Keeping Track to Stay on Track for Zero Net Energy: Modeling Building and End Use Consumption Targets for a ZNE Community

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ABSTRACT

Over 80% of commercial buildings declaring a zero net energy (ZNE) goal do not have data-verified actual ZNE status. Thus, building occupants, managers, and other stakeholders may wish to track progress toward ZNE throughout the year to ensure the goal is met at the year's end. This is difficult because the balance on any given day, week, or month need not be, and is unlikely to be, zero, given variation in solar production and energy usage due to weather fluctuations and occupancy patterns. This paper presents a model for calculating building and end use level consumption targets at multiple time-scales to serve as granular ZNE progress indicators for stakeholders and occupants. The process of developing these consumption targets involved multiple data sources, including loggers in each building configured to capture total PV production and consumption disaggregated by end uses. We provide an example for communicating ZNE progress indicators via an occupant-facing energy dashboard that we are currently developing. In order to offer occupants' more achievable goals, we weighted each building's targets based on pooled performance across the four buildings, and excluded end uses that were not part of the original ZNE design. Our process for modeling ZNE progress indicators can be replicated by other ZNE communities to keep stakeholders and occupants informed and engaged in reaching their energy goals.

Introduction

A zero net energy (ZNE) building is "a residential or commercial building with greatly reduced energy needs through efficiency gains such that the balance of energy needs can be supplied with renewable technologies" (Torcellini, Pless, and Deru 2006). Regulators have increasingly challenged building standards to move toward ZNE. For example, the California Public Utilities Commission put forward four "Big Bold" goals in the 2008 California Long Term Energy Efficiency Strategic Plan, one of which is a requirement that all new construction be ZNE by 2020 for residential buildings and 2030 for commercial buildings. These goals were determined to be feasible by California's Investor Owned Utilities (ARUP Davis Energy Group 2012).

One recent study found that 332 commercial buildings or developments (including multi-family housing) with a ZNE goal had been built or were in planning or construction phases in 2016 (New Buildings Institute 2016). Educational and office buildings are the most common. Only 53 of these buildings (16%) had data-verified actual ZNE status by that time.

One factor that can get in the way of ZNE or low energy communities achieving their technical potential is occupant behavior (Gil et al. 2010; Karlsson, Rohdin, and Persson 2007). A common and generally effective behavioral strategy to promote demand reductions among building occupants is feedback. Energy feedback that provides comparisons to a goal can be particularly effective (Karlin, Zinger, and Ford 2015). ZNE is a meaningful goal on an annual basis, but tracking progress toward ZNE throughout the year is difficult because the balance on any given day, week, or month need not be, and is unlikely to be, zero, given variation in solar production and energy usage due to weather fluctuations and occupancy patterns.

The present research provides an example of how to develop short-term building and end use level consumption targets to serve as ZNE progress indicators and meaningful goals for occupant feedback. We also present a first iteration of an energy dashboard that integrates the consumption targets. First, we briefly review the literature on energy feedback in commercial buildings and ZNE buildings, and energy dashboards.

Energy Feedback in Commercial Buildings

Feedback interventions have been more common in the residential sector than in the commercial sector. The appropriateness of energy feedback for employees is less convincing since they do not have a financial incentive to conserve and may lack control (or perceived control) of thermostats, lighting, or appliances due to access, automation, or the communal nature of resources. Nonetheless, workplace energy feedback delivered directly to employees via digital or paper-based displays has been found to be effective in reducing energy consumption (Carrico and Riemer 2011) and waste (Siero et al. 1996; Schwartz et al. 2010), and increasing awareness and concern about energy use (Borner et al. 2012). Important workplace energy feedback features include occupant participation in interface design (Borner et al. 2012; Foster et al. 2012), community goal creation (Foster et al., 2012), peer comparison and competition (Borner et al. 2012; Peschiera and Taylor 2012; Siero et al. 1996), and feedback at the department level (Foster et al. 2012). The latter is important because employees might perceive highly granular or disaggregated data (e.g., specific to individual, location, or end use), if accessible publicly or to supervisors, to be an invasion of their privacy (Coleman et al. 2013).

Energy Feedback in ZNE Buildings

Considerably less literature is available on energy feedback in the context of commercial or residential buildings with on-site energy generation, including ZNE buildings. See Bartram, Rodgers, and Muise (2010) for interesting ideas. Petersen, Shammin, and Frantz (2014) considered how the potential for energy feedback in smart buildings might be constrained by technologies that exclude the user from control systems (e.g., motion-activated lights). However, on-site renewable energy systems are not always accompanied by smart end use technologies. We argue that ZNE buildings are prime territory for energy feedback for several reasons.

First, research has found that households who adopt solar photovoltaics (PV) do not always fully understand the technology (Caird, Roy, and Herring 2008). Sometimes there are misperceptions that renewable energy means it is free, clean, and unlimited, so there is potential for a rebound effect whereby consumption increases (Madjar and Ozawa 2006). These misperceptions may be higher among home-renters (Outcault et al. 2016) and occupants of commercial buildings with PV. Thus, energy feedback could educate occupants about how renewable energy systems operate and what it means to be ZNE.

ZNE buildings also offer a unique opportunity to provide feedback on energy production, not just consumption, which could help users connect to their resource systems in a deeper way than consumption feedback alone, increasing motivation to use energy efficiently. For example, research has shown that households often become more aware of their energy use and concerned about saving energy after adopting PV (Caird, Roy, and Herring 2008; Keirstead 2006). Keirstead (2007) found that monitors displaying PV generation information had a notable influence on the behavioral impact (consumption reduction and load-shifting) of household PV.

Finally, ZNE buildings suggest inherently meaningful goals (i.e., keeping consumption within limits of local energy production) that can provide a feedback standard. Kluger and DeNisi (1996) described the feedback-standard comparison as a major mechanism behind the effects of feedback on behavior. In the absence of meaningful goals, energy feedback applications often rely on historical or social comparisons to motivate consumer response. The former essentially makes baseline the goal, and the latter can backfire if the consumer is already performing better than peers. Sometimes arbitrary goals are created; for example, Siero et al. (1996) set a goal for employees to engage in 75% of all available energy saving behaviors. In contrast, ZNE represents a much more meaningful target.

Energy Dashboards

Energy dashboards display information about building energy use gathered by hardware at the meter and/or circuit level. Dashboards can be geared toward building energy managers and/or designed as feedback for occupants. Analytic features such as multivariable analysis and fault detection alarms can help managers identify energy inefficiencies and track performance (Granderson, Lin, and Piette 2013; Lehrer and Janani 2011). Public-facing dashboards may contain simpler data, with a focus on aesthetics and message-framing to promote interest and engagement (Brewer et al. 2013; Schott et al. 2012). Dashboards can increase user awareness and understanding of energy sources and processes, as well as engagement in energy-saving behaviors (Petersen, Frantz, and Shammin 2014; Petersen et al. 2015; Peterson et al. 2017).

Energy dashboards have become popular at university campuses (Salmon et al. 2016) and in ZNE buildings (New Buildings Institute 2016). Businesses and institutions can purchase an all-inclusive dashboard product from a third party company (predominately Lucid), purchase particular elements to integrate into their own website, or create their own dashboard from scratch. Solar companies often provide commercial customers with access to a dashboard to monitor PV production and sometimes also consumption. In summary, there have been dashboards in ZNE buildings that provide consumption feedback and PV production monitoring, but to our knowledge none have integrated the two by tying day-to-day performance directly to ZNE via progress indicators. This is a central focus of our project.

Developing ZNE Consumption Targets for West Village at UC Davis

West Village (WV) is a mixed-use ZNE development at UC Davis (UC Davis West Village 2016). It has been described as “a ‘living laboratory’ and demonstration for ZNE community business models, strategy, and technology” (Finkelor et al. 2010). WV has yet to meet its ZNE goal (Dakin and German 2014; UC Davis West Village 2012-2013, 2013-2014; Wheeler and Segar 2013). In the UC Davis West Village 2012-2013 Annual Report, the community’s performance was determined to be 87% of ZNE; the measurement period was mostly prior to occupancy of the commercial spaces, which occurred in Fall 2013. Commercial spaces were fully occupied over the measurement period for the 2013-2014 Annual Report, which assessed WV at 82% overall, and commercial spaces in particular at 83% of ZNE.

Behavioral interventions have been highlighted as part of the solution for West Village to reach ZNE (Dakin and German 2014) and there have been a few discrete (rather than ongoing) interventions (Hammer et al. 2014; Outcault et al. 2016) with student residents. Less attention has been given to occupant behavior in the 60,928 sq. ft. of commercial space at West Village. This space was intended for retail, and PV volume was modeled accordingly. Instead, most retail space became occupied by research labs and offices, which are contributing to higher energy consumption than the dedicated PV panels produce (based on an annual ZNE calculation). Our research targets these spaces, which are located on the ground floor of four separate buildings.

Modeling Process

This paper focuses on modeling granular consumption targets for the West Village research centers to serve as ZNE progress indicators throughout the year. This was an iterative process that included some challenges along the way. We will overview our process to illustrate possibilities, problems, and solutions in order to inform others who are attempting a similar task. Later we discuss how the targets can be integrated in an energy dashboard.

Our first data sources were the developer's estimates of production and consumption for each of our target buildings and the solar company's dashboard providing production data for each building. We explored modeling consumption targets based on production data alone while we pursued access to actual consumption data. To derive a monthly consumption target, we simply divided the annual estimated or actual production by 12. Since there would be seasonal patterns in consumption, having the same target for each month was imprecise, but this was a starting point until we were able to access consumption data.

We then gained access to utility bills for our target buildings, which reported monthly net production (energy supplied to the grid) and consumption (energy provided by the grid); see Table 1. These data could not help us understand seasonal patterns in consumption since they did not include consumption of energy used directly from on-site generation. However, the bills did reveal that ZNE was likely out of reach for two buildings (Buildings 1 and 3) and might be too easy for another (Building 2). For example, net consumption for Building 1 was 13.3 MWh higher than net production, which averages to an excess of 256 kWh per week. For illustrative purposes, we later learned this amount is greater than the average weekly consumption of plug loads in that building (247 kWh), and about 20% of average total weekly consumption.

The two buildings for which ZNE seemed out of reach each included a significant end use which was not planned for in the community's design: (1) a large lab space for the Western Cooling Efficiency Center, which runs HVAC equipment for testing, and (2) extensive electric vehicle (EV) charging stations at the Plug-in Hybrid & Electric Vehicle Research Center. Since these features were not included in the original design and no additional PV panels were added to offset them, we decided to exclude the loads from our ZNE target and performance calculations. This was also deemed necessary because targets that are unattainable would not be motivating for occupants when integrated into feedback (e.g., in buildings dashboards).

Table 1. Net energy production and consumption (MWh/yr) for WV research offices from utility bills (March 2016 - February 2017), rounded to three significant digits.

Building	Annual Net Consumption	Annual Net Production
1	40.4	27.1
2	34.3	36.9

3	39.2	33.8
4	51.1	38.2
Total	165	136

Ultimately, we needed to collect our own consumption data for two reasons: (1) to ascertain total consumption over time; and (2) to disaggregate by end uses. In addition to tailoring targets based on seasonal patterns over a 12-month period, we wanted to tailor targets based on patterns at finer temporal scales (week v. weekend and work v. closed hours). Disaggregation was necessary in order to exclude the cooling lab and EV charging from ZNE consumption targets and performance calculations, and we also wanted to model consumption targets for specific end uses.

To collect our own data, we installed Onset HOBO loggers (models UB30 and HOBO RX3000) in each building and configured 50 Amp Current Transformers with FlexSmart TRMS Modules to capture different end uses as well as PV production. To map electrical circuits to end uses we consulted the buildings' electrical blueprints and electrical panel notations. Sometimes these source disagreed; in these cases, we employed testing methods. The measured current along with known voltages were used to calculate the end-use energy consumption. The loggers capture data every minute and upload to the HOBOlink portal every 10 minutes.

As we waited to accumulate 12 months of baseline data in order to understand seasonal consumption patterns, we experimented with different ways to weight consumption targets with more limited baseline data. For example, we tried a calculation based on 2-4 weeks baseline data at the beginning of each season. We calculated a weekly consumption target for each season, for each building, by weighting average weekly production (estimated annual production/52) by the proportion of baseline average weekly consumption to actual annual production provided by the solar company's user web portal. From there, we calculated a daily consumption target for each (a) weekdays and (b) weekend days/holidays by deriving an average daily target then weighting it based on baseline data for each type of day. Using this same logic, we derived weekly and daily consumption targets for end uses (plug loads, lights, HVAC, and kitchen).

Once we accumulated a year's worth of baseline data from our HOBO loggers (with the exception of one building where a logger malfunctioned and had to be serviced, then replaced), we were able to calculate more accurate ZNE consumption targets and extract the EV charging and cooling lab end uses from ZNE target and performance calculations. We took each building's actual annual PV production, as measured by our HOBO loggers, as its annual ZNE consumption target and broke that down into targets for smaller timescales and end uses, again weighting each target based on temporal consumption patterns and end use consumption distributions. We were also able to measure actual ZNE performance with our data. Table 2 shows these data, along with the developer's estimates of consumption and production.

Table 2. Estimated and actual (May 22, 2017-May 21, 2018) energy production and consumption for WV research offices, rounded to three significant digits, and annual ZNE performance (actual production/actual consumption)

Building	Annual Consumption (MWh/yr)			Annual Production (MWh/yr)		ZNE Performance	
	Estimated	Actual		Estimated	Actual	All end uses	Excluding EV and lab
		All end uses	Excluding				

			EV and lab				
1	55.3	67.7[b]	46.0	56.9	40.0	59%	87%
2	72.8	62.2[b]	53.6	74.7	47.6	76%	89%
3[a]	73.9	--	--	79.4	--	--	--
4	59.3	87.2[c]	74.4	86.6	74.9	86%	99%
Total	261	217	174	298	163	75%	94%

[a] Insufficient data due to problems with one of the loggers

[b] Including electric vehicle chargers

[c] Including cooling lab

Removing EV charging and the cooling lab improved ZNE performance, but performance still ranged considerably across buildings. We then realized that consumption targets derived separately for each building based on energy production from their respective dedicated PV panels would result in inequitable expectations for the different buildings. This would be problematic when integrating the targets into occupant feedback (e.g., a building dashboard). In particular, it would be unfair if these targets were used in competitive feedback elements (e.g., a building leaderboard) because some buildings would have an advantage over others whose baseline performance was worse (likely due to a number of factors beyond occupant behavior).

To even the playing field, we decided to: (a) pool consumption targets across the four buildings for a community consumption target; then, (b) weight each building's consumption target according to its proportion to the community target, essentially creating a handicap factor to cancel out building advantages and disadvantages. We applied this calculation to targets at varying time steps and for different end uses via the weighting procedures outlined above.

Ultimately, our process yielded ZNE consumption targets for each building and end use. We are preparing a further adjustment that automates the process of updating the targets based on recent consumption data. This process would follow the same principles as outlined above, but targets would be dynamic, based on a rolling baseline.

We have modeled targets at multiple time steps--monthly, weekly, daily, hourly, and even for 10 minute intervals, which is the finest granularity of consumption data we receive from the loggers. However, producing valid consumption targets at short time frames is challenging due to variations in weather, even though we are basing the targets on historical trends in consumption data (i.e., controlling for historical trends in weather). We are considering additional sensors to track and incorporate real-time weather conditions into the dynamic consumption target calculations.

We have also considered further adjustments that might need to be made based on occupant response to feedback that incorporates the consumption targets. Specifically, if the targets prove too challenging (i.e., are infrequently met), we will add an additional handicap factor to adjust them to an achievable percentage of what would actually constitute ZNE. In essence, we would set the target toward lower levels of baseline performance, then gradually raise the bar. We could also use this method to gradually incorporate some of the consumption from EV charging and the cooling lab if the targets that exclude these end uses are consistently met, in order to make the targets more challenging. This is necessary because occupants might tune out or give up if their building was virtually always on or off target, respectively.

Communicating ZNE Consumption Targets through an Energy Dashboard

Our team is currently developing West Village Energy Dashboard (WVED; wved.ucdavis.edu) as a prototype for integrating ZNE consumption targets in an occupant-facing dashboard. WVED is live online, but has not been offcially launched. We plan to launch soon by advertising WVED to occupants and displaying it intermittently on a large digital monitor in the entryway of each building. We will encourage occupant feedback on the dashboard design, continue to refine it, and measure its impact on occupant behavior an energy consumption.

WVED consists of a frontend javascript application written in AngularJS, which interfaces with a backend javascript API written in Node.js. It pulls the latest data from the HOBOlink web portal every 10 minutes at a one minute offset past the logger schedule, then inserts them into a database. It has two main elements: a splash screen (Figure 1) and building dashboards (one for each building).

We have integrated our consumption targets into each element, and are continuing to create and refine data visualizations to best communicate the targets. The splash screen will depict a panoramic view of the four targeted buildings, with near-real-time energy production and demand gauges, as well as a weekly community ZNE "budget", which is simply the community consumption target for the week (Figure 1). We are currently considering similar "budget" concept visualizations for end use consumption targets.

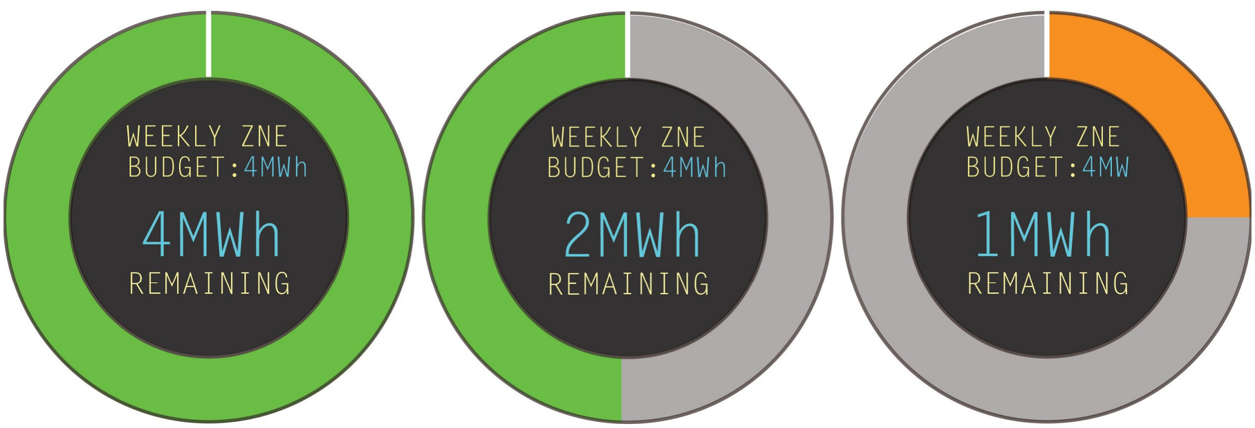

Figure 1. Weekly community ZNE budget. A weekly consumption target for all four buildings combined is represented as a budget that depletes over the course of the week, with fill color changing to yellow to warn that the rate is near target, and accumulating red after the rate exceeds target.

The building dashboards can be accessed from the splash screen via the menu or clicking on a particular building. Here, ZNE consumption targets are incorporated through an empathetic gauge (Petersen et al., 2014; Petersen et al., 2017) and leaderboard. An empathetic gauge is a lifelike character that conveys qualitative information through its changing moods or health. Animals are common empathetic gauges; they can be evocative of environmental impacts of consumption (e.g., polar bears; Loeb et al. 2010), or they may be a local, familiar, or relatable animal (e.g., albino squirrels at Oberlin College; Petersen et al., 2014). Research has shown that empathetic gauges can be an effective strategy in energy feedback (Bull, Stuart, and Everitt, 2012; Kim, Hong, and Magerko 2009; Loeb et al. 2010).

WVED's empathetic gauge is a horse, which is relatable to UC Davis West Village occupants because the school mascot is a horse and the school has a strong agricultural program.

Each building has its own unique horse, located at the top left of their dashboard. The horse's "mood" corresponds to the building's current position in a weekly leaderboard, relative to the other three buildings; thus, the horses have four possible expressions (Figure 2). The color of each horse's shirt and path on the leaderboard (Figure 3) reflects whether the corresponding building is currently on track for its weekly ZNE consumption target (green if yes, red if no; this is independent of leaderboard position).

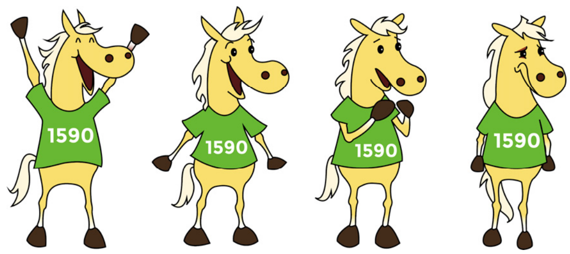

Figure 2. Empathetic gauge. Each building has its own horse mascot that conveys information about performance.

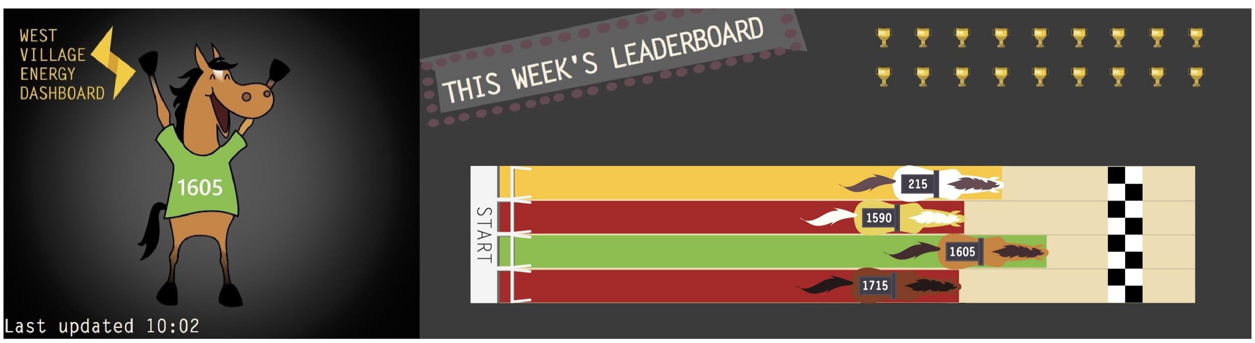

Figure 3. Empathetic gauge (left) and weekly leaderboard (right). Each horse's shirt and path color reflects the corresponding building's performance relative to their weekly ZNE consumption target.

The leaderboard shows each building's performance accumulating over the week, starting every Friday at noon. Each building's leaderboard position reflects its consumption relative to a weekly ZNE consumption target weighted over the elapsed minutes of the week. To illustrate, if a building exactly met their target throughout the week, they would progress at exactly the rate of the time-weighted target; they surpass that position if they use less energy than their target up to a given point in the week, and lag behind it if they exceed their target. For enhanced visualization, an exaggeration factor increases small differences between leaderboard positions.

Each Friday at noon the leading horse reaches the finish line to win the race and is celebrated on the dashboard with a trophy beside the winning horse (empathetic gauge) for the rest of the weekend before resetting on Monday 12:00 a.m. (to show the data accumulated since noon Friday and then continue for the rest of the week). When the leaderboard resets, the winner's trophy will shrink and move to the top of the leaderboard so each building can accumulate weekly wins.

Conclusion

This paper presents a process for calculating granular ZNE consumption targets to serve as progress indicators and meaningful occupant feedback, and provides examples for integrating the targets into an energy dashboard. Reaching ZNE was not feasible when considering each building on its own and including end uses not originally planned for in the community's design, so we adjusted the targets by pooling performance across buildings and excluding end uses that were not part of the original ZNE design. This means our targets do not represent true ZNE, but we considered this necessary for the feedback (dashboard) to not penalize occupants for misalignment between design assumptions and actual PV production and end uses.

We will continue to refine our models and design and test data visualizations in our dashboard. In particular, we will automate the consumption target calculations for more precise and dynamic assessment and feedback. Other future plans include incorporating West Village student and faculty housing and adding an educational component to WVED to help residents, commercial space occupants, and visitors understand what ZNE means and the important role of occupant behavior. We hope to eventually package and disseminate our modeling and dashboard technologies in open-source formats to be adapted for other ZNE buildings and communities.

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