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

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## Overview

Advances in semiconductor-based power electronics have made efficient direct current (DC) voltage transformation possible, leading scientists and engineers to reconsider the benefits of this previously niche technology. The resulting research has led to the adoption of direct current power in high voltage transmission, data centers, and commercial lighting installations, among others. In these applications, DC reduces the number of conductors needed to serve large loads and eliminates unnecessary and costly conversions between distributed alternating current (AC) and consumed DC. As these systems have been proven in other markets, a discussion has emerged as to whether more buildings should be wired with DC circuits in addition to – or in place of – AC. Around 50% of the energy presently used in buildings is either consumed as DC in electronic loads or passes through a transient DC state as a means of motor control, resulting in significant losses when grid distributed AC is rectified using inefficient power supplies. When a source of DC generated electricity such as a solar PV array is available, a dedicated DC circuit would eliminate the usual losses that occur both in the inversion from generated DC to grid AC, as well as the rectification back to DC at the end load.

The residential sector is seen as a potential candidate for a transition to DC. Residential buildings currently account for about 15% of all energy consumption in the US and 21% of all greenhouse gas emissions, 71% of which are a result of electricity use in homes. Making up approximately 35% of that energy consumption are appliances, electronics, and lighting, which can all operate on DC. Lastly, sharply declining module costs, the federal solar investment tax credit, utility net energy metering programs, and renewable portfolio standards have together resulted in consistent growth in residential PV installations that is not expected to slow. These factors have made DC microgrids the topic of substantial research which has detailed several aspects of these systems in residential and commercial settings.

Most of these previous studies have used simulated appliance load profiles to estimate savings from a conversion to DC distribution. This study takes the recommendation of one such report and models DC residential systems using a unique dataset with 15-minute interval data measured at the home-, circuit-, and appliance level in 120 single-family homes in Austin, Texas provided by the Pecan Street Research Institute. The use of monitored data allows us to understand the effect of highly variable energy consumption and solar generation patterns on DC-powered residences not available in the modeled data.

We provide a first analysis of the economic feasibility of a DC-powered home using levelized annual cost of electricity to the customer and the cost-effectiveness for avoided CO2 emissions. Additionally, we investigate voltage standards, utility billing and incentive programs, appliance and component markets, and building codes to determine their effects on increased use of DC power in the residential sector.

## Methods

The method established for this analysis uses Monte Carlo simulation to account for uncertainty in the technical and economic inputs to the model. To estimate energy, emissions, and cost savings associated with a transition to DC circuits, monitored appliance data for each home was separated into five classes based on power supply and load type. Savings for each class are estimated based on audit records from the monitored homes, existing power supply efficiencies, and market-available DC appliances. Adopting the approach to hybrid AC-DC systems seen in the commercial sector, ten configurations of DC and AC circuits are simulated for each of the 120 homes in the sample.

With annual electric consumption calculated, levelized annual cost (LAC) is used to evaluate the economic feasibility of each proposed scenario. This metric takes into account the varying lifetimes of system components as well as the time value of money. Capital costs for each major system component include equipment and installation costs, as well as applicable utility provider rebates. Electric costs and solar energy credits are calculated using a tiered rate structure for residential customers.

## Results

Average energy savings for whole-home DC systems are found to be between 10-21% (mean ±1 standard deviation) of each home’s baseline consumption and increase to 13-23% with battery storage for excess solar PV energy. The majority of these savings are attributed to DC condensing units, which alone generate around 12% mean savings that increase to around 13% with storage. These savings are a result of the large fraction of home energy consumption that these devices contribute, the efficiency gains associated with BLDC units, and load profiles that align well with solar output. Lighting loads and EV charging loads generate little energy savings when converted to DC due to their relatively small contribution to whole-home load and the modest savings associated with a conversion to DC. Additionally, these appliances typically have load profiles that do not align well with solar generation and therefore would not be expected to be good candidates for direct-DC. The relatively flat load profiles, substantial energy consumption, and the same efficiency improvements seen in air conditioning condensing units result in whole-home savings of around 1-6% when refrigerators are converted to DC.

## At present costs, only direct-DC-supplied variable speed brushless condensing units match the cost-effectiveness in achieving savings of a traditional home solar PV array. These systems were found to reduce homes’ baseline energy consumption and emissions by 7-17% while adding 18-78% to each homes’ baseline LAC. In none of the simulated configurations was the added cost of battery storage for excess solar PV energy justified by the energy and emissions savings it provided. Given these findings, the continued growth of distributed solar PV generation, the increasing home electronic loads seen in recent years, and industry interest in direct-DC, it is likely that a very small number of such systems in homes may soon appear.

## Conclusions

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

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

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