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Energy savings from direct-DC in U.S. residential buildings

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ABSTRACT

An increasing number of energy-efficient appliances operate on direct current (DC) internally, offering the potential to use DC directly from renewable energy systems, thereby avoiding the energy 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 a 'direct-DC house' compared to that of a typical net-metered house with AC distribution, assuming identical DC-internal loads. The model comparisons were run for 14 cities in the United States, using hourly, simulated PV-system output and residential loads. The model tested the effects of climate and battery storage. A sensitivity analysis was conducted to determine how future changes in the efficiencies of power system components might affect potential energy savings. 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. Direct-DC energy savings are sensitive to power system and appliance conversion efficiencies but are not significantly influenced by climate.

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1. Introduction

A convergence of factors is driving recent interest in using direct current (DC) from photovoltaic (PV) systems in its DC form to power electricity loads in buildings, rather than converting it first to alternating current (AC), as is current practice. The new millennium has witnessed sustained and rapid growth in the adoption of rooftop PV systems, as concerns about climate change have intensified. PV is a DC power source. Batteries also act as a DC source and are the dominant energy storage technology used with PV systems. In addition to these two factors, an increasing fraction of the most efficient electric appliances operate internally on DC [1,2], making the direct use of DC (direct-DC) in a building more effective and compelling.

Devices that operate internally on DC, referred to in this paper as 'DC-internal' appliances, include all consumer electronics—therefore, essentially all advanced communications technologies—fluorescent lighting with electronic ballasts, solid-state (such as light-emitting diode or LED) lighting, and brushless DC motors. Advanced 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 [3]. DC-motor-driven heat pump technologies for water and space heating can also displace conventional resistance heating with savings of 50% or more. Thus, 'DC-internal' technologies tend to be more efficient than their AC counterparts and are capable of servicing essentially all building loads [3]. These trends make a strong argument for investigating the potential benefits of directly coupling DC power sources with DC loads.

The direct use of DC has been recommended as a key strategy for improved reliability and increased energy savings at the building level [4–6], and it is already being implemented in commercial buildings, particularly for lighting applications [7], while DC-compatible appliances are emerging on the market [8]. However, residential applications have received little attention and differ considerably from commercial applications. Most importantly, residential loads have poorer coincidence with PV system output than commercial loads and are 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.

The majority of studies that address DC power systems in the context of electricity savings have been analytical, rather than experimental, in nature. Savage et al. [9] estimated that electricity savings of 25% can be achieved in the U.S. residential sector by replacing appliance AC-to-DC converters with a more efficient centralized rectifier and using DC distribution to power DC-internal loads. Hammerstrom [10] compared the power conversions for various residential appliance categories under AC and DC power distribution and found that a residential building coupled with a DC power source will use 3% less electricity with DC distribution,

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Nomenclature

AC	alternating current
BDCPM	brushless permanent magnet motor
DC	direct current
LED	light emitting diode
MPPT	maximum power point tracker
NEMS	national energy modeling system
PV	photovoltaic
SAM	system advisor model
VSD	variable speed drive

compared to AC distribution. Thomas et al. [11] reported that an LED lighting system supplied with DC power from PV can reduce its levelized annualized cost by 5% on average, as opposed to an LED lighting system supplied with AC power from PV. However, a 2002 U.K. study [12], found that a residential PV-powered DC distribution system with net-metering was 3% less efficient compared to the equivalent AC distribution system. Finally, Sannino et al. [13] compared the distribution losses of a DC power system in a commercial building with different supply voltages ranging from 48 V_{DC} to 326 V_{DC}, to an AC power system at 230 V_{AC}. According to their analysis, the highest tested DC voltage (326 V) was the most suitable level, from an economic and technical standpoint. The reported savings (or losses) of DC distribution in these studies are largely dependent on the varying assumptions about power system efficiencies, load timing and type, distribution voltage, and whether net-metering was taken into consideration.

This paper estimates the potential energy savings of direct-DC power systems in net-metered residences in the United States. Net-metered systems are considered explicitly here, both because they dominate on-site PV generation [14,15] and because savings could be overestimated if the DC-to-AC power conversions that occur when excess PV power is delivered to the grid are ignored. However, because of the increasing capacity of net-metered PV systems, the intermittence of the solar resource may become a barrier to their future penetration, because of too much power being released to the grid during solar peak periods [16]. Therefore, given that local battery storage, if handled properly, could buffer such fluctuations [17] and reduce the mismatch between PV generation and load [18], this paper also explores the impact of energy storage systems on direct-DC energy savings.

Because of the large variability in insolation across the United States, the paper examines energy savings potential in 14 U.S. cities. This paper also includes a detailed load analysis to account for the changes in the nature of the load needed to facilitate direct-DC and to account for the timing of the load. The latter is essential because, in the absence of energy storage, only loads coincident with PV system output can benefit from direct-DC. Finally, we investigate the potential benefits of shifting cooling loads to earlier in the day (pre-cooling) to make these loads more synchronous to PV system output and, therefore, more able to benefit from direct-DC.

2. Direct-DC house modeling

2.1. Model inputs

To address the research objectives, we developed a spreadsheet model of a hypothetical house with a net-metered rooftop PV system. To test the potential effect of large variations in insolation, we ran the model for an average house in 14 cities distributed across the contiguous United States. These cities, shown in Fig. 1, were chosen because they were the only cities for which consistent residential load data were available in the desired format, as described below. The distribution of the 14 cities is analogous to the solar resource distribution in the United States.

To obtain electricity load data and PV system output for the average house in each of the 14 cities, we used the System Advisor Model (SAM) [20]. The load data are provided in SAM as example average residential electricity loads and are climate-simulated for each hour of the year. These loads, therefore, already incorporate any building envelope effects. For the PV output data, we used SAM to generate hourly estimates of PV system output for one year for each of the 14 cities.[1] It should be noted here that the use of simulated hourly load profiles and PV output data is likely to overestimate the instantaneous PV output that can be absorbed by the load [21] and the system storage dynamics, thus affecting the final energy savings estimates.

2.2. Model development

2.2.1. Distinguishing the cooling loads

Because of the potential importance of load timing and type on energy savings and the large diurnal and seasonal variability of cooling loads, we separated cooling loads from non-cooling loads. To do so, we first converted each city's load data to load data for the average day of each month and plotted the resulting average diurnal load curves. An example is shown for Sacramento in Fig. 2, which also includes the average PV output for June and January, represented by the dotted lines. Based on an examination of the load data, cooling loads are clearly distinguished from non-cooling loads. As seen in the graph, six monthly load curves have clearly distinguishable afternoon-to-evening cooling loads, while the non-cooling load curves of the remaining six months are almost matching. Accordingly, the cooling load was obtained by subtracting the non-cooling load from the total load. Note that for cities with a potentially significant heating load during the winter period (Seattle, Medford, Helena, Denver, Chicago, Lexington, New York), we calculated the baseline load from months with minimum heating or cooling activity (April and October) to avoid including winter electric heating load. We used this approach based on the methodology provided by Reichmuth [22].

2.2.2. House configurations

To quantify the potential energy savings of direct-DC, the model compares power conversion losses in a house with AC distribution, called the *AC-house*, and a house with DC distribution called the *DC-house*, as shown in Fig. 3. The DC-house power system configuration eliminates DC–AC–DC conversion losses to DC-internal appliances when adequate PV power is available, but incurs AC–DC losses via the bidirectional inverter when grid backup power, delivered as AC, is used. In the AC-house, which constitutes the base case, all power is distributed in AC form to appliances that accept AC power. In the DC-house, all power is distributed in DC-form to appliances that accept DC power, but these appliances 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 on the input.

As discussed earlier, cooling loads are separated from non-cooling loads, while the latter are further broken up to high- (380 V) and low-voltage (24 V) loads. High voltage is used for high-power consumption devices and to distribute DC power throughout the house with fewer losses. Low voltage is used for low-power loads, like consumer electronics and lighting, to facilitate safer and easier

[1] The inputs used in SAM to generate PV system outputs are 180° azimuth, 20° PV array tilt angle, and a 0.85 derate factor. Each house's PV system DC rating was 1 kW, but the actual PV system capacity was later scaled to allow zero-net electricity consumption for the conventional AC-house, as discussed below.