An Evaluation Framework for Residential Zero Net Energy Buildings

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ABSTRACT

The push for zero net energy (ZNE) targets for residential new construction gives rise to two important evaluation questions: How will we know that these are truly zero net energy buildings? How do we know the building designer considered all cost effective energy efficiency measures before adding renewable energy sources?

The evaluation approaches to answering these questions will vary, depending on the definition of ZNE. For example, if the definition were that the net billing meter should be at zero for the year, the evaluator would simply wait for a year of occupancy, and confirm that the meter is at zero. Of course, if the building does not turn out to actually be ZNE, it's too late to do anything about it.

From a definitional and an evaluation perspective, it will be important to determine whether a building truly is ZNE, and not simply appearing to be ZNE (or not ZNE) due to circumstances such as unusual weather patterns or unique occupant behaviors (e.g. on vacation for six months).

This paper discusses the importance of establishing a ZNE definition that answers six primary questions before a jurisdiction embarks on energy savings or cost effectiveness evaluations of ZNE residences, and then discusses the evaluation implications of those answers.

Introduction

A great deal of policy attention, technical thought, and even efficiency program effort, has been devoted to the notion of zero net energy (ZNE) buildings (HMG 2012). The ZNE concept is simple enough: a building should produce enough energy from renewable sources to offset its energy use. Trying to implement this concept, however, raises a host of definitional questions.

This paper will not presume to identify the correct ZNE definition, as different jurisdictions will have different motivations behind their ZNE goals. Rather this paper will discuss how one would evaluate a building's claim to ZNE from the energy savings and cost effectiveness perspectives. This paper discusses the importance of establishing a ZNE definition that answers six primary questions before a jurisdiction embarks on energy savings or cost effectiveness evaluations of ZNE residences. The primary questions include:

- **Design vs. Performance** – Is the building *designed* to be ZNE, or must it be shown to *perform* as a ZNE building?
- **Timeframe** – Over what time period must the building achieve ZNE?
- **Multiple Energy Types** – Is the building ZNE for just electricity, both electricity and gas, or all energy sources?
- **Human Factors** – Are "typical" occupant energy use behaviors assumed, or are "actual" occupant behaviors included in the ZNE determination?

- **Renewable Energy Sources** – Must the renewable energy sources be part of the building, site, neighborhood, or region?
- **Cost Effectiveness** - Does the building's mix of energy efficiency and renewable energy measures achieve zero net energy for the least cost?

The evaluation issues that arise from these questions may, and probably should, influence how policymakers choose to define ZNE. These evaluation considerations are discussed in the following sections.

Ground Zero: Different Approaches to Zero Net Energy Definitions

Different states and local jurisdictions have taken differing approaches to defining ZNE. Most are using a site-energy based definition, where the building and its renewable sources are all on the same property, as the basis for ZNE. Several states, including CO, MA, MN, NM and others, such as Pima County in Arizona, have adopted policies that are promoting ZNE buildings. Many, but not all, of these policies include an implicit choice to use a year of actual energy performance to determine that the building is achieving ZNE. The Living Buildings Challenge has an active ZNE certification program based on measuring actual energy performance. Common to many of these approaches are two things – measured kWh consumption for the first year vs. predicted; and all-electric end uses, meaning no gas-fired (or other fuel-fired) equipment or appliances. Thus they conflate two issues – that ZNE requires an all-electric building and that first year performance is indicative of the 'real' energy use of buildings. However, any *design* done for ZNE typically will be based on an average year of weather, rather than on a specific year.

California has taken a different approach, defining ZNE using their unique TDV, or "time dependent valuation" metric (CEC 2008), which is essentially a zero net societal cost from the perspective of the participant homeowner. The California approach also presents a unique set of evaluation challenges, because TDV is a calculated value that is difficult to measure in practice due to the variety of forecasted assumptions embedded in its values. We leave that special set of evaluation challenges for a different paper.

So, it is clear that different jurisdictions will choose different ZNE definitions to suit their respective energy policy needs. From an evaluation perspective, the important issue is not which definition they choose, but rather that their definition includes answers to six questions in order to equip evaluators with sufficient parameters to effectively complete their evaluations.

Design vs. Performance

Is the Building Designed to be ZNE, or Must it be Shown to Perform as a ZNE Building?

It seems simple enough to observe whether a building achieves "ZNE performance": one would measure how much energy the building consumes and how much energy it produces and then do the arithmetic to determine whether the energy production is less than, equal to, or greater than the energy that was consumed. The problem arises when somebody asks, if it was indeed ZNE performance, "Was that a fluke, or will the building be ZNE in future years?" In other words, did the measured time period include unusually mild weather (corresponding to low space conditioning energy needs), or unusually sunny or windy conditions (corresponding to high renewable energy production), or unusually low occupant demands for energy (due to long vacations or unused appliances), or any of a number of such occurrences. Conversely, the building may have failed to achieve ZNE performance for the opposite reasons, such as extreme weather or poor renewable output or lots of visitors. So, direct measurement of performance is an imperfect way to determine whether a building is truly a ZNE building.

The other problem with the ZNE performance measurement approach is that it lacks predictive power. If one is investing in a ZNE building, one would prefer to know, before it is built, whether it will perform as expected, and under which set of circumstances. Will it achieve ZNE in a typical year, with typical operation? Or will it achieve ZNE under less favorable circumstances, such as an extreme weather year? Or will it only achieve ZNE if the occupants and the weather all converge to produce optimal conditions for energy performance? A buyer looking to purchase a ZNE building could reasonably expect the builder to provide the answer to those questions, a form of assurance that the building will perform as advertised.

The other reason there is a need to accurately predict ZNE performance comes during the building design process. An early, critical criterion to establish for "ZNE design" is the level of energy efficiency a building must achieve. In jurisdictions with ZNE policy goals, this criterion will likely be determined by state or local policy. In jurisdictions without ZNE policy goals this criterion will be left to the discretion of the building designer. For example, the policy-directed strategy for designing a ZNE building in California is first to make the building and its energy systems as efficient as is economically reasonable, and then to design the smallest renewable energy system necessary to supply the remaining energy needs of the building. Regardless of whether policymakers or building designers determine the optimal balance, to achieve ZNE design one needs to be able to quantify costs and performance among the various design options, and to predict the ZNE outcome. This requires design tools that can simulate energy performance in detail.

The energy simulation tools for ZNE buildings allow one not only to optimize the design of the building and of the renewable energy system, but also to explore the conditions under which ZNE performance was obtained and to perform scenario analyses to forecast how variances in those conditions over time could affect future performance. This requires state-of-the-art simulation tools, operated by analysts who have a deep understanding of the building science of advanced energy efficiency. It also requires careful delineation of the assumptions. For example:

Table 1. Specifying assumptions for zne analysis

Analysis parameter	Examples of choices
Weather data	Typical year? Extreme year? Last year's actual weather?
Operational protocols	Thermostat settings, ventilation schedules, etc.
Occupancy patterns	Two working adults who are seldom home? Four people including two teenagers who take extended showers and play lots of video games? Six people who entertain often?
Appliances & plug loads	One big TV or several? One refrigerator or additional Freezers/refrigerators? Pool and/or spa? etc.
Renewable energy system performance	Equipment degradation, Shading patterns, System faults, etc.

Pushing even deeper into energy efficiency, one could model different comfort protocols (e.g., enhanced air movement to allow for reduced air conditioning), or other strategies to reduce energy needed for lighting, fans, clothes dryers, and other energy uses.

The evaluation approaches will be different for ZNE performance than for ZNE design. As we observed at the outset, a simple measurement of "energy out" vs. "energy in" can be straightforward. It would be more useful and informative, however, if this could be supplemented by measurement of the key parameters governing performance: actual weather conditions, operational schedules, appliance and plug loads, renewable energy system performance, etc. Under the design approach, evaluators would examine the modeling assumptions, and could go farther by verifying that the building was actually built and operated as assumed, and that the renewable energy system performed as expected. The most thorough evaluation would do both model verification and as-built/as-operated documentation, and would adjust the simulation model to determine whether it matched the actual performance. Evaluators could then provide a thorough report on the ZNE building performance.

Efforts are underway to develop ZNE certification programs based on these considerations so that there is a standard, agreed-upon method for designing ZNE buildings and for verifying their performance (e.g., LBC 2014). However, these have limitations due to some of the assumptions made by these certification programs, such as the assumption of an all-electric building for the LBC.

Timeframe

Over What Time Period Must the Building Achieve ZNE?

Typically, ZNE definitions refer to a full calendar year of operation, encompassing all of the seasons, with the intention that by the time the year has ended, the energy use and production of the building will have netted out to zero. In some seasons, energy consumption will be lower than others; in some seasons renewable energy production will be higher than in others. In the end, they should balance out.

It is possible to choose other time periods. For example, a building might achieve ZNE performance after several years, smoothing out differences in weather or behavior over time. It is also possible to choose a shorter time period such as a summer cooling season for ZNE performance targeted at avoiding excessive peak energy use that could tax the grid (e.g. the SMUD Home of the Future has a zero peak goal (SMUD 2006; SMUD-HOF 2014).

In the case of an as-designed ZNE building, the question arises of what type of weather year to use. Some weather data files to be used in performance analysis are designed to present year-round average weather. These may be broadly representative of the conditions that the ZNE building will experience over time, but they may miss the peak design weather conditions, such as heat storms or extra cloudy/cold weeks, that would especially challenge ZNE performance. For example, if one of the goals of ZNE buildings is to reduce peak electricity demand on the grid during heat storms, the weather data used to design these buildings should include such extremes, so that the building design expected performance can be properly tested. Similarly, if the renewable energy system is a solar photovoltaic array, an extremely cloudy period should be included in the weather data; or if a wind system, periods of high and low wind should be included in the modeling.

From an evaluation perspective, the issues of design vs. performance discussed in the previous section apply equally to the timeframe issue. The evaluator will use the same tools to determine whether the building has been ZNE for the specified time period. In the case of a multi-year timeframe, it would be useful for the evaluation to assess ZNE performance for the individual years or for separate seasons within the timeframe, to better understand the variables that contribute to its' ZNE performance.

Multiple Energy Types

How Should ZNE Definitions and Evaluators Handle Accounting for Multiple Energy Types?

Various definitions of ZNE have struggled with the question of how to handle multiple energy types. It is easier to evaluate electric-only ZNE homes, because both energy use and production can be modeled and measured consistently. However, a comprehensive definition of ZNE would include multiple energy types both on the consumption and generation sides of the ZNE equation. For example, homes could consume non-electric fuels such as gas, wood, or oil, and may generate non-electric heat from solar water heating, or may generate local biogas. The non-electric fuels and generation present challenges for both the performance-based approach and the design-based approach to ZNE since there is more than one way to "equate" different energy types.

To assess the achievement of ZNE, all energy sources are converted into common units of measurement. The most common method to do this is to convert all site fuel sources to equivalent heat energy content; however, this method has its shortcomings since it gives no recognition to site vs. source conversion losses[1]. As a result, architects may be encouraged to use electric resistance heating for its low first cost and its high efficiency *at the site*. Another option for converting fuel sources to common units is to consider source energy heat content for

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[1] Electricity delivered at a home (site) is produced with roughly three times the amount of energy at the power plant (source), primarily from unavoidable losses from energy conversion, transmission, distribution and voltage transformation..

all fuel sources. A third option is to use a time-dependent-valuation (TDV) metric, as employed in California, that "values" energy sources based on fuel type and *when* the energy is used or produced. While this approach is more difficult to evaluate, it may provide a more meaningful valuation of energy consumption and generation, especially where system peaks and load shapes are important. Other, yet to be developed approaches to generating common energy units are also possible.

Regardless of the common units method used, the energy content of the non-electric fuels must be measured with reasonable accuracy. With biofuels, this can be difficult. For example, the heat content of wood fuels depends on its moisture and pitch content. Biogas heat content likewise depends on its moisture content and chemical composition. Third, feeding some types of renewables back to the utility can be complex; verifying the injection of directed biogas into an out-of-state utility's gas distribution system has been a challenging endeavor (Itron 2012). Finally, the performance of a building using these less conventional fuels may be more difficult to model over time.

From an evaluation perspective, all of these challenges can be met, given sufficient resources to measure consumption and generation, and given simulation tools that have the necessary capability to account for their energy behaviors within the larger building systems. At present, only the most sophisticated performance modeling tools have these capabilities.

Human Factors: Plug Loads and Occupant Behaviors

Are "Typical" Occupant Energy Use Behaviors Assumed, or Are "Actual" Occupant Behaviors Included in the ZNE Determination?

Notwithstanding the various complexities in designing and evaluating ZNE buildings that have already been described, perhaps the biggest challenges result from the widely-varying behavioral patterns of building occupants. For example, their comfort desires can strongly influence ZNE performance. It is well understood that some people are quite frugal in their demands for heating and cooling, and may simply turn off their systems except when the weather is very hot or very cold. There are other people who insist on what they view as optimal heating and cooling year round. Some people heat and cool their buildings whether they are at home or not, while others religiously turn down their thermostats whenever they are away. Similar issues apply to the lighting systems in the building and to how occupants operate other major energy using equipment. Clearly, these behavioral differences can have a substantial impact on the performance of a ZNE building.

Because ZNE buildings push the limits of building energy optimization, even relatively minor energy use choices may make the difference in achieving ZNE performance. For example, a typical hand-held hair dryer will use 1500 Watts or more of power. Over the course of a year, this could amount to 100 kWh per person, and perhaps four times that for a full household. If that power must be offset by renewable energy, it could tip the balance in the overall performance of the building. The same could be said for large flat screen TVs and other power hungry plug loads. It becomes even more critical with larger appliances such as clothes dryers. Occupants who are willing to line-dry clothing will have much lower energy requirements than those who frequently use a clothes dryer.

The difficulty for ZNE is estimating the magnitude of these behaviors and their resultant energy consumption. An early study of energy consumption in residences compared the energy use of identical townhouse units, and found a ±50% difference in energy use, attributable entirely to occupant behaviors (DEM 2014; SMUD-SG 2014). Determining occupant behaviors, and their effect on a ZNE building's performance, will be difficult enough for a real building, requiring extensive and detailed end use energy monitoring. Predicting the energy consumption due to human behaviors during the design phase will rely solely on informed assumptions. By extension, these issues also depend on the boundary of the ZNE project: is it at the individual unit level, at the building level for multifamily buildings, or even at the neighborhood or development level. Clearly, unit-by-unit performance can vary widely, but does the performance average out across multiple units?

From an evaluation perspective, the approach to accounting for human behavior will depend on whether the evaluation objective is verifying ZNE performance, or ZNE design. The measurement of actual performance will allow one to report on how close to ZNE the building performs, but will have difficulty detailing how occupant behavior contributed to that performance. It can be much easier to evaluate building *designs* for their potential to reach ZNE performance, because one would simply assume the human behavioral elements, based on some agreed set of conditions.

Of course, one could sidestep these human factors issues by using a ZNE definition that requires only that the design have the capability to achieve ZNE performance under ideal or standard conditions of weather, occupancy, plug loads, etc. This approach, however, does not satisfy the most fundamental goal to achieve ZNE performance in reality, not just in theory.

Renewable Energy Sources

Must the Renewable Energy Sources Be Part of the Building, Site, Neighborhood, or Region?

In the "Multiple Energy Types" section, we alluded to some of the challenges of including non-conventional energy types on ZNE projects. But there are also definitional and evaluation issues with more widely used renewable energy sources, such as photovoltaics and wind power.

The simple definition of residential ZNE typically assumes that the renewable energy source is at the same site as the building. This can work for photovoltaics on many single family residences standing on their own lots, although it presumes that all lots have adequate access to the sun in the south or west, and that either the building has adequate, unshaded roof area, or that there is some other mounting option at the property. If those conditions are met, it is straightforward to size the photovoltaic array and to measure how much energy it provides to the building. If the renewable energy system uses wind energy, then the challenge is simply to mount enough wind power on the site to meet the needs of the building.

These issues become more complicated with denser housing arrangements, such as townhouses, low-rise multifamily, and high-rise multifamily buildings. If it is not possible for each residential unit to have its own stand-alone photovoltaic system, then there must be a shared system, with generation allocated amongst the residential units. The same would be true if there were a wind system for the housing complex. People have talked about neighborhood-, city-, or even regional-scale renewable systems associated with numerous ZNE residences.

Evaluating photovoltaic or wind systems that are not on the customer-side of the meter is a more complex effort than evaluating customer-side generation. From a design perspective, precisely modeling the performance of these systems to offset each unit's load, and/or the aggregate building's load requires making many broad assumptions. These assumptions include, but are not limited to, equipment performance, such as capacity factor and system degradation, weather conditions, and other location specific variables, as well as assumptions about the collective performance and behaviors in multiple residences. To the extent one could treat the energy supply to each unit as if coming from a renewable grid source, these location-specific variables are not necessary for the evaluation and it can be simplified back down to the individual building or unit. Regardless of the modeling techniques used there would need to be an accurate accounting of the renewable output associated with the total grid consumption of all the units, to ensure that one is not claiming phantom renewable energy supplies.

Though evaluating the renewable energy component of ZNE design is complex, the necessary modeling and accounting techniques are currently in use today, and are not so complicated as to present a barrier to ZNE evaluation. Similarly, for measured performance, the availability of interval meter data for both the units' grid consumption, and the renewable system generation, simplifies the ZNE performance evaluation to an accounting exercise.

Cost Effectiveness: Balancing Efficiency vs. Renewables

Does the Building's Mix of Energy Efficiency and Renewable Energy Measures Achieve Zero Net Energy At Least Cost?

One of the biggest challenges facing policymakers and/or designers of ZNE buildings is to strike the right balance between investments to make the building itself energy efficient, so that it requires as little renewable energy as possible, and supplying sufficient renewable energy to offset the remaining energy consumption. This is a cost-optimization challenge. Most energy efficiency measures are relatively cheaper and longer lasting compared to renewables. Therefore, as a general strategy you should invest in ever greater levels of energy efficiency until it becomes too expensive or impractical to continue; at this point, you should switch to investment in renewables. You could make even an inefficient building into a ZNE building by installing enough renewable energy sources, but this would not be economically optimal for customer-owned renewable energy sources.

Developing the optimal mix of efficiency and renewables for customer-owned renewable energy sources becomes a design problem, and energy modeling tools are needed to try various design options until an optimum can be reached. We have discussed these energy challenges already, but here we introduce the cost factors associated with solving them. The building designer/contractor can provide cost information on the various energy efficiency strategies. The supplier of the renewable energy system can provide their costs as well. The energy modeling can determine how the energy balances out between consumption and supply. Tools such as the BEopt (Building Energy Optimization) software allow designers and policy makers to evaluate this for single family residential buildings based on the Building America simulation Protocols (BA 2014).

The remaining variable is the cost of grid-supplied power. Unless the building has sufficient energy storage capability, the grid will act as the storage reserve for the system, absorbing excess electricity production some of the time, and supplying make-up power during times when the renewable output is insufficient. The question then becomes, "What is the cost of grid power?" The answer depends on the utility or regulatory policies toward renewable energy systems. Some policies direct utilities to buy power that it absorbs from a renewable system at the same unit price as it charges for the power it supplies, which includes its generation, transmission and distribution costs. Other policies direct utilities to pay the cost they typically pay or incur for the generation of supplied power, and/or they will apply a fixed charge for grid connections. There are other variations on these two themes, depending on utility or regulatory policies.

Determining the cost effectiveness of a ZNE building depends on how the energy costs balance out, and how great is the cost of constructing the building and its energy system. The bigger challenge, however, is answering the question, “Compared to what?” The typical answer to that question would be to compare the ZNE building cost to that of a “conventional” building of similar design and reasonable energy efficiency, such as the code minimum. The energy cost of that base case building would be determined using energy performance modeling, and the cost would be determined using standard cost estimation methods. The underlying problem is that the base case building was never actually designed, so a base design must be developed for use in the comparison.

If the ZNE building is built as part of an incentive program, perhaps through a local utility offering, the cost effectiveness may be influenced by the value of the incentives paid. Similarly, there may be tax credits offered that can enter the equation.

To further complicate the issue, a business model in the photovoltaic market has emerged, that significantly impacts this balancing act, known as the third party ownership (TPO) model. This model, in which a financing company owns the renewable energy system and leases the equipment or sells its generation to the customer, presents an interesting definitional and evaluation challenge. Because the TPO pays for most equipment and maintenance costs, one cannot rely upon market economics to ensure that energy efficiency investment precedes renewable energy system investment.

ZNE definitions that provide clear energy consumption targets for building designers will also benefit evaluators charged with verifying whether the designer succeeded in thecost-optimization effort.

Conclusions and Recommendations

From a building performance perspective, ZNE design amounts to a cutting edge optimization exercise. Multiple, interacting energy factors must all be brought close to their optimal performance levels. The more optimal they become, the more opportunity for unanticipated failures, because there will be less room for the usual margins of error that are implicit in everyday building design decisions. Evaluating the details of such complex and interrelated performance factors will require substantially greater levels of detail and precision than are typically required by ordinary new construction evaluation. To summarize the key points we have raised:

- **Approaching ZNE:** ZNE building evaluation is not an insurmountable problem, but it must be considered at the definitional stage of any policy or project development.
- **Design vs. Performance:** Measuring ZNE performance for a specific year is the easiest approach, but it is subject to unusual circumstances that could improve the apparent performance or could defeat it.
- **Timeframe:** Modeled performance for a typical year (or for an extreme year) is closer to the spirit of ZNE performance, but doing it well depends on the accuracy and complexity of the engineering modeling.
- **Multiple Energy Types:** Treatment for handling multiple energy sources should be addressed in a comprehensive ZNE definition, and different jurisdictions have done so

differently. Once addressed, sophisticated performance modeling tools are available for use in ZNE evaluations.

- **Human Factors:** Human factors, plug loads and behavior are the biggest uncontrollable variables in ZNE performance, and must either be defined out of the problem, or else they must be rigorously addressed in the definition.
- **Renewable Energy Sources:** The necessary modeling and monitoring techniques needed for ZNE evaluation are not so complicated as to present a barrier to ZNE evaluation.
- **Cost Effectiveness:** ZNE definitions that provide clear energy consumption targets for building designers will also benefit evaluators charged with verifying whether the designer succeeded in the cost-optimization effort.

In conclusion, because different jurisdictions will choose different ZNE definitions, it is critical that their chosen definition answers the six questions discussed in this paper in order to equip evaluators with sufficient parameters to complete energy savings and cost effectiveness evaluations. From that point forward ZNE evaluation should conform to other evaluation best practices: Settle on the objectives for the evaluation, such as energy savings or cost effectiveness, and then develop the evaluation plan to collect the necessary information to assess achievement of ZNE goals relative to ZNE definition.

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