A Net-Zero Energy Home Grows Up: Lessons and Puzzles from 10 Years of Data

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ABSTRACT

In 2005, Habitat for Humanity of Metro Denver, with support from the National Renewable Energy Laboratory (NREL) and other partners, built one of the first homes in the United States to achieve net-zero energy (NZE) based on monitored data. A family of three moved into the house when it was completed and continues to live there. The home has been monitored continuously for the past 10 years. Although photovoltaic (PV) production has remained relatively steady, net energy performance has varied each year. The home was a net producer of energy annually in each of the first 3 years and in the ninth year, but not in years 4 through 8 and 10. Electricity use in the home increased steadily during the first 8 years. Miscellaneous electric loads (MELs) and space heating appear to be primarily responsible for the increase in energy use. The long-term results from this home have highlighted some research needs. MELs as an end-use category are becoming a larger fraction of whole-home energy use, especially in low-load homes, and we do not have a good way to curb their growth. Changes in people's behavior can make achieving NZE a difficult design problem that may force home builders to put larger PV arrays on homes where NZE is mandated for each home. Large amounts of solar generation can be challenging for electric utilities. Adding a requirement that all NZE homes include feedback for the occupants and grid-responsive capabilities may help alleviate some of the concerns of electric utilities.

Introduction: Net-Zero Energy Habitat Home in Wheat Ridge, Colorado

In 2005, Habitat for Humanity of Metro Denver teamed up with the National Renewable Energy Laboratory (NREL) to design and build a net-zero energy (NZE) home. A main goal of the project was to show that a NZE home was feasible to build within the Habitat for Humanity model: (1) the home design, repeatable and cost-effective for the climate region, was simple enough to be built largely with volunteer labor, and (2) there was no special training required for the occupants to be able to operate it. The home is highly insulated (R40 walls, R60 ceiling, R30 floor), solar tempered, and equipped with heat-recovery ventilation, a solar water-heating system, and a 4-kW photovoltaic (PV) system. Figure 1 is a photo of the home and additional details on the building design can be found in NREL's technical report on the project (Norton et al. 2008).

Figure 1. The Net-Zero Energy Habitat for Humanity House in Wheat Ridge, CO.

When the house was completed, a family of three—a mother and her two young sons—moved in. The home was fully instrumented with sensors and dataloggers so that NREL engineers could monitor the equipment performance, as well as observe the home's energy consumption over time. We have been monitoring this house continuously for the past 10 years, and the resulting dataset is rich with surprising and thought-provoking trends. This paper examines some of the questions that arise when we look back on a decade of energy use for a single family in the same house. Some of these questions prompt us to reconsider how we think about designing and building NZE homes in the future.

Net-Zero Energy?

What does it mean for a home to be truly NZE? According to the U.S. Department of Energy (DOE), a net-zero energy building is one where the source energy consumed is less than or equal to the energy produced by the on-site renewable energy resource on a source energy basis (DOE 2015). This formal definition was in large part based on results of early NREL studies on this topic (e.g., Torcellini et al. 2006; Crawley, Pless, and Torcellini 2009; Pless and Torcellini 2010). This house uses both electricity and natural gas, so the site energy-use for both fuel types was converted to source energy in common units of kBTU.[1] The bar chart in Figure 2 shows source-energy ratio: the annual energy produced by the PV system divided by the total energy (electricity and natural gas) consumed by the house, in terms of source energy. The horizontal line indicates the 100% level, where PV production and source-energy use are equal. The home is a net producer in years 1, 2, 3, and 9, but falls short of the NZE goals in years 4–8 and 10. Overall, the home has not achieved NZE status in its first 10-year period, even though the annual source-energy ratio for nearly half the years on record has been over 100%.

What happened after the first 3 years of operation? Figure 3 shows the annual source-energy use alongside the source-energy offset by the PV system. It appears that the sudden shift from net producer to net consumer is the result of a combination of two effects: From year 3 to year 4, the PV production dropped by roughly 10%, while at the same time, the household energy use continued to rise at roughly 10% per year (when averaged over the first 8 years).

[1] All the energy consumed by the house was converted to source energy using site/source conversion factors of 1.09 and 3.15 for natural gas and electricity, respectively (DOE 2015).

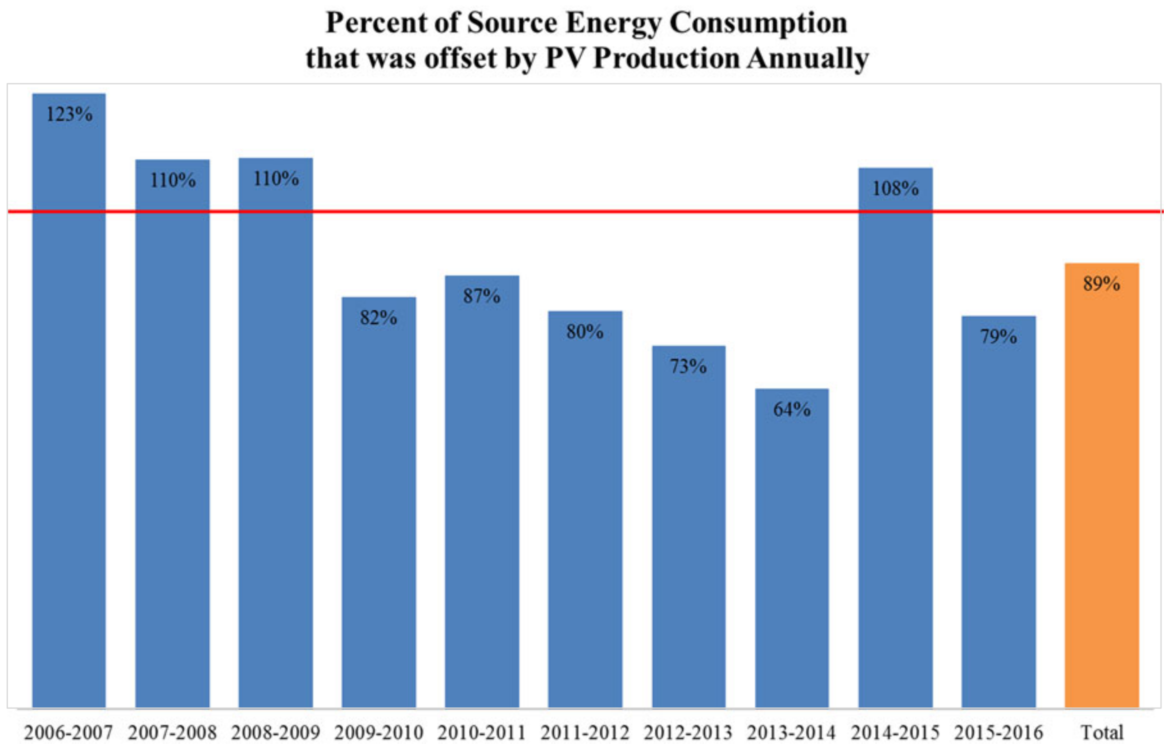

Figure 2. 10-year summary of the source-energy ratio (% of energy consumed that was offset by PV production).

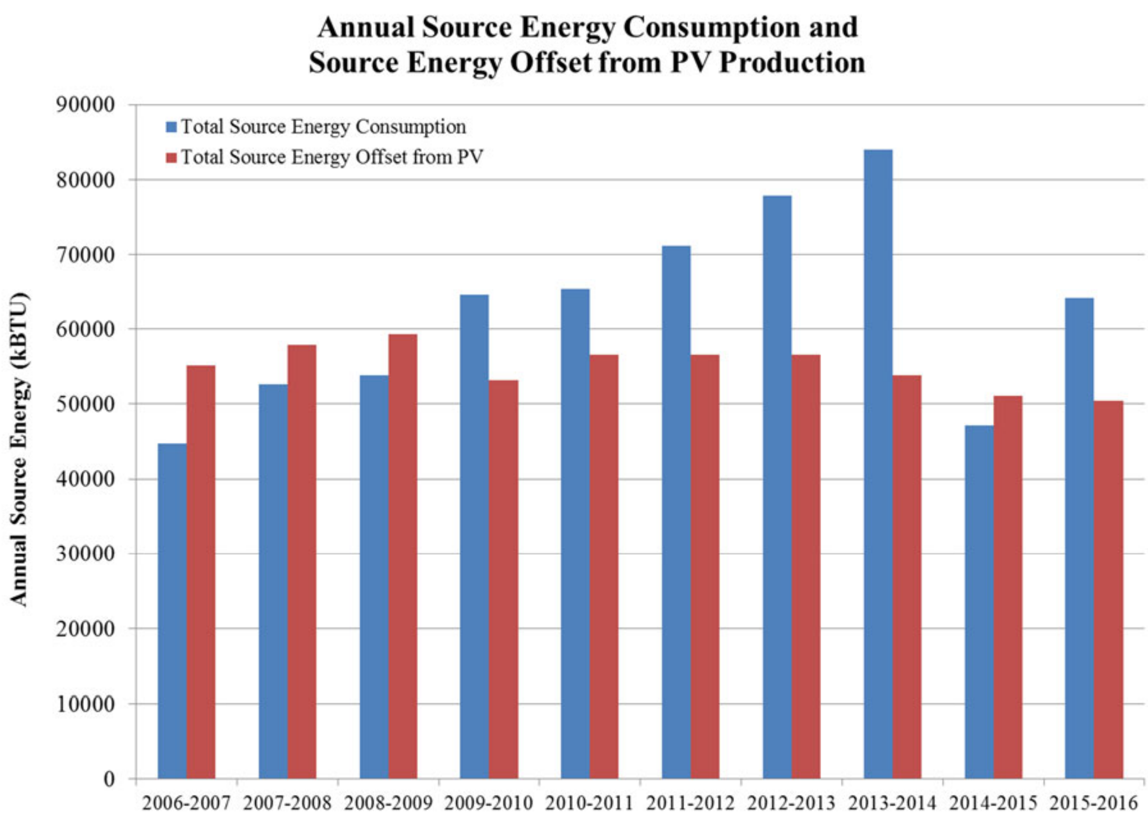

Figure 3. Annual source-energy consumption and offset provided by PV system.

End-Use Trends

Figure 4 shows the annual source-energy consumption, including both gas and electric, broken down by end use. From year 1 through 8, energy consumption generally increased, which also corresponds to the overall trend in source-energy ratio generally decreasing over the same time period. Source-energy consumption dropped by nearly 45% between years 8 and 9, which was a major factor in the source-energy ratio increasing from 64% to 110% between those years.

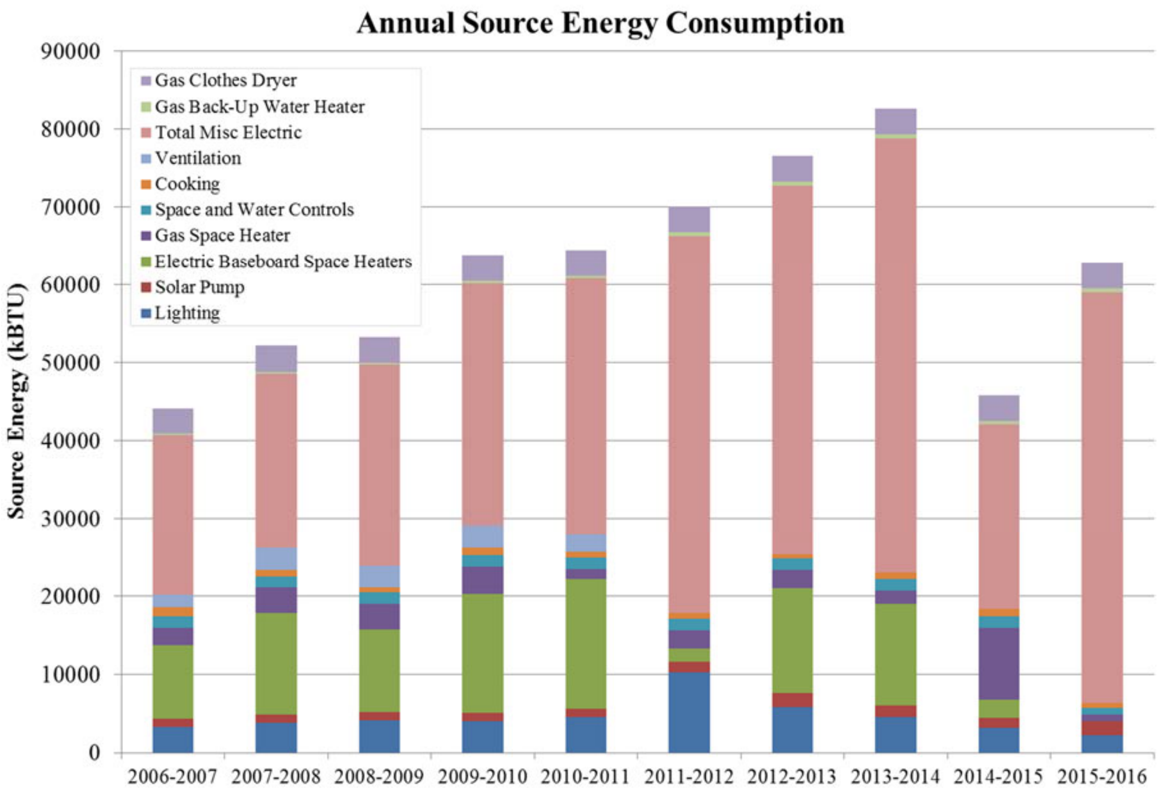

Figure 4. Annual source-energy consumption, broken down by end use.

Despite some fluctuation in the energy generated by the PV system annually, energy consumed in the home is the main driver for the 10-year pattern of source-energy ratio. Looking more closely at the energy consumption by end use, a number of interesting trends are apparent.

The category of miscellaneous electric loads (MELs) in this dataset includes all plug loads and any appliances not individually submetered. Although we do not know what these end uses are, we see in the data that MELs are the main energy user in the home and have grown over time. They likely include home entertainment/office equipment (e.g., TV, DVD player, computer), countertop kitchen appliances (e.g., toaster, microwave), any plug-in lights (all hard-wired lights are captured in the lighting category), and other, less common plug loads (e.g. aquariums, space heaters). Given the proliferation of modern consumer electronics, it is not surprising to see MELs energy use increase—but to see them increase to the point that they make up the *majority* of the energy use in the home is dramatic. An interesting aspect of this dataset is that it spans a 10-year period over which two small children grew into teenagers, and we can reasonably attribute at least some fraction of the growth in MELs to this demographic shift.

The trend in heating is somewhat puzzling. The home has two known sources of space heating—a central gas space heater and small electric baseboards in the bedrooms, which have a high degree of annual variation in use. In some years, the home was heated primarily using gas, and in some years, by the electric baseboards. In other years, neither was used much, although the historical weather data indicate that those winters were not significantly warmer than average. As shown in Figure 5, MELs use increases significantly in the winter months, particularly in years where the heating energy use for both the gas and baseboard heaters are low, strongly suggesting that the occupants may be using additional plug-in space heaters to keep the house warm. MELs usage is significantly lower during summer months than in winter, so it is unlikely that window air conditioners were installed (the home does not have a central cooling system).

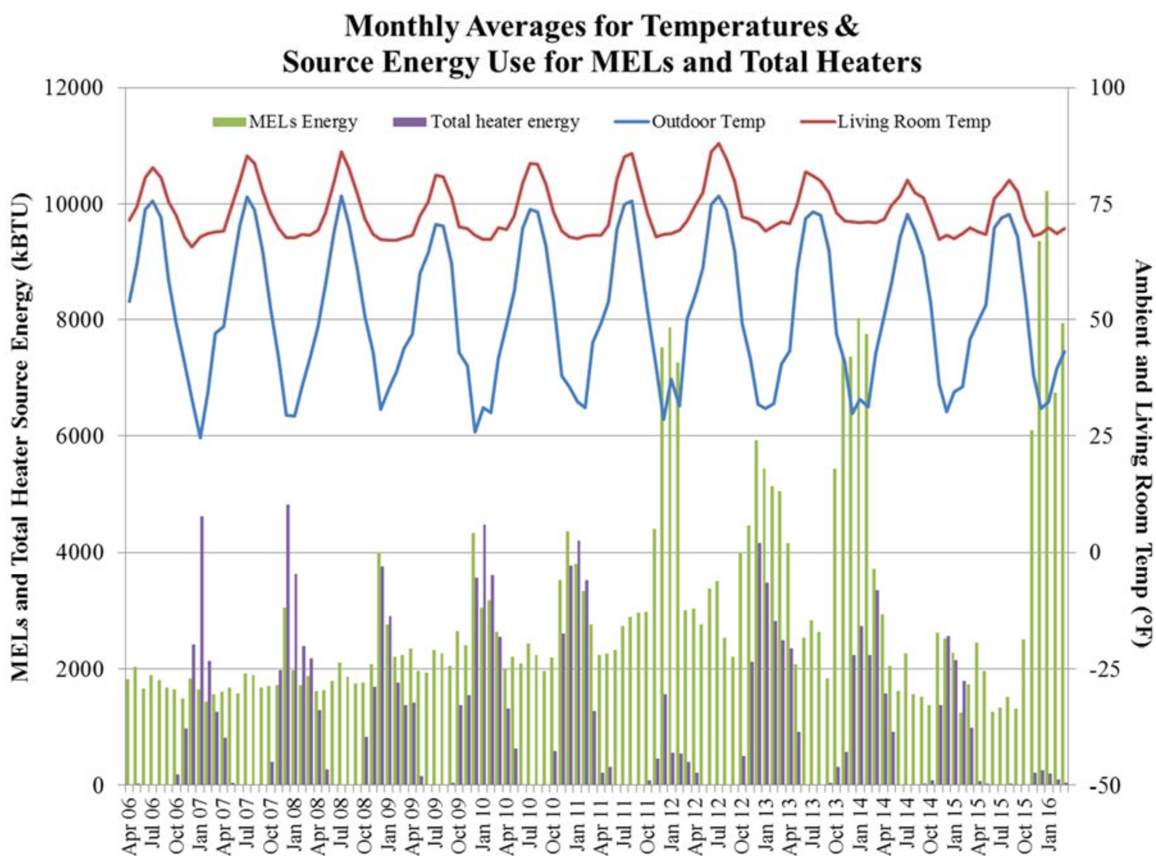

Figure 5. Monthly averages of indoor and outdoor temperatures, as well as monthly source-energy use for MELs and both types of heaters.

The two categories of loads that have the biggest impact on the overall source-energy ratio are MELs and space heating. This case study shows that changes in occupant behavior can drive high variability in annual energy use. The same occupants have lived in the house for the entire duration of the project; yet the evolution of their collective MELs usage pattern is significant enough to impact whether the home achieves NZE annually.

Even in a home with an extensive data acquisition system, it is impossible to fully understand the variability in energy use. In addition to highlighting the variability and unpredictability of MELs use for a single home, are there other lessons offered by this long-term dataset that are broadly applicable?

Understanding and Controlling MELs

As residential building research and improved energy codes have pushed homes to be built with better envelopes and more-efficient HVAC and water-heating equipment, the smaller loads in the home have become a larger fraction of residential energy use in aggregate (Bianchi 2011, Auchter et al. 2014). Improvements in technologies and building methods have enabled reduction to all major loads in a home, but MELs reduction continues to be an elusive goal. Ten years ago, researchers at NREL recognized the need to devise strategies to reduce MELs energy-use in order to achieve 50% whole-house savings (Hendron and Eastment 2006). We have moved beyond the goal of 50% energy savings and little progress has been made to reduce MELs energy use. Consumer electronics are increasingly becoming more efficient (e.g., LCD and LED TVs, laptops, and tablets are more common in homes), but the number of devices in homes has exploded. A number of studies over the last 10 years have identified MELs as a challenging problem that will only become more prominent as homes become more energy-efficient (Earle and Sparn 2012).

One main hurdle to researching the rampant growth in MELs is the challenge to monitor and inventory these end uses that are a moving target by nature. We have general knowledge of the types of devices that people have in their homes and how that mix has changed over time, but there is a dearth of empirical data on people's usage patterns of those devices. Detailed field studies to generate statistically meaningful results would be labor intensive and cost prohibitive. Currently available monitoring equipment for plug loads do not meet the cost and ease-of-use requirements suitable for large-scale field studies. As difficult as it is to measure the energy use of all the individual MELs in a home, MELs energy reduction is an even more challenging task. The MELs category includes a diverse assortment of devices, used in all rooms of the house by different people at different times of day. Most MELs are small loads, distributed throughout a home, and every single one would need a dedicated controller. A MEL controller could be located at the breaker level (depending on the loads connected), integrated into the device, into the wall outlet, or be a pass-through controller that sits between the plug load and the wall outlet. However, the cost to install distributed controllers for all the MELs in a home would likely be much higher than the potential energy savings. Improving the energy-efficiency of the individual devices may reduce the need for sophisticated control, but most new electronics are already fairly efficient and the large overall MELs load is mainly driven by a combination of legacy devices and the sheer number of devices, not the efficiencies of the newest devices. With the advent of the Internet of Things (IoT), the rapid increase in connected devices that have built-in communication capabilities may deliver new opportunities for data collection, as well as personally tailored energy management features.

This particular NZE house offers a unique perspective on MELs and their growth over time. Several studies have looked at multiple homes for relatively short durations and found that the energy use between similar homes can vary wildly based on different occupants (Kerr and Toy 2007). In contrast the subject house exhibits significant changes in MELs usage over an extended time period but with the same occupants.

Is Net-Zero the Right Goal?

Beginning in 2020, California aims to become the first state in the nation to require all new homes to achieve NZE based on 1 year of meter data (Tweed 2015). While California is working to change their building codes to meet this goal, other cities and smaller municipalities are also planning to mandate NZE homes in all new construction in the coming decade (Castle 2015). NZE homes, no longer a niche concept, will become commonplace in the very near future. As the 10-year dataset from this case study shows, meeting NZE in the long term is not as simple as choosing the right building systems, because occupants are a primary driver of a home's energy profile. It may be worth asking the question: is NZE even the right metric to gauge our progress toward sustainable homes?

The process for designing a NZE home naturally starts with a very energy-efficient house. By improving the building envelope and installing an efficient and climate-appropriate package of equipment in the home, the home's energy requirements are minimized. Energy modeling can be used to estimate the amount of PV that is needed to offset the annual energy consumption based on "typical" occupant behavior. Of course, this procedure will result in some homes being net producers and some homes being net consumers (and some homes that alternate between the two, depending on the year), because very few families, if any, match the statistical average energy-use profile. Some of the variability could be reduced by understanding the behavior of the future homeowners, but as this case study shows, families grow up and people change their habits over time. This NZE home has only achieved net-zero status for four out of 10 years; but overall, energy generated by the PV system has offset nearly 90% of the home's consumption. Is that good enough or is this a failed effort to build a NZE home?

Until recently, the cost of solar panels limited the amount of electricity homeowners or builders could reasonably plan to offset, but this factor has changed dramatically in recent years. As the overall cost of installing rooftop PV plummets, the way that builders plan for NZE is certain to evolve. If building codes require NZE, builders could easily install more PV than would be needed for "average occupants" to ensure the homes achieve net-zero energy for nearly all people. Taking this concept to its extreme, it may be easier for developers to shift their focus from improving the thermal efficiencies of their houses to simply installing larger—and now affordable—PV arrays to achieve NZE status; the only limiting factor is rooftop real estate. So will architects design houses differently to maximize PV installation possibilities? Will decades of work on cost-effective efficiency measures be rendered obsolete by cheap solar panels?

Grid Implications of Net-Zero Homes

Maximizing the efficiency of a building before turning to on-site renewables makes practical sense. Excessive distributed PV creates a complex problem for the grid, especially when NZE homes are concentrated together—a likely scenario for production-built housing developments (SMUD 2015). Solar panels are inherently intermittent in their generation profile: a home can transition from being a net-producer of energy to a net-consumer over the span of a few minutes, such as when a cloud covers the sun or when the sun sets. The grid may be a large enough "sink" to absorb this effect for a handful of homes, but when there are many NZE homes on a single distribution feeder, the result can cause instability for the grid.

More important is the fact that the peak output from solar systems usually does not coincide with the peak demand for electricity. The infamous “duck curve” predicted by the California Independent System Operator illustrates how this mismatch impacts the net load for the electric utility as the amount of solar energy on the grid increases (California ISO 2013). The temporal mismatch has the effect of amplifying the transition from peak PV output to peak demand: the “belly” of the duck dips lower with increased PV penetration; when the productive PV hours give way to the early evening peak-load period, there is a sharp ramp in demand. This transition from high generation to high demand that occurs at the end of the day when the sun goes down is particularly challenging for large coal or nuclear power plants to accommodate because of the time constant required to ramp these sources up and down.

Although there are a number of solutions available to mitigate the impact from high concentrations of distributed solar on the electric grid, some utilities have resorted to restricting the number of grid-connected PV systems to avoid these problems (Mulkern 2013). Such a strategy may not be sustainable in the long term, given the dropping price for solar installations combined with increasing public interest in energy independence. A more prudent approach may be to employ active power controls and energy storage, either at the home or feeder level, designed to “flatten” the duck curve and support grid stability (Lazar 2014, Denholm et al. 2015). NZE homes need to work in conjunction with the grid, relying on, as well as supporting, utility-scale power.

The Role for Occupants

Although utilities can address some of these challenges with utility-scale technological solutions (e.g., installing community energy storage systems), many of the strategies identified in California in response to the CAISO “duck curve” report are focused on what homeowners can do (SMUD 2015).

Many people do not think about how their behavior affects energy consumption, but an analogy to driving illustrates how these habits can change. Drivers have traditionally not been concerned about how the way they drive affects gas mileage, but as newer cars have incorporated fuel-economy metrics into the dashboard display, drivers have been prompted to rise to the challenge, many making a game of driving as efficiently as possible. This suggests that energy feedback should also be available to interested homeowners so that they too can learn how to operate their homes in the most energy-efficient manner. Drivers may be more receptive to feedback since they are constantly looking at their dashboard while driving and feedback at the house-level would not be as visible, but feedback may still produce some meaningful behavior change. There are a number of devices that can be installed to provide instantaneous power consumption or overall energy-use numbers, but they can be complicated to install and few people know how to interpret feedback in units of kilowatts or kilowatt-hours. A Nest thermostat, for example, shows a little leaf (like the Toyota Prius) to indicate when an action improves energy efficiency. Similarly, simplified feedback could be provided for whole-house energy efficiency, especially for cases when the homeowner is trying to achieve net-zero status. Studies have shown that feedback alone can produce energy savings in the 5%–10% range of whole-house consumption, although long-term data to investigate persistence are limited (Ehrhardt-Martinez, Donnelly, and Laitner 2010). Education for homeowners before they move into a NZE home could also help give people a realistic expectation for how their behaviors play a prominent role in the home’s energy performance.

Automated Solutions

Controllable loads in the home can participate in demand-side management strategies such as demand response and dynamic pricing. Controllable loads have been explored by appliance manufacturers over the last several years and are mostly hindered by a lack of demand from consumers, but that could change as utilities change their rate structures or rules surrounding rooftop solar.

Other examples of automated ways to flatten the demand from the home to reduce instability on grid include on-site energy storage (e.g., lithium-ion battery pack) and solar inverters with sophisticated control features capable of curtailment. Efforts are under way to develop and vet these possible solutions as complementary pieces to the ever-increasing rooftop solar installations. Controllable inverters are being built by many of the major inverter manufacturers, and early laboratory tests of their performance has helped convince the Hawaiian Electric Company (HECO) to lift their moratorium on connecting residential solar panels to the grid (Ayre 2015).

As more jurisdictions encourage—or mandate—NZE homes, incorporating a variety of automated solutions for mitigating the impact of distributed solar on the grid will become important to ensure that NZE homes do not create problems for the utility. Although grid-responsiveness does not necessarily reduce energy use inside the home, the framework enables utilities to add more on-site (and grid-scale) renewables to the grid, resulting in a much greater impact on long-term sustainability than improving the efficiency of a single home. States and municipalities that are planning to require NZE status should coordinate with their local utilities and Public Utility Commission to evaluate options for incorporating grid-responsiveness to the NZE requirements before they take effect. Forward thinking in this area would ensure that NZE homes have a positive effect on our reliance on fossil fuels by being a partner to the utility of the future.

Conclusions—and More Questions for Future Work

The energy performance of the NZE Habitat Home varied substantially from year to year. For 4 out of 10 years, the home achieved NZE status per the annual definition. Despite a rigorous design process led by a team of experts, increasing energy use in the home was the main reason that the home failed to meet NZE in some years, although some variation in the PV system output also contributed. MELs and heating equipment (along with the occupants) are the biggest sources of variability in annual energy use. Over the entire 10-year period, the rooftop solar system offset nearly 90% of the source energy used by home. It seems possible that over the next several years the home could achieve “to-date” NZE status overall, particularly if the occupants manage to reduce their MELs and heating energy use. What does it mean for a home to be NZE? Is assessing performance on an annual basis somewhat arbitrary?

During the first 8 years of occupancy, MELs use increased annually to become the dominant load in the home. The prominence of MELs in low-load homes is a well-known problem, but there are still few solutions to address it. Control strategies for MELs are difficult to develop because there is no convenient and cost-effective way to measure their energy use. There is no one-size-fits-all solution or even a few standard solutions for MELs control strategies due to the diversity of loads that make up MELs. How can we improve our understanding of how people use the many different MELs in their homes? What are the barriers to creating control strategies that can minimize MELs energy use without inconveniencing the users?

We may soon see larger PV systems installed to ensure that even moderate-load (or possibly even high-load) homes achieve NZE, which can bring additional challenges for the grid. High penetrations of rooftop solar can stress the electric grid when multiple homes simultaneously transition between producing energy and consuming energy and vice versa. Adding a grid-responsiveness requirement for NZE homes could help mitigate problems for utilities, especially in places that are planning to require NZE in the coming years. The best solution will vary depending on the local utility and the location of the home relative to other NZE homes, but could include features such as controllable loads, smart solar inverters, or on-site energy storage (electrical or thermal). Moving forward, both utilities and homes (and their occupants) will need to have the capabilities and willingness to be flexible and responsive to ensure stable and reliable power service. What are the key technical challenges to meeting these objectives?

Occupant behavior is a significant factor in whether a home will reach net-zero status, so diversity in occupancy must be accounted for in estimates of energy performance. Additionally, real-time feedback of the home's performance and homeowner education seem to be important components to helping more NZE homes achieve their goals. Can simplified and straightforward feedback be provided to homeowners in a way that is integrated into the home and does not require a particular brand of thermostat or smart meter to work? Can such feedback truly change behavior in a lasting way? What kinds of datasets are needed to establish confidence in persistent savings from feedback?

What have we learned? A decade of performance data on a NZE-designed home has shown that consistently achieving net-zero status annually is not easy. How important is achieving NZE? Even if a NZE-designed home does not meet the target every year—or ever—it seems there are significant benefits to the homeowner and to the larger society. To put it another way, it is not an all-or-nothing proposition. At the same time, challenges related to grid integration are still present for homes with large rooftop solar arrays, regardless of whether they achieve NZE. What is our true mission? Perhaps the concept of NZE is gradually evolving to represent an inspirational vision rather than a mandate, but pushing the housing industry towards building NZE homes is a step in the right direction, even if some buildings fall short. Ultimately, the goal is to create an electrical infrastructure that relies more on renewable energy sources and less on fossil fuels and reducing the energy consumed by residential buildings is part of this complex challenge.

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