest in direct-DC: the expansion in the current and expected future use of energy efficient products that utilize DC power internally, the rapid increase in PV power systems in the United States, the current emergence of direct-DC power standards and products designed for grid-connected products, and the demonstrated energy savings of direct-DC in commercial data centers.

1.2.1. Increased Use of DC-Based Loads

Important factors that favor the use of DC is the growing number of electric appliances that operate internally on DC and the fact that these new 'DC-internal' technologies tend to be more efficient than their AC counterparts [6]. 'DC-internal' appliances include communication technologies and all consumer electronics, such as computers, telephones, televisions, compact fluorescent lighting with electronic ballasts, light-emitting diodes (LEDs), and efficient DC motors [7]. Fluorescent and LED lighting uses one-quarter of the power, or less, than the traditional incandescent lighting it is replacing in the residential and commercial sectors. Brushless DC permanent magnet motors can save 5-15% of the energy used by traditional AC induction motors, and up to 30-50% in variable-speed applications for pumping, ventilation, refrigeration, and space cooling [6]. DC-motor-driven heat pump technologies for water and space heating can also displace conventional resistance heating with a savings of 50% or more.

Thus, three factors together suggest that DC-internal loads will continue to grow and will probably grow rapidly: the intensified focus on energy efficiency due to climate change, the fact that new DC-internal technologies can be significantly more energy efficient than their conventional AC counterparts, and the fact that those technologies are capable of servicing virtually all building loads. Indeed, the fact that global residential electricity consumption by electronic appliances grew by about 7% per annum between 1990 and 2008, and is expected to increase by 250% by 2030 [8], makes continued intensive investment in energy efficiency an imperative.

In addition to DC-internal appliances, electric vehicles (EVs) and plug-in hybrid electric vehicles (PHEVs) are expected to constitute a rapidly growing pure DC load in the foreseeable future. Pure EV models currently available on the market include the Tesla Roadster and the Nissan LEAF (Nissan USA, 2011); many more models are anticipated [9]. The Chevrolet Volt PHEV-35, the first mass-marketed PHEV in the United States was released for sale November 2010. Many other car companies plan PHEV releases in 2011 or 2012. Pike Research [10] projects rapid growth in world PHEV sales with a compound annual growth rate of more than 100% between 2010 and 2015 and that the United States will lead global sales in 2015, with more than one-third of the world market share.

1.2.2. Rapid Increase in U.S. Residential PV

While DC power sources for residential applications include PV, DC micro-wind turbines, and micro-hydro, PV dominates building-sited renewable electricity generation. According to representatives of Real Goods, one of the largest and oldest vendors and installers of building-sited renewable energy systems and components in the United States, Real Goods sales and installations breakdown approximately as follows:

- 95% solar (>95% grid-integrated),
- 3% micro-hydro, and
- 2% micro-wind.

Grid-connected PV installations have experienced large and sustained growth in the United States since the start of the new millennium. As shown in Figure 1, between 2000 and 2009 U.S. residential PV installations exhibited an annual growth rate of about 20% with significantly higher growth rates in more recent years [11]. This growth was accompanied by a decline in the unsubsidized cost of PV installation of 43% between 1998 and 2010 [12].

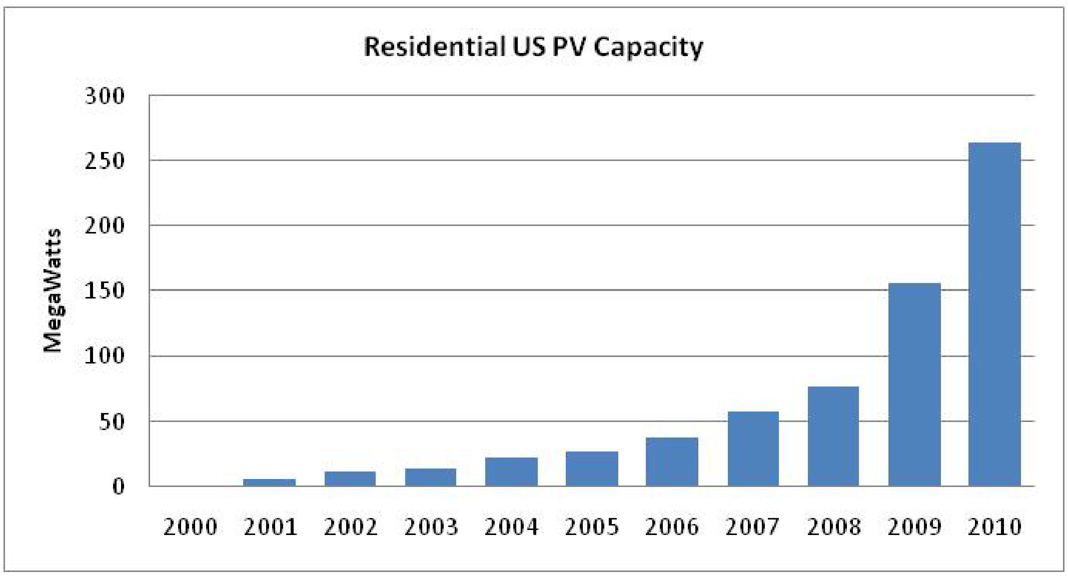

Figure 1. Residential U.S. PV capacity growth.
U.S. annual capacity additions of residential and commercial grid-connected PV in megawatts.
Data sources: [13, 14]

1.2.3. DC Power Standards, DC Products, and Demonstration Projects

The EMerge Alliance, an association of about 80 industry and research institute members, is guiding the development of DC technologies and standards in the U.S. [15]. It has already developed a $24V_{DC}$ standard for commercial buildings, and a $380V_{DC}$ standard for DC data center and telecom central office applications is currently underway. EMerge anticipates the development of residential standards as well. EMerge has dominated the debate on direct-DC in the United States, hosting international meetings on the subject as part of the Darnell Group's Green Building Power Forum and Smart Grid meetings held for the past three years in the United States and Japan. These meetings have been the major U.S. forum for the evolving discussion of direct-DC power systems for buildings.

The Green Building Power Forum meetings have demonstrated growing interest internationally in adopting the EMerge standards. The two main international players in direct-DC have been Japan and Korea. Japan's New Energy and Industrial Technology Organization (NEDO) has modeled the potential energy savings of direct-DC (Arthur D. Little is the consultant on that work) and has engaged Panasonic in the assessment and development of DC appliance prototypes. Japanese home electronics company Sharp is also testing DC-enabling technologies and equipment [16] and has presented a replica of a solar-assisted, DC-powered home. Korea appears to be farthest along in direct-DC research and development, having completed a large residential DC demonstration project in 2009 (a 30KW project by Samsung C&T Corp). This project showcases the integration of DC distribution and appliances with 22 kW of PV, 3 kW of wind power, and 200W of fuel cell capacity, along with 22 kWh of battery storage. This study by Baek et al [17] claims only a modest 1.5-3% efficiency improvement resulting from direct-DC. These groups have been participating in meetings addressing DC voltage choice issues and desire a unified approach to DC standards.

In the United States, new DC products that meet the EMerge standards are being developed for mainstream applications by member companies of the EMerge Alliance. These include both DC end-use products and products for DC power distribution and management. For example, Armstrong Ceiling Systems is currently selling a ceiling suspension system called the DC Flexzone™ Grid [18] for low voltage DC distribution of power to ceiling mounted appliances. Nextek Power Systems has DC power controllers that manage low voltage DC in the context of AC grid backup[19], and Nextek and others have developed direct-DC lighting systems, fans, and controllers that can operate off the DC Flexzone Grid [20] and are developing products for higher (380 V_{DC}) voltage applications.

Others have been working on new DC technologies independent of EMerge: The California Lighting Technology Center at the University of California at Davis is developing a DC LED system powered by a PV array [21]. The Center for Power Electronic Systems at the Virginia Institute of Technology is researching the development of a centralized or string-level maximum power point tracker (explained below) that interfaces directly with a residential PV system and provides $380V_{DC}$ power directly to the building loads [22]. It appears likely that all of these efforts will converge with the standards currently being developed by EMerge.

1.2.4. DC Distribution in Commercial Data Centers

Though not the subject of this paper, DC probably makes more sense in data centers than in any other type of facility. This is because the servers that provide the bulk of the load in data centers are inherently DC and require an uninterruptible power supply (UPS) in the form of an energy storage system that also operates on DC. In a typical data center, AC power is converted to DC at the UPS only to be switched back to AC before it is finally converted to DC at each server's power supply unit. A data center with DC distribution could eliminate these power conversions, which would lead to substantial energy savings.

A Lawrence Berkeley National Laboratory (LBNL) study [23] addressed these energy savings by comparing the energy use of data centers with DC distribution to AC data centers with best-in-class components and concluded that a 7.2% decrease in energy use can be achieved with DC distribution. The same system yielded an estimated 28.2% efficiency gain compared to AC data centers with standard efficiency components.

Overall, these trends make a strong argument for investigating the potential benefits of directly coupling DC power sources with DC loads in residential buildings, because the intermediate DC-AC, AC-DC conversions losses could be avoided, as shown in Figure 2. However, houses are likely to continue to rely on grid power for backup for the foreseeable future, because currently being entirely off-grid is much more costly and complex, with the need for energy storage and an alternative supply, or both. For these reasons, the reconfiguration of the power system for direct-DC would not be nearly as simple as implied by Figure 2.

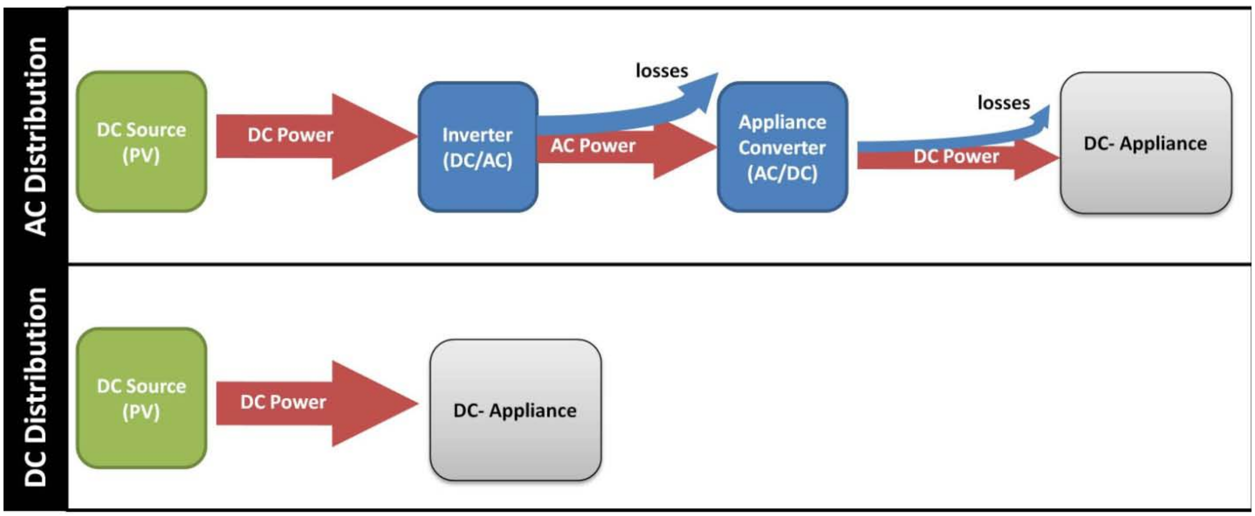

Figure 2. AC versus direct-DC distribution.
Comparison of power losses between a DC source and a DC-internal appliance for AC distribution and DC distribution. With AC distribution, power is lost due to the DC-AC and AC-DC conversions between the DC Source and the DC-internal appliance, whereas with DC distribution, power is sent directly to the load.

1.3 Related Research

In addition to the data center research described previously, a number of studies have been published on the potential use of direct-DC and DC microgrids in residential and commercial buildings [24, 25]. This section addresses those studies that focus on the power system configuration of residential and commercial buildings with direct-DC power distribution and on studies and demonstration projects that determine direct-DC energy savings.

Sannino, Postiglione, and Bollen [26] evaluated a DC distribution system in a commercial facility with different supply voltages ranging from $48V_{DC}$ to $326V_{DC}$ and compared these energy losses to an AC power system at $230V_{AC}$ (line to ground). The authors modeled distribution losses for the tested systems and found that, at the highest voltage level (326 Volts), DC distribution can be most beneficial, from both an economic and technical standpoint. Additionally, Nilsson [27] created an office laboratory setup with four loads (a coffee maker, a computer, and two fluorescent lamps) and evaluated the system's operating characteristics with DC distribution versus AC distribution. He concluded that a DC system could be preferable to an AC system in applications with many electronic loads, because DC distribution provided higher power quality and lower harmonics.

A number of studies have examined residential DC systems. The majority of studies have been purely analytical in nature, involving no demonstrations or laboratory measurements. A recent study by Savage, Nordhaus, and Jamieson [28] estimated the potential energy savings that can be achieved by replacing appliance AC-to-DC converters with a more efficient centralized rectifier (that converts AC power coming from the grid to DC) and using DC distribution within the house to power DC-internal loads. The authors assumed 70-75% efficiency for appliance AC-to-DC converters and 90% efficiency for the centralized rectifier and accounted for some efficiency improvements from switching from AC-powered to DC-internal appliances, such as refrigerators. The overall addressable residential sector energy savings were estimated at 25%, corresponding to a 3% U.S. load reduction. Hammerstrom [29] created a model that compared DC versus AC distribution in a residential building with and without an on-site DC power source. He divided household appliances into eight different categories, in accordance with 2001 Energy Information Administration data, and assigned each category a power conversion loss for AC and DC distribution, assuming that conduction losses were equal for both the AC and DC system. He found that a residential DC power system connected to the AC grid by itself would not be advantageous unless a local DC energy source was available to feed power directly to the DC bus. In addition, Paajanen et al. [7] ran a model that estimated the costs and energy use of residential power distribution for five scenarios, including AC distribution, hybrid AC and DC distribution, and DC distribution for various voltage levels. They concluded that for all scenarios that included DC distribution, energy efficiency and costs were improved. It should be mentioned that this study assumed high DC voltages (220V-750V) and power conversion efficiencies that favored DC distribution. In another study, Lee, Lee, and Lin [30] acknowledged the increasing use of DC-internal home appliances and proposed a hybrid DC and AC power system that included energy storage and allowed for DC generation from solar cells. Engelen et al. [31] calculated the conduction losses within a house with DC distribution at different line voltages and found that very small efficiency benefits can be achieved with DC distribution (depending on line voltages). Like Hammerstom, Engelen et al. do not recommend DC distribution in residential buildings unless on-site DC power generation is available.

While residential demonstration products are currently under discussion, Cetin et al. [32] have produced the only published demonstration project for residential buildings. The researchers constructed a mini-residential power system with a combination of a 5kW PV array, a 2.4kW fuel cell, and a 400W wind turbine as DC energy sources supplying direct-DC to 12V and 24V DC-internal loads. The authors projected that the use of micro-DC distribution systems will be more widespread as the share of DC devices increases in the future.

1.4 Research Objectives

1.4.1. House Model

Section two describes the modeling work used to calculate the energy impacts of direct-DC on home energy use. This research expands on earlier work by others in important ways: it explores the means to optimize those savings, and it anticipates likely future changes in loads and power system configurations that could affect those savings. Specifically, this study addresses the following issues:

- It explicitly analyzes the potential impacts of using direct-DC in the context of grid-integrated, net-metered homes.
- It quantifies the potential effect of climate conditions on direct-DC energy savings.
- It includes a detailed load analysis, investigating which products can be operated on direct-DC and the energy savings that could be obtained both from switching to DC-internal products and by avoiding the AC-to-DC conversion losses that are currently incurred by operating these products on AC power.
- It incorporates a sensitivity analysis on the effect of load variability vis-a-vis the impact of partial loads on power system component efficiencies. Prior studies assume that all power system components operate at constant full-load efficiency.
- It explores the impact of energy storage systems on direct-DC energy savings.
- It includes the impact of EV loads, a large anticipated future DC load.
- It investigates the potential benefits of shifting cooling loads to earlier in the day to make the load more nearly synchronous to PV system output.

The following sections give additional justification for addressing net-metered homes, energy storage, EVs, and load shifting in the context of direct-DC residential distribution.

1.4.1.1. Net-Metering

Because the grid provides low-cost backup power when sunlight is unavailable or insufficient to produce enough PV power to meet the load, more than 95% of PV systems are grid-connected [33]. Net metering makes grid-connected PV more economical by allowing periods of excess generation to be credited toward periods of deficit. State net-metering laws currently make this option available in 43 U.S. states [34]. In a net-metered system, the PV system's power output is connected on the house side of the utility meter. The load consumes whatever power it needs, drawing first from the PV system if available and from the AC system to make up any deficit. At any instant, if there is an excess of PV power, it is sent to the grid driving the meter backwards. Depending on state net-metering rules and the available metering technology, time-of-use pricing may be used to determine the price or credit value of power drawn from or delivered to the grid.

If direct-DC has a future in residential and commercial power supply, for the foreseeable future it will be in net-metered grid-connected buildings. Not only is grid power far less costly than battery backup power, but the cost of battery storage per unit of load served goes up sharply as one tries to reach 100% of backup load requirements [35]. Thus, it is not expected that economically viable storage technologies will entirely displace the grid in this service. For these reasons, this project assumes that future DC products and power systems will be operating in net-metered grid-connected buildings.

1.4.1.2. Energy Storage

While the capacity of net-metered grid-connected PV systems is increasing, the intermittence of the solar resource is a barrier to their future penetration [36]. A number of problems arise as penetration increases: If other local loads are unavailable to absorb excess PV, then local distribution systems and utility transformers, which were not designed for the purpose, would have to accommodate potentially large and variable reverse flows. At very high levels of penetration, utility base load capacity would be required to respond quickly to solar fluctuations. Because much base load supply, specifically nuclear and large coal plants, cannot respond instantaneously, excess power would have to be dissipated. According to Denholm and Margolis [37], local battery storage for building-sited PV, if handled properly, could be used to buffer such fluctuations at lower cost than reconfiguring the utility generation and distribution system.

Ultimately, the decision to include energy storage in a future scenario that enables high PV penetration is one that depends on economic, environmental, and technological factors, the analysis of which exceeds the scope of this study. However, because residential energy storage systems are DC devices and, given the national and global interest in achieving high PV penetration, which necessitates storage, this study considers the implications of energy storage on potential energy savings from direct-DC.

1.4.1.3. Electric Vehicles

EV and PHEV charging require the delivery of DC power to the vehicle's battery. While the current vision is to charge vehicles from rectified AC, EV charging would be more simply integrated into houses with DC distribution systems. The $380V_{DC}$ standard currently under development by the EMerge Alliance could accommodate EV charging; SAE International is currently developing a DC EV charging standard at a voltage range of 300-600 V_{DC} [38]. In addition, EV batteries could perhaps even serve as storage for building electricity, although currently an EV battery warranty will be void if it is used to provide power to any load except the EV.

1.4.1.4. Load Shifting

Ignoring temporal changes in cloud conditions, PV output peaks at solar noon, but house loads usually peak during evening hours. If the load were more nearly synchronous with solar peak, more of the PV system output could be used directly by the DC loads. This raises the possibility that additional savings can be achieved with load shifting, which might, in theory, be implemented through the use of a home energy management system.

1.4.2. Potential Future Impact of Direct-DC

One of the goals of the project was to determine the potential future significance of direct-DC energy savings. Such savings will depend on a number of factors: the changes in installed capacity of PV systems over time, the fraction of these systems that are direct-DC, and the fraction of the installed capacity that includes storage. These in turn are affected by price signals, policy decisions, and public perceptions of the risk of climate change, which are well beyond the scope of this study. Section 3, therefore, develops a simplified approach to assess an upper bound on the likely impacts of direct-DC, based on forecasts of residential PV penetration obtained from the National Energy Modeling System.

2 . Direct-DC House Modeling

2.1 Model Overview

A spreadsheet model was developed for a hypothetical house with a net-metered rooftop PV system. To test the potential effect of climate on direct-DC energy savings, the model was run for the average residence in 14 cities distributed across the contiguous United States. These cities, shown in Figure 3, were chosen because they were the only cities for which consistent residential load data were available in the desired format, as described below.

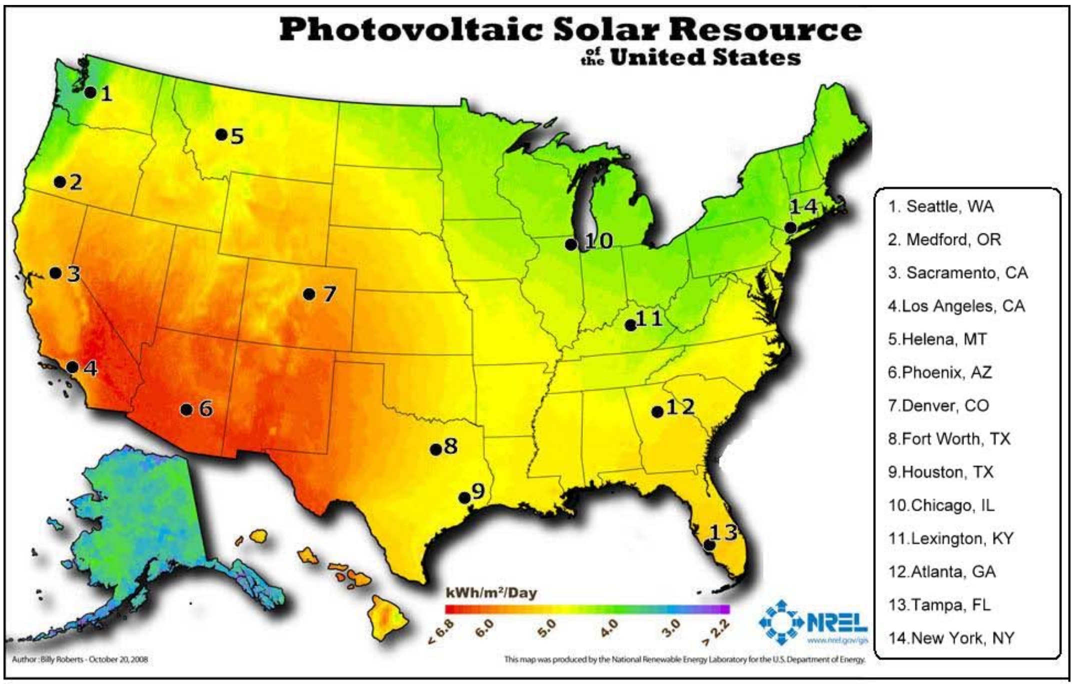

Figure 3. PV solar resource map.
Fourteen cities for which the model was run are superimposed on a PV solar resource map of the United States. As can be seen on the map, the distribution of the sampled 14 cities is analogous to the distribution of the solar resource on U.S. soil. Source: [39]. Reproduced with permission from the author.

2.2 Data Inputs

2.2.1. Load Data

The model uses simulated average residential electricity load data from the Solar Advisor Model (SAM). The SAM simulation software, developed by the National Renewable Energy Laboratory (NREL), is an open access tool, used widely by the renewable energy industry, that provides performance and economic estimates for renewable energy projects. The load data for the 14 cities are provided as example characteristic loads and are climate-simulated for each hour of the year (in kWh/hr for 8,760 hours). It should be noted here that these are smooth load profiles characteristic of average loads, not of individual house loads, which are highly temporally variable. Because the smooth load assumption could affect both the instantaneous PV output that can be absorbed by the load and the system storage dynamics, this could affect the final energy savings estimates. It would therefore be beneficial to test load profiles that better simulate real house loads. Unfortunately, characteristic load profiles were not available for different parts of the country, and it was beyond the scope of this study to develop them.

2.2.2. PV Output

SAM (version 2010.11.9) was also used to generate hourly estimates of PV system output for the entire year (8,760 hours) for each of the 14 cities using the modeling inputs indicated in Table 1.

Table 1. Inputs Used in SAM to Generate the PV System Outputs for the 14 Cities

Input parameters	Input value	Explanation
PV system DC rating	1kW[a]	Although 1kW was used as each city's PV system capacity, the actual capacity of each PV system was determined after scaling the PV output to match the yearly electric load for the AC house.
PV array tilt angle	20°	The majority of residential PV systems are mounted on house roofs, parallel to the plane of the roof. Most house roofs have a pitch that ranges between 15 and 25 degrees. Also, a 20-degree tilt maximizes summer energy production, which is preferable for utilities and owners of net-metered PV systems.
Azimuth angle	180°	It was assumed that the PV systems have optimal (true south) orientation for maximum performance.
Derate factor	0.85	The DC-to-AC derate factor accounts for losses due to ambient conditions, inverter losses, mismatched modules, line losses, soiling of the panels, and other factors.[b]

[a] Note that the PV output was later scaled to accommodate a level of production that would result in zero-net electricity consumption for the conventional AC House (as discussed below).
[b] The derate factor is immaterial for the modeling because it is a uniform scaling factor and SAM's PV output results were rescaled to effectively size the system for a zero-net electricity AC household. It is included here for completeness only.

2.3 Model Development

2.3.1. Distinguishing the Cooling Loads

Cooling loads were separated from non-cooling loads in the modeling because of their varied large dynamic changes throughout the year, their distinct deviation from the base load, and their significance as a critical candidate load to test for load shifting. In addition, a DC house's high-power loads were handled differently from low-power loads, and cooling is typically the most significant high-power load. Cooling is also a load that is influenced by solar irradiance and, therefore, by PV output.

Based on visual examination of the load data, cooling loads are clearly distinguished from non-cooling loads (Figure 4). One can clearly see a common base load in the winter months. In warmer months a peak begins to grow in, which is the cooling load. The method used to estimate the cooling and the non-cooling loads is described below. Each city's 8,760 hourly load data were converted to 12 multiplied by 24, or 288, hourly load data for the average day of each month. The resulting average diurnal load curves for each month were plotted. An example is shown for Sacramento in Figure 4, which also includes the average PV output for June and January (represented with the dotted lines). According to the graph, six monthly load curves have clearly distinguishable evening cooling loads, while the load curves of the remaining six months are almost matching.

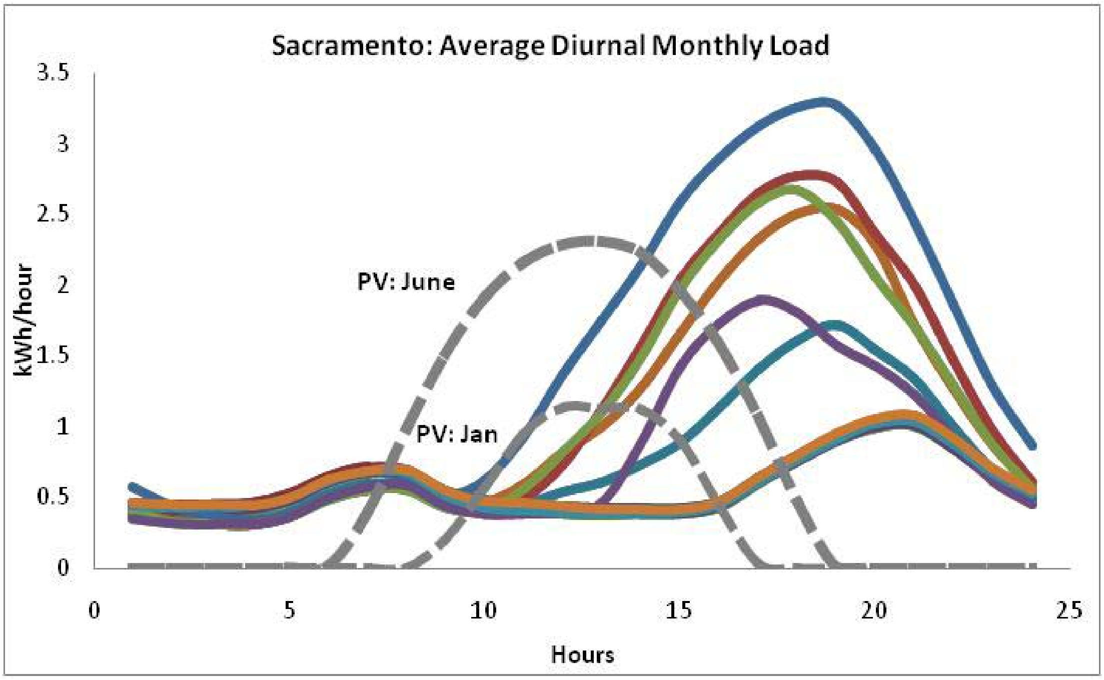

Figure 4. Average monthly diurnal load curves for Sacramento.

The monthly load curves have two characteristic peaks: a common, small peak during the morning hours (7am-9am) and a larger peak later in the day (3pm-8pm), which grows significantly in the summer months. From top to bottom, the visible larger peaks correspond to the months of July, August, September, June, October, and May. The superimposed curves correspond to the months of November to April. This variance is attributed to the cooling load. It was assumed that the common load visible in the winter months is representative of the non-cooling load and that any excess is the cooling load.

2.3.2. Modeling AC-House versus DC-House Energy Use.

To quantify the potential energy savings of direct-DC, the model compares the energy conversion losses in two hypothetical houses: a house with AC distribution, called the *AC-house,* and a house with DC distribution called the *DC-house*. Figure 5 shows the modeling configuration for the AC-house (top) and DC-house (bottom).

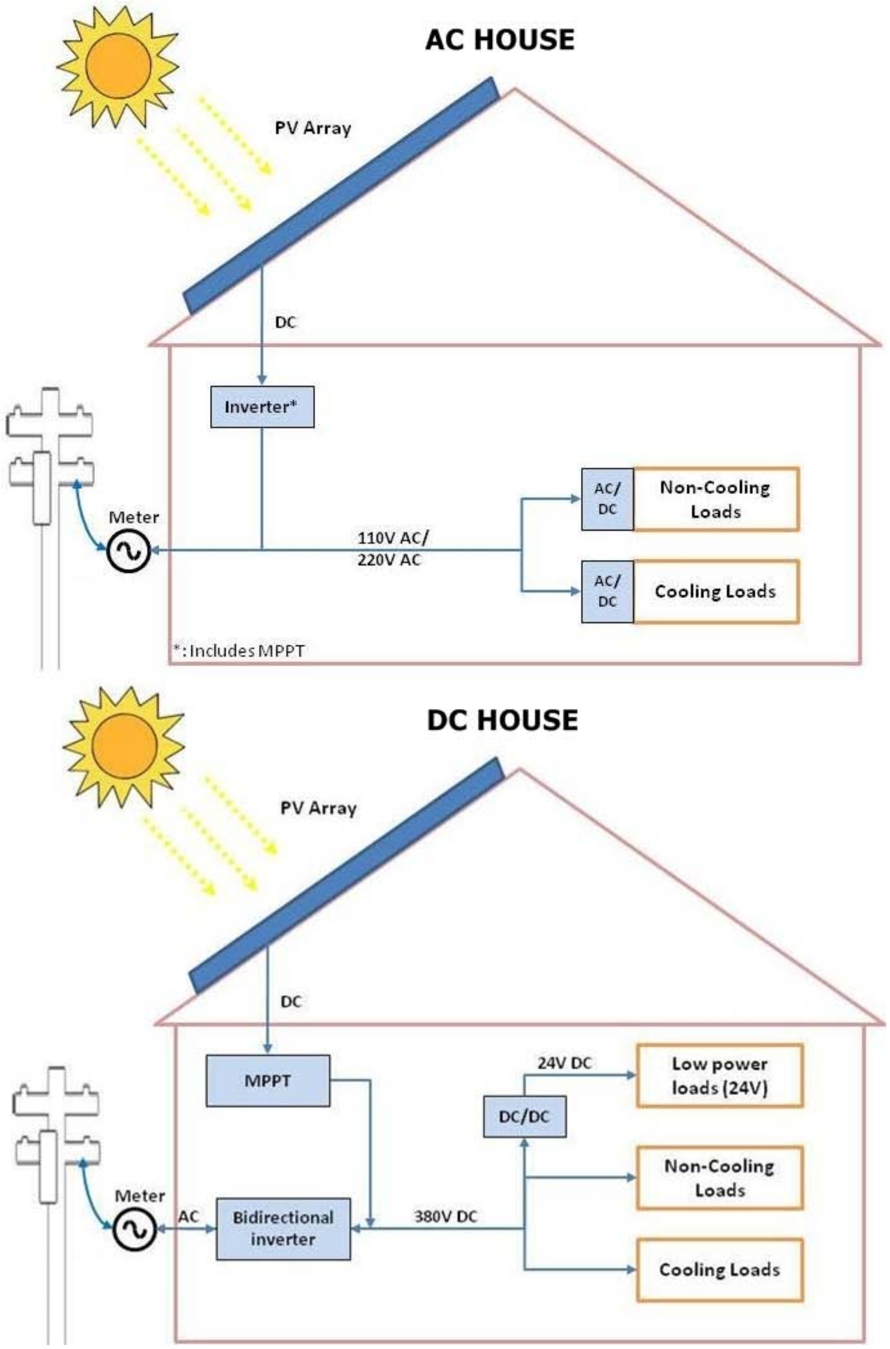

Figure 5. AC- and DC-house power system configuration.

Only components that generate, convert, and consume power are shown. The AC-house inverter (top) includes MPPT. The DC-house bidirectional inverter (bottom) does not include MPPT, because it is included separately.

Specifically, in the AC-house, which constitutes the base case, all power is distributed inside the house in AC form to appliances that all accept AC power inputs. In the DC-house, all power is distributed inside the house in DC-form to appliances that accept DC power inputs, but are identical in every other way to their AC counterparts. That is, the AC appliances are assumed to be the DC-internal appliances with an AC-DC power converter (also called a power supply) on the input. As discussed, the model incorporates separation of cooling and non-cooling loads for both house configurations. The non-cooling loads in the DC house are separated into high- and low-voltage loads. The low- and high-power voltages indicated are based on the existing and pending EMerge standards, respectively.

2.3.2.1. AC-House

In the AC house, DC power produced by the PV array is converted to AC by the inverter. That power is then distributed to the AC loads, supplying $240V_{AC}/120V_{AC}$ to cooling and non-cooling loads, as shown in Figure 5. Any excess power produced by the PV system is sent to the grid via net-metering. The grid supports the house electricity needs when the PV system cannot provide the necessary power to the loads. Other PV system components include wiring, combiner boxes, DC and AC disconnects, etc. For simplicity, these components are not included in the figure. The arrows in the schematic show the possible direction of power within the distribution system.

2.3.2.2. DC-House

The DC-house power system configuration eliminates DC-AC-DC conversion losses to DC-internal appliances when adequate PV power is available to supply such appliances. However, it incurs other losses when AC grid backup power is used. Grid power must now be converted to DC to supply loads, and excess DC power must be inverted to AC for net metering. This is done with a bi-directional inverter, which combines a rectifier (AC/DC) and inverter (DC/AC). Even though the PV array no longer requires an inverter, it still needs a maximum power point tracker (MPPT) to provide the necessary constant voltage to the load and adjust the apparent load characteristics seen by the PV array to force it to operate at the maximum possible power output [22]. MPPT is typically built into today's PV-system inverters and is therefore omitted from the AC-house schematic, but the power losses associated with the MPPT in the inverter are included in the modeling. Beyond that, most researchers envision that using direct-DC in residential and small commercial settings will require the use of high and low voltage DC [17];[40]. Low voltage (in the range of $12 – 48V_{DC}$) would be used for low-power loads, like consumer electronics and lighting, to facilitate safer and easier handling and flexibility. High voltage ($200 – 400V_{DC}$) would be used for high-power consumption devices, like air conditioning systems and large appliances, and to distribute DC power throughout the house with fewer losses. Given that this would result in some mix of DC distribution at voltages both higher and lower than the standard 220 or $110V_{AC}$ and that this mix will depend on the house geometry, it is assumed that the DC-house has about the same resistance losses in wiring as does the AC-house. The chosen voltages for the DC-house reflect existing ($24V_{DC}$) and pending ($380V_{DC}$) EMerge Alliance standards for direct-DC. This configuration requires a DC/DC converter before the low-power loads. (The figure shows one; in reality a number might be distributed to provide low-voltage power to buses in different regions of the house.)

The characteristics of AC and DC loads for both AC- and DC-house configurations (including appliance converters) are discussed below.

2.3.3. PV Sizing

The PV arrays in both houses are assumed to be identical, that is, to have the same DC output. The PV system in the AC house for each of the 14 cities is sized for annual zero-net electricity. Thus, over a one-year period the PV system's energy production (including inverter losses) equals the total annual AC-house electricity consumption.

2.3.4. Power System Conversion Efficiencies

Based on Figure 5, it is evident that any direct-DC energy savings depend inherently and sensitively on the conversion efficiencies of the AC versus DC power system components (shown in the figure as blue rectangles). A brief description of these components and a discussion of their efficiencies can be found in Appendix A. This section documents the modeling assumptions on conversion efficiencies of power system components and justifies the choices. Because DC products are only now beginning to emerge in the market and are not yet produced for building-scale systems that include both high and low voltage DC, all power system component efficiencies were based on similar devices used for other purposes and are representative of high-end products on the market. Table 2 presents the values used in the model for the power system conversion efficiencies, as well as corresponding efficiency values found in recent literature. It should be noted that the efficiency values presented here have been reviewed and influenced by industry experts at the 2011 Green Building Power Forum, including makers of the new generation of DC power supplies for data centers and by EMerge Alliance members.

Table 2. Power System Full-load Conversion Efficiencies

Power System Component	Model Efficiency	Component Efficiency in Literature
PV Inverter (AC House), includes MPPT[a]	95%	[7]: 90%, [41]: 95%
DC-House Rectifier (meter → DC)[b]	93%	[42]: 90%, [41]: 95%, [43]: 90%
DC-House Inverter (DC → meter)[b,c]	97%	Not available in the market
Charge controller or MPPT[d]	98%	See Appendix A
DC-House DC-DC Converter: 380V – 24V[b]	95%	[7]: 90%, [41]: 95%
Battery (one way)[e]	90%	Varies depending on storage technology and state of charge

a Typical of today's new PV-system string inverters.
b Represents best models that could be built today, according to industry experts interviewed.
c Today's PV-system inverter minus the MPPT, which has estimated losses of 2%.
d Typical of today's high-end charge controller efficiencies.
e Consistent with findings by Stevens and Corey [44].

2.3.5. Switching to DC-Internal Loads

To fairly compare the performance of the AC- and DC-house, their loads needed to be identical except for their power input characteristics. Figure 6 shows a breakdown of the average U.S. residential electricity consumption by end-use for 2009, according to the Energy Information Administration (EIA).

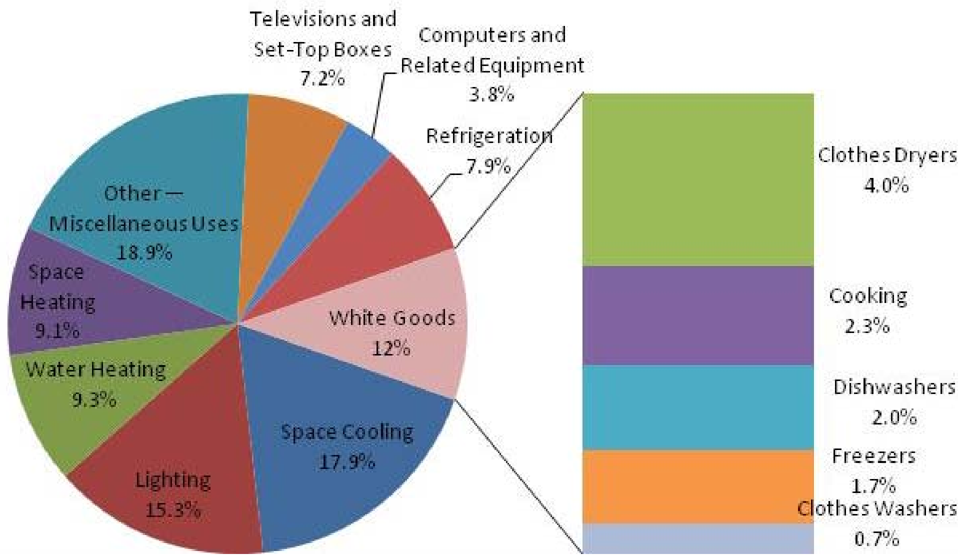

Figure 6. U.S. average residential electricity consumption by end-use in 2009.
Source: [45]

In order to obtain the most current U.S. residential end-use consumption at as high a resolution as possible, EIA's National Energy Modeling System (NEMS) was used[1] [46]. This resulted in an average annual U.S. residential electricity consumption for 2010 for 32 different appliances. The next step was to determine whether these appliances could operate on DC power. For this, the internal functions of appliances were considered in terms of whether or not they could operate on DC. Table 3 summarizes the results of this investigation.

[1] Annually the U.S. DOE presents U.S. energy use forecasts in its Annual Energy Outlook (AEO), based on results from NEMS. Forecasts are necessary to estimate current year energy use because actual data are not yet available. While NEMS builds its estimates based on appliance-level energy use data, only broader 'end-uses' are reported in the AEO publications. To obtain energy use estimates at the appliance level for the residential sector, we ran NEMS (the 2010 EIA release) using the AEO reference case assumption.

Table 3. Residential Appliances Functions and Equivalent DC-Internal Technologies

Function within appliance	Appliance type	Standard technology	DC-internal best technology	Energy savings compared to standard technology[a]
Lighting	Incandescent, fluorescent, LED	Incandescent	Electronic	**73%**
Heating	Heater	Electric resistance	Heat pump operated by BDCPM (for space and water)	**50%**
Cooling	Motor (& compressor, pump, & motor-driven fan)	Induction motor, single-speed compressor, pump, and fan where applicable	BDCPM operating variable speed	**30%-50% (VSD)** **5-15%** (motor only depending on size)
Mechanical work	Motor	Induction motor	BDCPM	**5-15%** (depending on size)
Cooking	Electric cook top	Electric resistance	Induction cooker	**12%**
Computing	Digital technology	Digital technology already DC	Same	**0**
Notes: BDCPM: Brushless DC permanent magnet motor; VSD: Variable-speed drive				

[a] Energy savings assuming AC power source

2.3.6. Energy Savings of DC-Internal Loads

Many products, such as electric lighting, televisions, computers, and other electronics, are already DC-internal and currently use AC-DC converters at their input stage. Resistance heating applications like electric space heaters and water heaters can use either AC or DC as input power. All other major applications use motors, compressors, pumps, or fans, all of which proved to be most efficient in their DC-internal form [6]. Therefore, with energy efficiency guiding the selection of the hypothetical suite of appliances for both houses, it was decided to:

- replace all non-DC compatible equipment with DC-internal models currently on the market;
- replace electric resistance heating applications with DC-driven heat pump technologies where applicable models exist (electric water heaters, electric driers, electric furnaces); and
- replace all incandescent lights with electronic (fluorescent or LED).

This suite of appliances constitutes the *efficient DC-compatible load* assumed for both the AC- and DC-house load modeling. For a detailed presentation of the 32 house appliances considered, the assumed replacement DC-internal technology (if applicable), and the estimated energy savings that would be obtained by switching to efficient DC-internal appliances, see Appendix B. Note that the model actually uses a synthesis of the results of this analysis. Specifically, the weighted average of cooling and non-cooling load energy savings was determined that would be obtained if DC-internal technology operating on AC power was used. The results of the analysis presented in Appendix B are summarized in Table 4.

Table 4. Weighted Average Energy Savings Due to DC-Internal Loads

Load type	Energy savings
Cooling load	36.5%
Non-cooling load	32.8%

To be consistent across all end-uses, in every case current electric loads were assumed to be met by the most efficient DC-internal technologies currently on the market. In every case, this resulted in a substantial increase in energy efficiency with overall energy savings of about 33% (weighted average) relative to current residential loads. So, in the case of lighting, even though incandescent lighting is DC compatible, it is not nearly as efficient as electronic ballast fluorescent and LED lighting, which are DC-internal and far more efficient. Similarly, electric resistance heating (for space and water heating) was assumed to be replaced by heat pump heating operated with variable-speed brushless DC motors.

2.3.7. Low-Power Loads

According to the power system topology of the DC-house, certain loads are powered at $24V_{DC.}$ These loads include lighting and consumer electronics. Based on the total yearly energy consumption of these loads, shown in Appendix B, the fraction of non-cooling loads powered at $24V_{DC}$ is 43%.

2.3.8. AC-DC Appliance Conversion Efficiences

Because the appliances in both houses were assumed to be DC-internal, each AC-House appliance was assumed to have an AC-DC converter appropriate to the power consumption of the appliance. The conversion efficiencies of the AC-house AC-DC appliance converters were estimated using external power supply (EPS) data from the Energy Star database and 115V and 230V EPS data from the 80plus[2] database. Figure 7 shows the compiled efficiencies versus EPS power output from these two data sets. It should be noted that the power supplies included in the Energy Star and the 80plus program are the most efficient on the market. Standard power supply efficiencies range from about 70% to 75% [23], whereas the power supply efficiencies plotted in Figure 7 range from about 85% to 95%.

[2] The 80plus power supply efficiency data correspond to desktop computers and servers typically used in data centers.

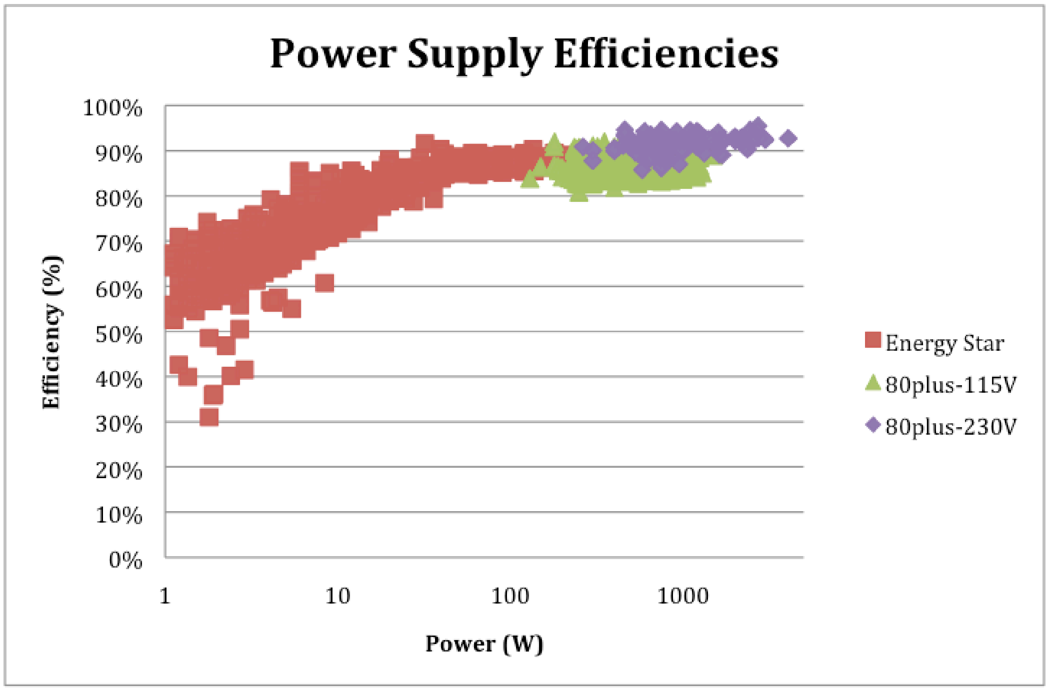

Figure 7. AC/DC power converter efficiencies of AC-house appliances.
Sources: [47]

Similar to Table 4, the weighted average AC/DC appliance converter efficiencies for cooling and non-cooling loads respectively are shown in Table 5. See Appendix B for the appliance AC/DC converter efficiencies assumed for each of the 32 house appliances.

Table 5. Weighted Average AC/DC Appliance Converter Efficiencies

Load Type	AC/DC appliance converter efficiency
Cooling load	90%
Non-cooling load	87%

2.4 Modeling Scenarios

2.4.1. Overview of System Configurations

To compare the energy use of the AC- versus the DC-house and to test implications of storage, load shifting, and EV, the following system configurations were considered, as presented in Table 6. Note that for every system configuration, the AC-house remains identical to the DC-house, except for the power system components and the form (AC or DC) in which power is delivered to the loads. Thus, both houses are assumed to have identical electricity storage systems in configurations where storage is considered (1b, 2b, and 3b), the same EVs in configurations 3a and 3b, and the same load-shifting mechanisms in configurations 2a and 2b.

Table 6. System Configurations for the Six Modeling Scenarios

Without electricity storage	With electricity storage
1a. Average residential load*	**1b**. Average residential load
2a. Shifted average residential load	**2b**. Shifted average residential load
3a. Average residential load & EV	**3b**. Average residential load & EV

*Configuration 1a, Average residential load (no energy storage) was presented in Figure 5.

2.4.2. Configurations with Storage

Battery storage was included in both houses[3]. Battery efficiency was assumed to be 90% one-way (81% round-trip), as shown in Table 2. Although real-world batteries have efficiencies that vary depending on various factors, including state of charge, ambient temperature, and battery age, for the purposes of the study these factors were overlooked. In both house configurations, the charge controller, which includes MPPT, regulates current to and from the batteries. The battery voltage, while assumed to be $380V_{DC}$ in both the AC- and DC-house, is immaterial to the modeling. The storage system is assumed to be charged only by excess PV power, which is instantaneous PV power exceeding total load capacity, but not by rectified grid power. This is done because storage is being used to maximize PV penetration by buffering the PV grid from large output spikes. Stored electricity is used to power loads when PV output is not sufficient to supply the load. When both the PV array and the battery do not have enough power to supply the loads, electricity is drawn from the grid. In addition, when the battery reaches its maximum charging capacity, excess PV power is sent to the grid via net-metering. The AC-house inverter is bidirectional, as is the norm for modern grid-interactive inverters with battery back-up (see Appendix A for details). Figure 8 shows system configuration 3b, *Average residential load & EV (with storage),* for both houses. The EV configurations are discussed below and are shown here for completeness.

[3] Because the model compares energy losses between the AC-house and the DC-house, only the storage system efficiency affects the modeling results and not the assumed storage technology.

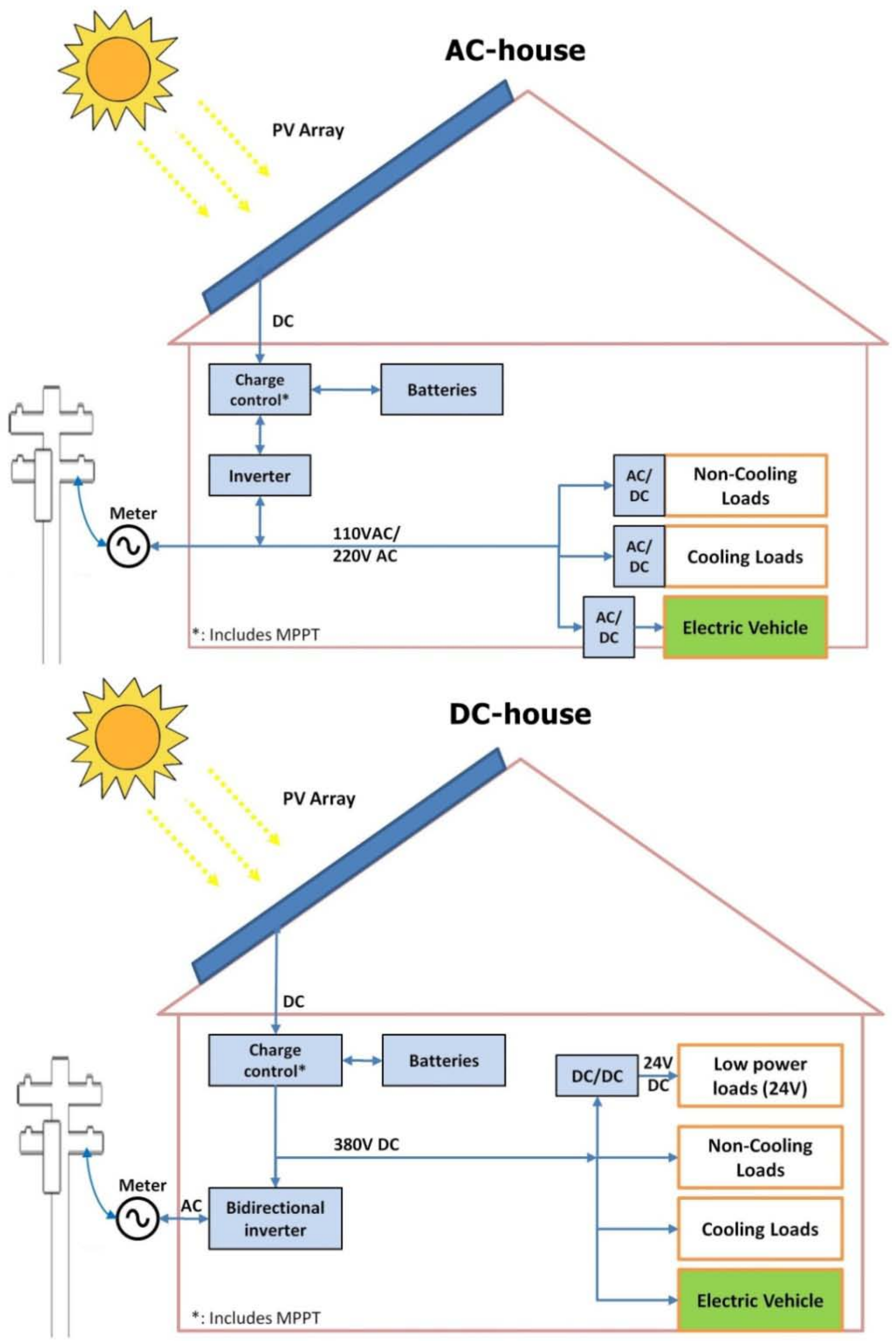

Figure 8. House configurations with storage.

Top: AC-house with storage and optional electric vehicle load. Bottom: DC-house with storage and optional electric vehicle load. Both house inverters are bi-directional, allowing battery charging from the solar system during the day and from the grid at night.

To identify a reasonable value for the maximum charging capacity of the battery (in kilowatt-hours, kWh), the model was run for one city (Sacramento), and a sensitivity analysis was performed to determine how the amount of excess PV power sent to storage varied with battery capacity. The results of this analysis are presented as Figure 9. For charging capacities up to about 10kWh, a linear relationship exists between the charging capacity and the percentage of excess PV sent to storage. For charging capacities greater than 10kWh, the relationship becomes one of diminishing returns. Therefore, taking into account the results of this analysis, which are consistent with the findings of Mulder et al. [35], a battery capacity of 10kWh was assumed. The minimum charging preserved in the battery was taken as 20% of full capacity (2kWh), a typical value for deep-cycle batteries.

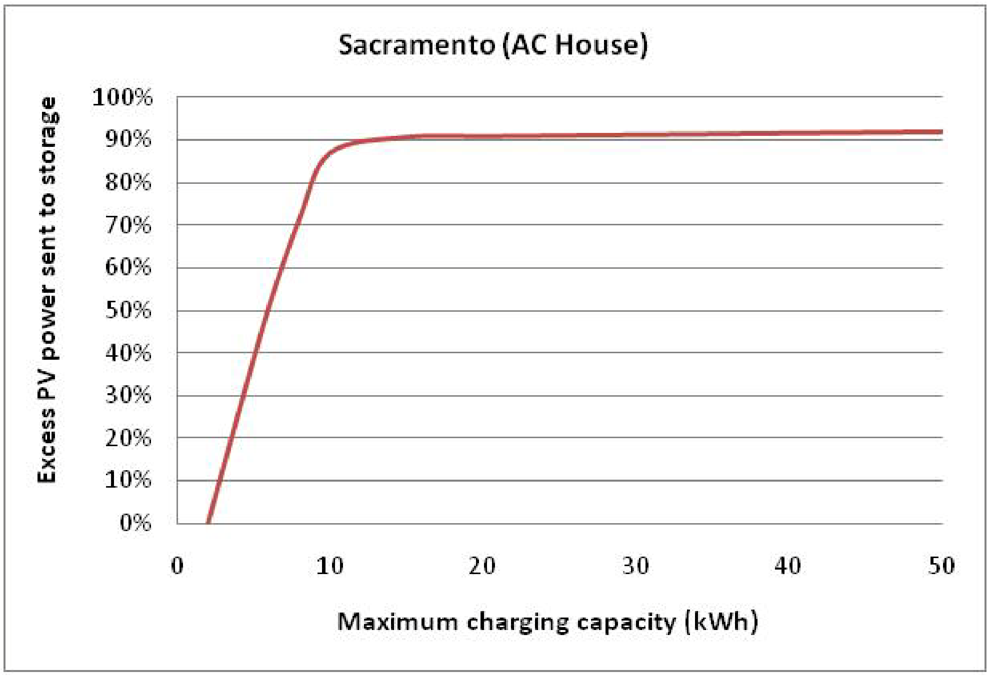

Figure 9. Relationship of maximum battery charging capacity to excess PV.

In addition, to test if the modeling calculations lead to reasonable results, the model results were analyzed for all 14 cities to determine the percentage of time that the battery was at minimum and maximum capacity, the percentage of PV output not going directly to loads that was sent to the battery, and the percentage of excess PV power that would have been sent to the grid in the absence of storage but was sent to storage instead. The results are shown in Table 7.

Table 7. Storage System Performance in the AC and DC Houses

#	CITIES	Cooling load fraction	Percent of time storage is at minimum capacity		Percent of time storage is at maximum capacity		Percent of non-coincident with PV loads serviced by storage		Percent of excess PV power sent to storage	
			AC	DC	AC	DC	AC	DC	AC	DC
1	Phoenix	66%	33%	28%	18%	21%	42%	46%	54%	48%
2	Tampa	56%	34%	27%	12%	16%	57%	65%	73%	65%
3	Houston	48%	32%	24%	13%	15%	57%	66%	73%	67%
4	Fort Worth	43%	30%	21%	11%	13%	58%	68%	74%	70%
5	Sacramento	32%	32%	22%	6%	9%	68%	78%	87%	80%
6	Atlanta	28%	25%	16%	6%	9%	68%	79%	87%	81%
7	Lexington	17%	27%	17%	6%	8%	68%	80%	88%	81%
8	Medford	17%	34%	23%	9%	10%	63%	73%	81%	75%
9	Los Angeles	15%	26%	14%	3%	5%	74%	86%	95%	88%
10	New York	11%	25%	15%	4%	7%	72%	82%	92%	84%
11	Denver	10%	24%	13%	5%	7%	73%	85%	94%	87%
12	Helena	9%	28%	20%	8%	11%	64%	73%	82%	75%
13	Chicago	8%	28%	17%	7%	9%	67%	77%	86%	79%
14	Seattle	3%	29%	24%	8%	10%	60%	64%	77%	67%
AVERAGES:			**29%**	**20%**	**8%**	**11%**	**64%**	**73%**	**82%**	**75%**
Standard Deviation			**3%**	**5%**	**4%**	**4%**	**8%**	**11%**	**11%**	**11%**

As shown in Table 7, the battery assumptions appear viable for all cities. In none of the cities are the batteries at minimum or maximum capacity for an undue period of time. In addition, the batteries appear highly active, receiving a high percentage of excess PV power and serving a high percentage of the load that is not serviced directly by PV. Thus, all houses with storage systems achieve their primary goals, which are to minimize power coming from the grid and to buffer power sent to the grid.

2.4.3. Configurations with Load Shifting

To test the potential of load shifting to improve direct-DC savings, the impact of shifting the residential cooling load two hours earlier in the day throughout the cooling season was modeled. The cooling load was shifted because (1) cooling dominates residential electricity use in general, and particularly in high electricity use areas, and (2) the residential cooling load is skewed toward evening hours, as shown in Figure 4. Load shifting was limited to two hours because of the limited ability of the system to store ‘coolth’ (with typical home air exchange rates on the order of one-half an air change per hour). While large shifts could be obtained using dedicated thermal storage technologies (like chilled water storage), they are cost prohibitive, at least for most residential applications, in the foreseeable future. The house configurations with load shifting do not require any additional power system components, apart from the home energy management system, which is assumed to have a negligent effect on the house electricity consumption.

2.4.4. Configurations with Electric Vehicle

The EV battery was considered to receive power from the house electric distribution system and not to discharge power to the house loads. As a result, it was modeled as an additional DC-internal load. As shown in Figure 8, the AC distribution house requires a rectifier and a charge controller, which are not necessary for the DC distribution house. To estimate the total energy use of the EV per annum, the following assumptions were made:

- The EV battery capacity (in kWh) is 24kWh, equal to the battery capacity of the Nissan Leaf [48].
- Each night, the EV returns to the house charging station at two-thirds (16kWh) of its charging capacity, and each morning it is fully charged (at 24kWh).
- Charging occurs for 8 hours during the night (between 10 pm – 5am) at a rate of 1kWh/hr. This includes the losses from the EV appliance AC/DC converter (which is assumed to have a 93% efficiency, equal to the house rectifier) and the charge controller losses. Charge controller losses are assumed to be identical for both the AC- and the DC-houses.

Based on these approximations, the total energy use of the EV is 8kWh x 365 days = 2,920kWh/yr. It should be noted that the PV array was not resized to accommodate the EV load in the net-zero energy requirement for the AC-house.

2.4.5. Model Runs

As mentioned earlier, the model tracks the efficiency losses throughout the residential electricity distribution system and in the AC appliance AC-DC power converters. The model was run as a Microsoft Excel spreadsheet that calculates the impact of net-electricity at the electric meter for both houses on a yearly basis for each system configuration. The reported energy savings are the direct-DC savings as a percent of the total AC-House load for each city. The following model runs were performed:

- Configurations 1a and 1b (average residential load without/with storage) for all cities.
- Configurations 2a and 2b (average residential load shifted without/with storage) for all cities.
- Configurations 3a and 3b (average residential load with EV without/with storage) for one city (Sacramento). This model run was limited to one city because the effect of climate on the previous model runs was not significant.

In addition to the above model runs, sensitivity analyses were conducted to test the effect of partial load conditions and possible future technology improvements.

2.5 Modeling Results

This section presents the modeling results for all system configurations. It should be emphasized that the energy savings reported here exclude the appliance efficiency savings (shown in Table 4), which were obtained from switching existing appliances to DC-internal appliances. Thus, the model addresses only the *direct-DC energy savings* (shown with the green arrow in Figure 10).

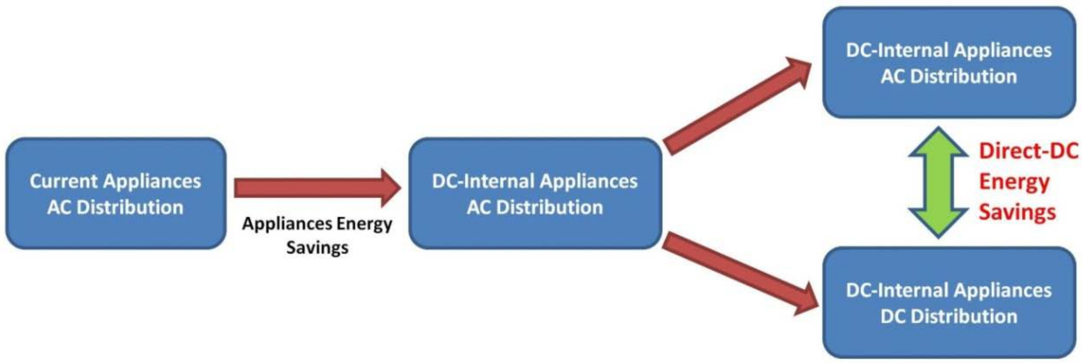

Figure 10. Appliances energy savings versus direct-DC energy savings.
The energy savings estimated by the model do not include energy savings from switching to more efficient, DC-internal appliances.

2.5.1. Average Residential Load, with and without Storage

Table 8 shows the results for system configurations 1a and 1b (Table 6), which modeled the energy use of the AC- versus the DC-house, with and without storage, assuming the average annual residential load profile for each of the 14 cities. The cities are ranked by cooling load fraction to test the effect of climate (reflected here by the cooling load fraction). Thus, together these results show the impact on AC versus DC energy use of both the presence or absence of battery storage and the climate, as described below.

2.5.1.1. Direct-DC Energy Savings

The model predicts that the direct use of DC power will save energy with respect to conventional AC distribution and that the savings for battery integrated systems are about twice that of non-storage systems. Averaging over all cities, direct-DC saves an estimated 7% of total (AC-house) electricity use without storage (1a) and 13% with storage (1b).

2.5.1.2. Climate Effect

The results show only a weak trend between cooling load fraction and direct-DC savings. For the non-storage case, the savings tend to be marginally higher for cities with a high cooling load fraction, ranging only from 7% for low cooling load areas to 8% for high cooling load areas. The opposite trend occurs for the storage case, with savings that range from 11% for high cooling load areas to 13.6% for low cooling load areas. Thus, climate does not have a strong effect on direct-DC savings.

2.5.1.3. Load Fractions Directly Serviced by the PV system

The average fraction of the load serviced directly by the PV system is both significant and virtually the same for the AC-house and DC-houses, 37% and 38%, respectively, as shown in Table 8 (lavender columns). For load shifting (reported next) to significantly improve direct-DC energy savings, the fractions would need to be significantly increased.

Table 8. Direct-DC Savings and Load Serviced Directly by PV

		Fraction of load serviced directly by PV system		Direct-DC savings as percent of total AC house load	
Cities	**Cooling Load Fraction**	**AC-house**	**DC-house**	**No-Storage**	**Storage**
Phoenix	66%	41%	42%	7.6%	11.0%
Tampa	56%	44%	45%	8.0%	12.2%
Houston	48%	43%	44%	7.9%	12.2%
Fort Worth	43%	40%	41%	7.6%	12.1%
Sacramento	32%	37%	38%	7.4%	13.2%
Atlanta	28%	38%	40%	7.5%	13.0%
Lexington	17%	37%	38%	7.4%	13.1%
Medford	17%	34%	35%	7.2%	12.6%
Los Angeles	15%	36%	37%	7.3%	13.6%
New York	11%	36%	37%	7.3%	13.5%
Denver	10%	34%	35%	7.2%	13.6%
Helena	9%	35%	36%	7.2%	12.8%
Chicago	8%	35%	36%	7.2%	13.1%
Seattle	3%	32%	33%	7.0%	12.8%
All Cities	**Averages:**	**37%**	**38%**	**7.4%**	**12.8%**

System configurations 1a & 1b (average residential load without and with storage).

2.5.2. Average Residential Load Shifted, with and without Storage

Table 9 shows the modeling results for system configurations 2a and 2b (Table 6), in which all cooling loads were shifted two hours earlier than currently indicated by SAM's simulated load data. The results are presented as in Table 8. The results show that no significant impact is obtained from the two-hour load shift.

2.5.2.1. Direct-DC Energy Savings

The direct-DC energy savings with and without load shifting are virtually identical. Averaging over all cities, direct-DC saves an estimated 8% of total (AC-house) electricity use without storage (2a) and 13% with storage (2b). The negligible improvement resulting from load shifting is explained by the fact that the load shift increased the fraction of load serviced directly by the PV system only modestly and by about the same amount (by 4%) to 41% and 42% in both the AC- and the DC-houses, respectively. Again, the effect of the inter-city climate differences is minimal, and the estimated savings with storage are close to double those without. Therefore, the magnitude of load shifting that might be facilitated by pre-cooling, given the constraints of typical building thermal mass and air exchange rates, has a negligible effect on direct-DC energy savings. However, it should be noted that larger shifts are possible using dedicated technologies like chilled water storage.

Table 9. Direct-DC Savings and Load Serviced Directly by PV (Load Shifting)

		Fraction of load serviced directly by PV system		Direct-DC savings as percent of total AC house load	
Cities	Cooling Load Fraction	AC-house	DC-house	No-Storage	Storage
Phoenix	66%	48%	49%	8.3%	11.3%
Tampa	56%	50%	51%	8.5%	12.3%
Houston	48%	48%	49%	8.3%	12.3%
Fort Worth	43%	47%	48%	8.2%	12.3%
Sacramento	32%	45%	46%	8.2%	13.1%
Atlanta	28%	44%	45%	8.0%	13.0%
Lexington	17%	41%	42%	7.8%	13.2%
Medford	17%	39%	40%	7.6%	13.1%
Los Angeles	15%	40%	40%	7.6%	13.5%
New York	11%	38%	39%	7.5%	13.5%
Denver	10%	37%	38%	7.4%	13.5%
Helena	9%	37%	38%	7.4%	13.1%
Chicago	8%	37%	38%	7.4%	13.2%
Seattle	3%	33%	34%	7.1%	12.8%
All Cities	**Averages:**	**41%**	**42%**	**7.8%**	**12.9%**

System configurations 2a & 2b (average residential load shifted without and with storage)

2.5.3. Average Residential Load with EV, with and without Storage

The model was run for Sacramento, a city with a cooling load fraction (32%) that was close to the average of the cooling load fractions for the 14 modeled cities. Figure 11 shows the modeling results for configurations that included an EV (system configurations 3a and 3b, Table 6), compared to the ones that did not (configurations 1a and 1b), for Sacramento.

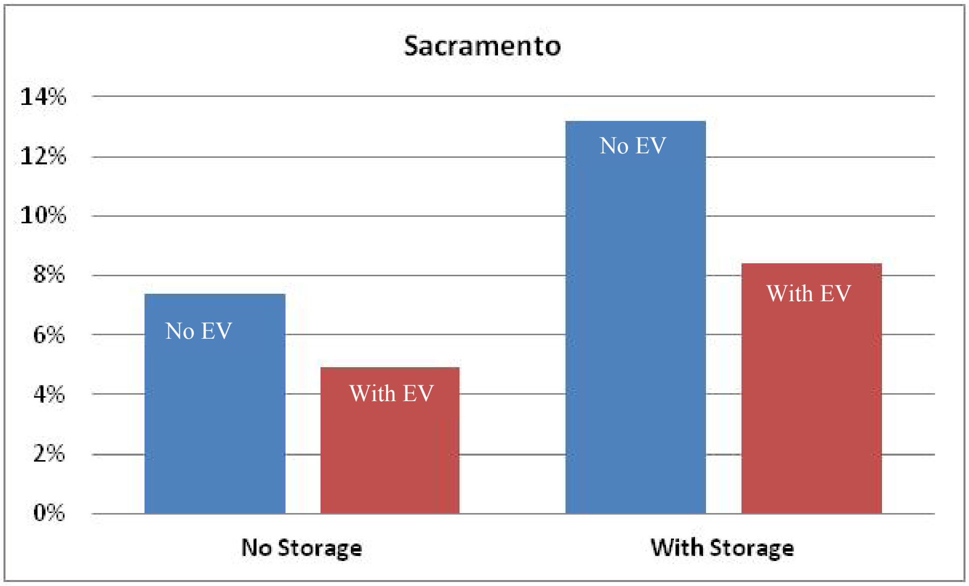

Figure 11. Effect of added EV load on direct-DC savings.

Because the EV is assumed to charge only at night, charging does not add to the absolute energy savings achieved from direct DC. However, the estimated percent savings were reduced from 7.4% to 4.9% for the non-storage case and from 13.2% to 8.4% for the storage case. The reduction in percent savings is explained by the fact that while the total house load increased significantly, none of that EV load was direct-DC because all charging was assumed to occur at night. The reason for the significant percent decrease in the non-storage house is because the EV represents a significant additional load (consuming 2,920kWh/yr), but none of it is assumed to be direct-DC, because the vehicle is assumed to be charged at night.

2.5.4. Sensitivity Analyses

2.5.4.1. Technology Improvements

As discussed previously, direct-DC savings depend inherently on the relative efficiencies of the power system components (inverters, rectifiers, voltage converters, and MPPT) and the appliance converters. Although this study uses current high-end efficiencies for the modeling, it is likely that these technologies will improve in the future. Therefore, the model was run for all cities testing the following efficiency improvement scenarios:

1. Improved power system conversion efficiencies. (These products are fairly new in the market, and their efficiencies are expected to improve.):
    - House rectifier: 93% → 95%
    - DC/DC converter (380V-24V): 95% → 97%

2. Improved appliance AC-DC conversion efficiencies. (Appliance converter efficiencies have been continuously improving. Energy efficiency standards for external power supplies are likely to continue to stimulate improvements both directly and indirectly, in the case of products with internal power supplies.):
   - Cooling loads: 90% → 95%
   - Non-cooling loads: 87% → 90%

The results are summarized in Table 10. As expected, if rectifier and DC/DC converter efficiencies improve, direct-DC energy savings increase. On the other hand, if appliance AC-DC conversion efficiencies improve, direct-DC energy savings decrease. Given that such improvements are likely to proceed together, the relative effects are likely to cancel each other out, and therefore the model estimates of energy savings will be relatively insensitive to future changes in the efficiencies of power system components and appliance power supplies.

Table 10. Direct-DC Savings for Improved Power System and Appliance Technologies

Efficiencies	Non-storage savings	Storage savings
Standard Efficiencies	7.4%	12.8%
Improved Power System Conversion Efficiencies	9.3%	13.7%
Improved Appliance AC-DC Conversion Efficiencies	4.0%	9.3%

2.5.4.2. Variable Conversion Efficiencies due to Load Conditions

Power converter efficiencies are considerably lower during part-load conditions than during full-load conditions (see Appendix A). The AC- and DC-house power system components (Figure 5) experience a wide range of operating conditions, because both house power demand and PV system output are highly variable. If multiple power system components were used (multiple rectifiers, inverters, etc.) and those that were not needed were turned off, components would operate closer to full-load conditions and have lower overall losses. New utility transformers that use this approach are emerging on the market, and a similar approach is being discussed for power supplies. Future PV power system technologies (and currently developing ones) might follow this approach as well; however, in the foreseeable future power system components will operate at part-load conditions.

To model the magnitude of the impact that part-load conditions might have on direct-DC energy savings estimates, part-load efficiencies (for load levels <20% of full load) were assigned for five power system components, as shown in Table 11.

Table 11. Power System Components Part-Load Efficiencies

Power system component	Full-load efficiency	Part-load efficiency*
AC-house Inverter, includes MPPT	95%	90%
DC-House Rectifier (meter →DC)	93%	84%
DC-House Inverter (DC → meter)	97%	92%
Charge Controller or MPPT	98%	94%
DC-DC Converter: 380V – 24V	95%	87%

*Part-load efficiencies were derived from the efficiency-load curves available in Appendix A

The above efficiencies were incorporated in the model (system configurations 1a & 1b, Table 6 – average residential load without and with storage), which was run for all cities. The results for the average city are shown in Figure 12.

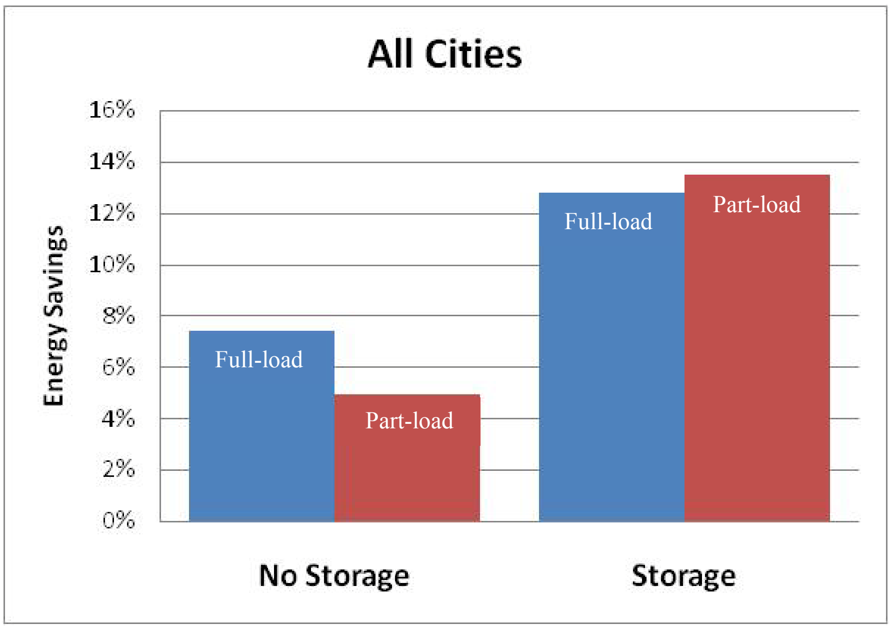

Figure 12. Effects of part-load conditions to direct-DC savings.

Partial load effects reduce estimates of direct-DC energy savings from 7.4% to 5.0% for the non-storage case, but increase them from 12.8% to 13.5% for the storage case. The decrease in savings for the non-storage configuration (1a, Table 6) is because of the low part-load efficiency of the DC-house rectifier (Figure 5). On the other hand, the increase in savings for the configuration with storage (1b, Table 6) is because of the higher AC-house versus DC-house losses incurred between the batteries and the loads, due to the presence of the inverter in the AC-house (Figure 8).

3 . Potential Future Savings from Direct-DC

3.1 Introduction

Forecasting the development and diffusion of energy technologies is as challenging as it is important for policy analysis. Developing full scenarios for the penetration of direct-DC technologies is beyond the scope of this study. Instead, to illustrate the possible future impact of these technologies on U.S. residential electricity consumption, a simplified approach was used to determine plausible future penetration rates for residential PV systems, given a range of policy scenarios, drawing upon the U.S. Energy Information Administration's detailed national supply and consumption projections created with the National Energy Modeling System and reported in the Annual Energy Outlook (AEO) 2011 [49]. In this section we describe this approach and the results, beginning with a brief background sketch of the relevant aspects of NEMS and the AEO projections.

3.2 NEMS and the AEO

NEMS is a partial equilibrium engineering-economic model of the U. S. energy system containing a relatively high degree of detail on energy supply and demand (end-use) technologies. The equilibrium concept underlying the model is that of supply equaling demand in interconnected markets for energy (i.e., fuels - primarily electricity including both conventionally and renewably-generated, natural gas, and petroleum products). In each market, both supply and demand are functions of a range of assumptions regarding costs, technologies, economic and demographic factors, and other inputs. The underlying philosophy of the model is that energy supply and demand are determined primarily by physical, engineering, and simple economic characteristics of energy technologies and of buildings, vehicles, and other energy-using devices and systems. The economic criterion used in most of the model is life-cycle cost minimization. A single solution or "run" of NEMS yields supplies, demands, technology penetrations, and other key quantities on an annual basis from the present to the year 2035.

The NEMS projections reported in the AEO are organized into "cases" defined by quantitative assumptions on key inputs. The core projection is the "Reference" case, which is essentially a baseline, an extrapolation of current trends, including energy policies and regulations. The standard set of 40 AEO cases also includes, for example, "High and Low Economic Growth", "High and Low Fossil Fuel Prices", and a number of projections defined by alternative policy and/or technology-cost assumptions. In all cases, EIA reports a standard (very large) set of outputs, including projected energy supplies and demands, as well as information on the characteristics of technology stocks, including their efficiencies and penetration rates. A subset of outputs are reported on a regional basis; in the case of energy demands, this geographic disaggregation is defined by the nine U.S. Census regions.

NEMS has a modular structure with components including a Residential module, or sub-model, which represents non-transport energy demands in U.S. residential buildings as well as residential end-use technologies [50]. Energy demands are disaggregated by housing type (single-family, multi-family, and mobile), by fuel – electricity, natural gas, and other – and by end-use – space cooling, appliances, electronic equipment, etc. While the Residential module itself calculates only delivered energy consumption, for electricity EIA also estimates system losses (in the NEMS Electricity module) and allocates these proportionally according to consumption categories. Delivered electricity and corresponding system losses are then reported both separately and in combination, with the latter referred to as “total” consumption.

The Residential module contains a Distributed Generation sub-module, which represents technologies for on-site single-family electricity generation, including solar PV, and projects their penetrations. Beyond the fundamental economic and demographic assumptions underlying the entire NEMS model, key inputs determining these penetrations include technology cost and performance characteristics, policy variables such as tax credits, and so-called “niche” variables such as solar insolation (which is spatially disaggregated and based on data from NREL) and average single-family roof areas. Neither DC distribution systems nor storage are currently represented in NEMS.

3.3 Approach

We use these electricity consumption and residential PV projections in combination with the house modeling results presented in section 2 to estimate a likely upper bound on the future electricity savings from the deployment of direct-DC systems. The essence of our approach is simply to posit that single-family dwellings with installed PV are converted to direct-DC distribution, and AC appliances in these dwellings are replaced by their DC-internal counterparts. We then compare the electricity consumption with and without these changes to direct-DC.

In order to obtain a range of penetration levels sufficient to support a meaningful comparison, we examined the consequences of various core NEMS input assumptions on residential PV penetration as reflected in ten AEO cases (Reference case and nine others) characterized by variations in technology and/or fuel costs as well as in policies that would be expected to affect PV deployment.[4] With the exception of the so-called “Extended Policies (EP)” case, the results were clustered around the Reference case estimate of roughly 3% penetration (among single-family households) by 2035. By contrast, the estimate in the EP case was roughly 11%, the highest by far. Thus, these two cases represent the range of PV penetrations in the AEO cases, and we use them for our analysis.

As noted above, the Reference case embodies current energy and environmental policies and regulations, which is interpreted to mean those already in place as well as those approved or enacted but not yet implemented. In both instances, the policies’ or regulations’ representations in NEMS include their planned durations. The EP case assumes that a number of these are instead extended through the year 2035, the model forecast horizon – in other words, made permanent within the span of time represented in the projections. Of particular interest to this analysis are tax credits for energy efficiency and renewable energy purchases and investments, which apply to residential solar PV and are extended through 2035 in the EP case (and which result in the relatively high penetration).

[4] These were Reference, Extended Policies, Integrated High Technology, Integrated Low Technology, High Coal Cost, Low Coal Cost, High Renewable Technology Cost, Low Renewable Technology Cost, No greenhouse gas (GHG) concern, and Economy-wide GHG price. The definitions of these cases are presented in the AEO.

Rather than speculate on penetration paths for direct-DC technologies, we carry out the comparison of electricity consumption sketched above for a single future year – the NEMS model horizon of 2035. The reason for this simplification is that creating a plausible actual scenario of the time-path of direct-DC penetration that is consistent with the NEMS (or any other) projections of residential electricity demand would require modeling and data resources that are significantly beyond the scope of this study. Among other things, such a scenario would require cost estimates for direct-DC systems and appliances, which are not yet on the market, and integration of our house model with the NEMS Distributed Generation sub-module. (Both these cost estimates and some form of model integration would also be required were we to base our analysis on, for example, NREL's "Solar-DS" model[51]). Thus, we adopt the more modest analytical goal of estimating an approximate upper bound on the impact of direct-DC.

Accordingly, we assumed a 100% penetration of both direct-DC distribution systems and DC-internal appliances in year 2035 in homes with installed PV, in both the Reference and the Extended Policies cases. Given the likelihood of increased use of on-site electricity storage over time to buffer the grid impacts of localized high penetration rates, but the lack of a sound basis to forecast the penetration of storage in 2035, we estimated the upper bound energy savings in 2035 independently for the two cases (with and without storage).

Although NEMS disaggregates the PV penetration projections on a regional basis, the corresponding regional disaggregation of electricity consumption data is not available. We therefore rely solely on the national estimates of both quantities, using the city-average estimates of energy savings estimated in section 2.

3.4 Forecasting Results

Table 12 displays the outputs of the NEMS Reference and Extended Policies cases that we use to estimate the direct-DC energy savings, shown in Table 13, for the cases just described. In Table 13, we first allocate national total electricity consumption by end-use category to homes with installed PV, using the proportions of the latter in the total (single-family) housing stock. Using the same simple proportional allocations, we then estimate savings from conversion to DC-internal appliances and the resulting net electricity consumption totals. Next, we apply the estimates from section 2 to estimate the further savings from DC-distribution systems, applied to the appliance-adjusted totals, distinguishing the storage (14% average savings) and non-storage (5% average savings) cases. Finally, we show total savings from both DC-internal appliances and DC distribution, and net total consumption, with and without storage, in the Reference and Extended Policy cases.

Table 12. NEMS residential energy and technology projections, year 2035*

	Reference case	*Extended Policies case*
Total electricity consumed for space cooling	2.99	2.31
*Total electricity consumed for non-cooling end-uses***	13.59	11.81
Total electricity consumption, cooling and non-cooling	16.58	14.12
Percentage of single-family dwellings with installed solar PV	2.69%	11.17%

* Electricity consumption is in quads (quadrillion British Thermal Units (btu)).

** Does not include personal/household transportation.

Sources: i) Electricity consumption: "Residential Sector Key Indicators and Consumption" table, AEO 2011 (USEIA 2011). ii) PV penetrations: Data accompanying Fig. 61 in "Market Trends" section, AEO 2011 (ibid).

Table 13. Estimated impacts of direct-DC technologies in single-family dwellings with installed PV, year 2035, in quads

	Reference case[1]	Extended Policies case[1]
A: Total electricity consumption in homes with installed PV		
Space cooling	0.08	0.26
Non-cooling end-uses	0.37	1.32
All end-uses	0.45	1.58
B: Conversion to DC-internal appliances		
37% savings from DC-internal cooling equipment	0.03	0.10
Net total electricity for cooling	0.05	0.16
33% savings from DC-internal appliances, non-cooling end-uses	0.12	0.44
Net total electricity for non-cooling	0.24	0.88
Total electricity consumption including savings from DC-internal appliances, all end-uses	0.30	1.05
C: DC distribution in homes with DC-internal appliances		
Without storage: Savings of 5% from DC distribution[2]	0.01	0.05
With storage: Savings of 14% from DC distribution[2]	0.04	0.15
D: Combined DC distribution and DC-internal appliances		
Without storage: Savings from appliances and distribution	0.17	0.58
Net total electricity consumption without storage	**0.28**	**0.99**
With storage: Savings from appliances and distribution	0.19	0.68
Net total electricity consumption with storage	**0.25**	**0.90**

[1] Source: Authors' calculations using results of Chapter 2 and estimates in Table 12.
[2] Savings are based on part-load efficiency assumption for power system components.

4 . Conclusions

4.1 Overall Findings

This paper finds that direct-DC could yield significant energy savings in U.S. houses with net-metered PV systems, if the entire load is constituted of DC-powered appliances, especially if those systems incorporate battery storage of sufficient capacity to significantly buffer the grid from PV system output fluctuations. Assuming full-load power system component efficiencies, for the average city direct-DC saves about 7% of total house electricity consumption for the non-storage case and about 13% for the storage case. Assuming part-load efficiencies, the corresponding values are 5% and 14%. While there are design approaches that can minimize reductions in efficiency with load, for the foreseeable future, significant part-load losses are likely to persist. These savings estimates do not include the substantial (about 33%) energy savings that are obtained by switching the entire load to efficient DC-internal appliances. While those savings might occur with or without a conversion to direct-DC power systems, they demonstrate that appliance modifications needed to accommodate direct-DC offer significant energy benefits to the nation.

This study also explored the impact on direct-DC energy savings of climate, EV loads, and load shifting. The estimated percent energy savings from direct-DC varied relatively little under the wide range of climate conditions represented by U.S. cities distributed throughout the contiguous United States. Of course, the absolute savings potential, which is approximately proportional to the load, will vary significantly from region to region. Not surprisingly, direct-DC has no advantage for EV charging, if charging occurs at night, as most of it would in the residential sector. Two-hour shifting of the cooling load to better coincide with insolation only marginally increases the percentage energy savings from direct-DC.

The results are sensitive to assumptions about the energy efficiency of the power system components. In an effort to be conservative in our estimates of direct-DC potential, we assume high-end power conversion efficiencies in all AC appliances. If improvements in appliance conversions efficiencies (power supplies) improve faster than DC power system component efficiencies, the relative benefits of direct-DC over AC will go down. Of course, if the reverse is true, they will go up. Our judgment is that both are likely to improve, and the effects will, to some degree, cancel.

Year 2035 projections were based on PV penetration rates estimated for single-family dwellings by the National Energy Modeling System: 2.7% for the reference case and 11.2% for the extended policy case. Assuming that all PV systems are converted to direct-DC by 2025, for reference case PV penetration, we estimate a national maximum savings of direct-DC of 10 trillion Btu and 40 trillion Btu, for the non-storage and storage cases, respectively. For extended policy case PV penetration, we estimate a national maximum savings of direct-DC of 50 trillion Btu and 150 trillion Btu, for the non-storage and storage cases, respectively. If the savings of converting to DC-internal appliances is added to the equation, the total savings range increases from 170 trillion Btu (for the non-storage, reference case) to 680 trillion Btu (for the storage, extended policy case).

4.2 Discussion

It is difficult to compare our estimates of energy savings with the work of others, because of the different scope and approach of prior studies. For example, Savage et al. [28] reported a 25% energy savings potential, but they assumed today's average power supply efficiency for the AC/DC appliance conversion efficiency rather than best-on-market efficiencies and did not account for different efficiencies for different power supply capacities. They also addressed only a subset of the residential load (significantly, space cooling was excluded) and reported the savings for only that portion of that load. While similar in scope and more comprehensive in terms of dealing with variable loads, Baek et al. [17] did not model a net-metered (hybrid energy source) residence; they consider only an all AC or an all DC source. We considered it critical to model the net-metered house because current trends strongly suggest that the major portion of the PV market will remain in grid-connected buildings for the foreseeable future.

While detailed price forecasting is not feasible at this time, given the fact that DC products are not yet on the market and there is no price history to determine likely future price trajectories, we follow Aristotle's injunction to "rest satisfied with the degree of precision which the nature of the subject admits", and therefore address the issue only in broad conceptual terms. The DC approach will eliminate a large number of AC-DC converters embedded in appliances and replace them with a centralized rectifier and one, or a few, DC-DC converters. While this adds marginally to the complexity and the cost of the DC-power system relative to the AC-power system in the non-storage house, the savings on appliance power supplies could offset those costs. Moreover, low-voltage wiring can be worked on by those who are not trained electricians, saving on installation and retrofit cost. Therefore, it is not unreasonable to expect that, after the market settles, the net cost of electricity services in a DC house would be no greater than in an AC house without storage. With storage and EVs, the DC power system is no more complex than the AC power system; indeed, if additional renewable energy supply technologies are integrated into the system, DC is less complex than AC. Therefore, in the types of systems that are likely to be more prevalent in the future, we would expect DC both to save significant quantities of energy and to reduce costs.

Despite the fact that direct-DC holds little advantage for EV charging, to the extent that charging occurs at night, it could in one context provide large offsets to future residential loads, specifically if commuter vehicles are charged at work, during the day, when the sun is out. Fueling a car with sunlight is already approximately competitive with the cost of fueling with gasoline, because of the far higher efficiency of electric motors than internal combustion engines. Large centralized DC-charging stations in commercial environments could drive the cost down further. Moreover, large centralized solar charging facilities will have significantly lower costs than residential charging, on a $/W basis for PV, and likely economies of scale for the installation of charging systems. If companies were to offer charging services to their employees at a lower cost than they would pay for electricity at home and still make some money on these services, this might be a viable option even without policy intervention.

The modeling work could be extended and improved in a number of ways. The reasonably promising results obtained here for the residential sector argue for a similar analysis of potential commercial sector savings. We expect higher savings in the commercial sector, because of better coincidence of load and insolation. With respect to load data, real loads are much 'spikier' than the smooth average utility profiles used in the modeling. This would require a significant data analysis effort using spectral analysis of high time-resolution data to obtain representative load characteristics for different regions of the country. Datasets used for non-intrusive load monitoring could be a good source.

In conclusion, current trends suggest that the transition to a DC-based power future is feasible and may indeed be underway. The energy efficiency imperative, along with continual product quality improvements, is driving the adoption of DC-compatible products, such as electronic lighting, efficient DC motors, ultra-efficient space cooling, and electric heat pumps. The rapid adoption of building-sited solar power, along with new DC power standards of the EMerge Alliance, is already stimulating the entry of DC products to mainstream commercial markets. The ease with which energy storage and EV charging can be added to a direct-DC power system will increase the future attraction of direct-DC, and the EV charging standards for DC technology that are currently under development by SAE International will further ease the path to entry. While direct-DC for residential applications will most likely arise as a spin-off of developments for the commercial sector, because of that sector's load having more overlap with PV output and therefore higher energy savings and economic benefits, this paper clearly illustrates that there are substantial benefits in the residential sector as well, especially in a future with high PV penetration buffered by local energy storage.

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Appendices

Appendix A: AC- and DC-House Power System Components

This appendix describes the power system components included in the modeling of the AC and DC houses, specifically all power system components downstream of the PV array. Each entry indicates whether the component is used for the AC- or the DC-house. The primary purpose is to explain the energy efficiency assumptions used in the modeling and certain decisions about component configurations. PV-power systems for AC-distribution houses are now commonplace, and data on such systems are widely available. The modeling assumes efficiencies that represent the high end of the current market. Because the DC-house's power system is hypothetical, the assumed characteristics of its components are based on similar products currently on the market, but used for other purposes, and on extensive discussions with industry experts involved in the design and manufacture of new power supplies for DC data centers and other power system components. The final values were also vetted with members of the EMerge Alliance technical committees for the $24V_{DC}$ and $380V_{DC}$ standards at the January 2001 meeting of the Green Building Power Forum in San Jose, California.

Inverter without Battery Backup (AC-House)

Description

Grid-interactive (also known as grid-tie) inverters convert DC coming from the PV array into AC that is synchronous with the grid. Residential PV systems generally have a single central inverter that converts the entire array's DC power to AC, although the relatively new micro-inverter technology that converts the output of each PV module to AC is becoming more common. This section addresses central inverters, because they provide architecture analogous to the DC-House.

To maximize PV system efficiency, modern grid-interactive inverters include maximum power point tracking (MPPT), described below. Therefore, the efficiencies quoted for these systems include the efficiency losses of the MPPT.

Efficiency

Typical full-load efficiencies of grid-interactive inverters range from 94% to 97% while some manufacturers have reported peak efficiencies of more than 98%. However, the AC-house inverter peak efficiency used in the modeling is 95%, based on industry expert input. The efficiency curve of the SMA America SB7000US (7kW) inverter, shown in Figure A1, reveals how efficiencies plummet at very low loads.

The California Energy Commission (CEC) has established the *weighted* efficiency as a more appropriate inverter efficiency metric. The weighted efficiency corresponds to the weighted average efficiency for various inverter input power points, thus accounting for both full-load and part-load conditions [52]. Weighted efficiencies are generally about 1-2% lower than manufacturer peak efficiencies. According to the CEC's list of eligible inverters for the California Solar Initiative, weighted efficiencies for grid-interactive inverters with capacities up to 10kW range between 84.5% and 98%. [53]

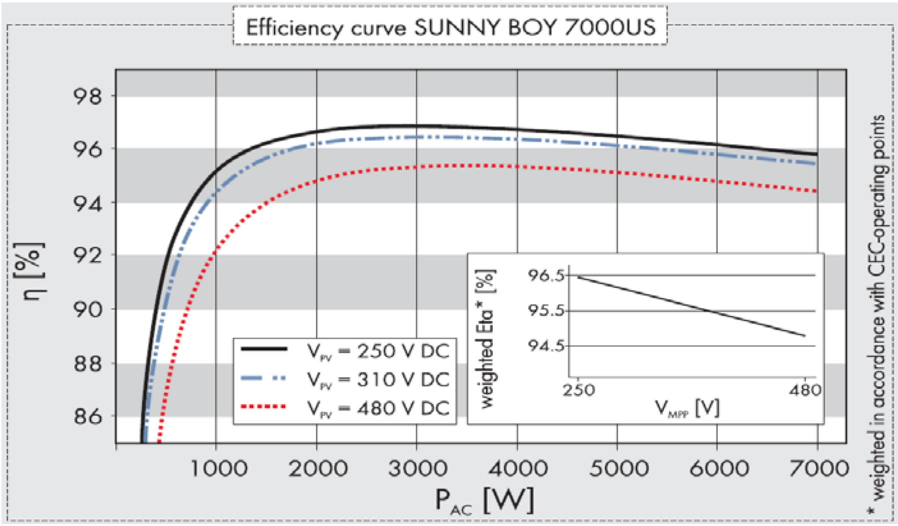

Figure A1. Grid-interactive inverter efficiency curve.
SMA inverter efficiency curve for the SMA Sunny Boy 7000US string inverter (with multiple MPPTs). The efficiency peaks after 30% load to 96-97%. Part-load efficiency (below 1000W power capacity) ranges between 86 and 95%. Source: SMA [54]. Reproduced with permission from SMA-America.

Inverter with Battery Backup (AC-House)

Description

Inverters with battery backup convert DC power coming from the battery, or directly from the PV array, to AC power, which is sent to the loads or to the grid for net-metering. These devices differ in an important way from their non-storage counterparts: They also have a built-in rectifier to convert AC grid-power to DC, as required for battery charging, and would be better described as bidirectional inverters. These inverters manage power flows to and from the battery, but the batteries are external to the device. However, unlike most inverters without battery backup, battery backup inverters do not include MPPT [55], as this function is performed by an upstream-located charge controller (see Figure 8). There are far fewer models of battery backup inverters on the market than there are non-storage inverters.

Efficiency

Efficiencies of inverters with battery backup are generally lower than their non-battery counterparts. Outback Power offers models with weighted efficiencies of 91%. Princeton Power Systems recently developed a 100kW inverter with battery backup with a 98% peak efficiency and a 94.5% weighted efficiency [56].

Bidirectional Inverter/Converter (DC-House)

Although bidirectional inverters designed for direct-DC power systems are not on the market, in fact, the battery-storage inverter described above is a virtually identical device. It serves to both rectify (AC-

DC) power from the grid to the building distribution system and invert (DC-AC) excess power from the PV system or the battery to the grid. The only possible difference between the existing device and one designed for the DC-house modeled here is the requirement in the DC-house that the DC output be at 380 V.

MPPT (DC-House)

Description

An MPPT is a high efficiency DC-to-DC converter that produces a constant output voltage required by the load and adjusts the apparent load characteristics seen by the PV array to force it to operate at the maximum possible power output. Because the voltage and current supplied by the PV system depend on ambient conditions, the DC power from the array must be conditioned to provide appropriate power quality for the load. MPPTs are usually included in grid-tie inverters without battery backup and in modern charge controllers.

Currently there is only one such centralized MPPT emerging on the market. Nextek Power Systems has produced a 1kW MPPT for DC power distribution in commercial lighting applications [57] with a reported 98% efficiency. Substantiating this high efficiency are data on MPPTs designed to operate on individual modules. These devices, called DC-to-DC optimizers, track the array's maximum power point at the module level.

Efficiency

Table A1 shows power characteristics and efficiencies of DC-to-DC optimizer models. As can be seen, MPPT efficiencies range between 97.5% and 99.5%.

Table A1. DC-DC Optimizers, Their Power Characteristics and Peak Efficiencies

Manufacturer	Model	Input Power (W)	Max Input Voltage (V)	Nominal Output Voltage (V)	Peak Efficiency (%)
eIQ energy	Vboost 250	250	50	250-350	98.0
National Semiconductor	SM1230	230	100	89	98.5
Tigo Energy	MM-EP35	200	55	375	97.5
Tigo Energy	MM-ES170	300	170	variable	99.6
Xantrex	SunMizer	350	80	65	>99.0

Data Source: SolarPro magazine [58]

Charge Controller (AC- and DC-House)

Description

Charge controllers are used in battery backup systems to regulate the current sent to, or coming from, the battery. Modern charge controllers include MPPT. The charge controllers for the AC- and DC-house are assumed to be identical in the modeling.

Efficiency

Typical efficiencies of high-end charge controllers with MPPT range from 97-99%. Figure A2 shows the efficiency-load curve of the Morningstar SunSaver charge controller, which has a peak efficiency of 97.5%.

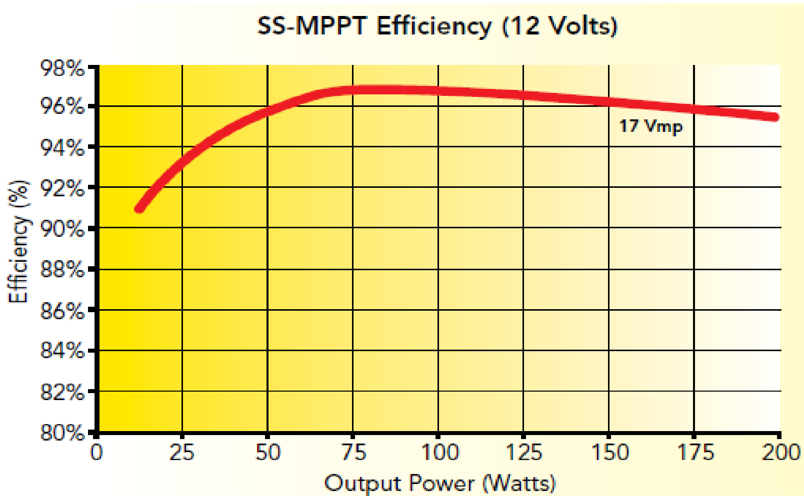

Figure A2. Charge controller efficiency curve.

Efficiency curve of the MorningStar SunSaver charge controller with MPPT. Part-load efficiency (below 30W output power) is about 90-94%. Source: [59]. Reproduced with permission from Morningstar Corp.

DC/DC Converter (DC-House)

Description

DC-DC converters are solid-state devices that convert DC power from one voltage level to another. They are widely used in low-power, low-voltage applications and are found in appliances with electronic circuits. The DC-to-DC converter envisioned for the DC-house is a high-power converter (1-5kW) that requires an input voltage of $380V_{DC}$ and output of $24V_{DC}$. Because this converter ties directly to the loads, it is likely to need isolation from the ground, though the relevant standards have not yet been established. This DC-DC converter does not exist yet specifically for residential applications, but is currently in the research and design stage.

Efficiency

Step-down converters are highly efficient electronic devices with efficiencies that typically reach 95%. Figure A3 shows the efficiency curves of an existing 700W AC power supply that has been modified for DC input. According to power supply manufacturers, it should be possible to produce more efficient DC-DC converters now. As shown in Figure A3, the power supply is about 2% more efficient with DC power input ($400V_{DC}$ narrow range) than with AC power input ($220V_{AC}$). High-end AC power supplies can achieve efficiencies that exceed 92-93%. Thus, it is assumed, with the concurrence of industry experts, that DC power supplies can reach efficiencies of 94-95% at the high end.

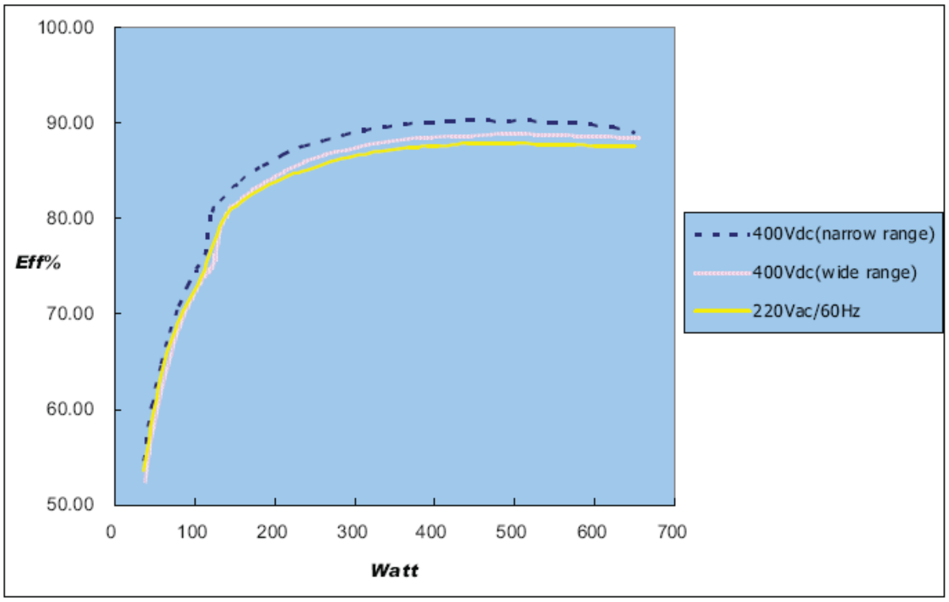

Figure A3. DC power supply efficiency curve.

The power supply's peak efficiency with DC power input (narrow range $400V_{DC}$) is 2% higher than with AC power input ($220V_{AC}$). Data Source: Delta Corporation [60]. Reproduced with permission from the author.

Appendix B: Efficient DC-Compatible Load

(Cooling loads are shaded; non-cooling loads are not shaded. The table is sorted by AC-DC conversion efficiency.)

Appliance	kWh/yr in 2010	Assumed Replacement Technology	Energy Savings	AC-DC Conv.Eff
Central Air Conditioners (SEER)	1328	DC motor with variable speed compressor and fans	47%	89%
Room Air Conditioners (EER)	235	DC motor with variable speed compressor and fans	34%	89%
Electric Heat Pumps (SEER) AC	355	unchanged	0%	88%
Geothermal Heat Pumps for AC	10	unchanged	0%	88%
Electric Clothes Dryers	677	heat pump	50%	89%
Electric Secondary Space Heaters	68	unchanged	0%	89%
Dishwashers	232	controls and DC compatible motor	51%	88%
Electric Water Heaters (EF)	1128	heat pump	50%	88%
Other Electric Space Heaters	463	heat pump	50%	88%
Spas	72	heat pump	50%	88%
Electric Cooking Equipments 5/	273	Induction cooktops	12%	88%
Electric Heat Pumps (HSPF) for Heating	185	unchanged	0%	88%
Geothermal Heat Pumps	7	unchanged	0%	88%
Solar Water Heaters	3	unchanged	0%	88%
Refrigerators (kWh per year 6/)	930	assuming 85% standard-size @587kWh AEU has EURF 0.49 and 15% compact @331kWh AEU has EURF 0.25	53%	87%
Freezers (kWh per year 6/)	199	assuming 80% standard-size @565kWh AEU has EURF 0.47 and 20% compact @246kWh AEU has EURF 0.48	53%	87%
Furnace Fans and Boiler Circulation Pumps	366	Brushless DCPM variable speed	30%	87%
Ceiling Fans	158	Brushless DCPM variable speed motor	30%	87%
Clothes Washers	83	Brushless DCPM variable speed motor	30%	87%
Electric Other	1468	unchanged	0%	87%

Appliance	kWh/yr in 2010	Assumed Replacement Technology	Energy Savings	AC-DC Conv.Eff
Microwave Ovens	114	unchanged	0%	87%
Coffee Makers	36	unchanged	0%	87%
Color Televisions and Set-Top Boxes	938	unchanged	0%	85%
Security Systems	17	unchanged	0%	83%
Lighting-Incandescent	1370	14LPW goes to CFL (electronic ballast) @52LPW	73%	82%
Lighting-Reflector	216	15LPW goes to CFL (electronic ballast) @52LPW	71%	82%
Lighting-Torchiere	89	assuming 80% incandescent @14LPW goes to CFL @52LPW and 20% CFL stays the same	69%	82%
Lighting-Fluorescent	148	assuming 10% linear @83LPW goes to 100LPW and 90% CFL @52LPW stays the same	1%	82%
Personal Computers and Related Equipment	473	unchanged	0%	80%
Rechargeable Electronics	78	unchanged	0%	80%
Home Audio	100	unchanged	0%	79%
DVDs/VCRs	217	unchanged	0%	69%

Source: [6].