Analysis of Different Methods for Computing Source Energy in the Context of Zero Energy Buildings

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ABSTRACT

Building energy consumption can only be measured at the site or at the point of utility interconnection with a building. Often, to evaluate the total energy impact, this site-based energy consumption is translated into source energy, that is, the energy at the point of fuel extraction. Consistent with this approach, the U.S. Department of Energy's (DOE) definition of zero energy buildings uses source energy as the metric to account for energy losses from the extraction, transformation, and delivery of energy. Other organizations, as well, use source energy to characterize the energy impacts.

Four methods of making the conversion from site energy to source energy were investigated in the context of the DOE definition of zero energy buildings. These methods were evaluated based on three guiding principles—improve energy efficiency, reduce and stabilize power demand, and use power from nonrenewable energy sources as efficiently as possible. This study examines relative trends between strategies as they are implemented on very low-energy buildings to achieve zero energy.

A typical office building was modeled and variations to this model performed. The photovoltaic output that was required to create a zero energy building was calculated. Trends were examined with these variations to study the impacts of the calculation method on the building's ability to achieve zero energy status. The paper will highlight the different methods and give conclusions on the advantages and disadvantages of the methods studied.

Introduction

Zero energy buildings represent a strategy for minimizing non-renewable energy sources. Currently, almost all buildings consume non-renewable energy derived from fossil fuels and transported directly to the building site or by electricity from central power plants. Nuclear energy and fossil fuels are used to make electrical energy through a thermal cycle at the power plant. In addition, a small portion of the electrical power is renewable. Energy is measured at the utility meter (typically for natural gas and electricity) or at the point of delivery to the site for fuels such as oil and propane. At each conversion step or transportation event, energy is consumed that is not delivered to the site or end user. Each step results in inefficiencies. For all non-renewable fuels, extraction, refining, cleaning, and transportation are losses. In the case of electricity, the exchange of heat energy to high-grade electrical energy has losses. To understand the impact of energy consumption of buildings, all these losses should be accounted for.

To capture those inefficiencies in energy analyses, source energy is used as a metric because it represents the total energy impact of using non-renewable fuel sources with respect to the building. The source energy includes all the inefficiencies in non-renewable fuel cycles—

losses from extraction, conversion, transmission, distribution. Conceptually, it documents the total energy consumed to condition and operate a building.

For a zero energy building, renewable energy is generated on site and typically used in the building. Excess from the building is exported from the building, usually in the form of electricity and usually back to the utility grid.

It is impossible to measure source energy. Site energy, however, can be measured at the site boundary, which typically is the point of the building metering. Different calculation methods exist to translate measured site energy to source energy, yielding different results for the total operational impact of the building. In general, the variations in the methods are a result of how the on-site renewable energy is valued. This paper examines these approaches by looking at several building scenarios and using these site-to-source calculation methods to study the benefits and challenges of each.

As this study is done in the context of zero energy buildings, the definition needs to be established. This definition requires three elements: (1) a definition of the boundaries and the metrics, (2) a method for using the site-to-source ratios in conjunction with on-site renewable energy, and (3) a method for calculating the site-to-source ratio. In 2015, DOE created a common definition for zero energy buildings (DOE 2015). This common definition also had an exhaustive nomenclature section, including standardization of the name "zero energy buildings" to represent "net zero energy," "zero net energy," and "net-positive" energy. While not discussed in this paper, the authors of the common definition concluded that though these different terms were closely tied to personal preferences and often regional in nature, all referred to the concept that buildings can generate as much energy as they consume. This document used ASHRAE Standard 105 site-to-source conversion values (ASHRAE 2014). Note that in some references, the site-to-source ratio is referred to as the source conversion factor.

Note that there is some variation in this ratio as calculated by different entities based on the dataset used and the date of the dataset; however, these numbers typically are within 10% of each other and would not skew the overall trends. In general, the source conversion is calculated based on the energy content extracted from the ground (and going into thermal power plants) divided by the electrical energy that is sold to the customer. It can only change based on improving the heat rate efficiencies of the power plants and is not dependent on the amount of renewable energy on the grid. This factor is important because the source conversion serves as an accounting system that calculates the amount of non-renewable energy not consumed by adding renewable energy. It also emphasizes building level energy efficiency; a perfectly renewable energy grid could be highly inefficient and the buildings could be highly inefficient if the source metric is not based on fossil fuel equivalents.

Analysis Methods

A typical office building was used to compute site energy. This building was based on information from the DOE reference buildings meeting ASHRAE 90.1-2004 (Deru 2011). Which building was used for the analysis is not crucial because the calculation methods to arrive at source energy are being compared rather than examined as trends. Modelling was needed to generate hourly building loads including heating, ventilation, air conditioning, lighting, and plug loads.

The amount of renewable generation (supplied by solar photovoltaics [PV]) required to achieve zero energy according to the DOE definition (DOE 2015) was determined using each of the methods. It was important to identify whether energy was entering or exiting the building boundary at each time step, because some of the calculation methods are dependent on this "instantaneous use" of energy. The methods studied included the following:

1. **Site**: Energy consumed at the site as determined by the site boundary. Typically this boundary is the electrical meter, gas meter, or other method of billing, such as refilling a fuel tank. Energy inputs from various sources measured at this point are summed to arrive at the total energy.

2. **Source-Equal**: Each energy source is measured at the site and multiplied by the corresponding site-to-source ratio. The current site-to-source ratio for electricity is 3.15 (ASHRAE 2014). Renewable energy used on site directly reduces the amount of imported energy. Typically, renewable energy takes the form of electricity and reduces the amount of purchased electricity; however, renewable energy need not be limited to electricity as an energy form. Exported renewable energy uses the same site-to-source ratio as imported energy. This is a common, industry-accepted approach for source calculations and represents the industry norm of true net metering because energy exported has the same value as energy imported.

3. **Source-Consumption**: On-site renewable energy used in the building on an instantaneous basis (not exported) has a site-to-source ratio of 1.0. All imported electricity consumed by the building uses a ratio of 3.15. The resulting sum of the on-site renewable energy and grid source energy yields the source energy for the building. On-site renewable energy that is exported (rather than used immediately) is treated like grid source energy: it can be imported from the grid to the site at a ratio of 3.15. As a result, renewable energy that can be used in the building or stored within the building site has a much higher value than exported renewable energy.

4. **Source-Grid Storage**: All electric energy imported into the building has a site-to-source ratio of 3.15; however, energy exported to the grid is valued at 80% of the conversion rate to approximate losses in exporting electricity to the grid. In other words, the round-trip efficiency of the grid acting as a storage element is 80%. Note that the exact round-trip efficiency is not critical to this analysis because the trends will be similar, giving flexibility to future work that could create a method for determining this number. This accounting of measuring energy is used by most electrical utility meters with energy flows measured into and out of the building. (Note that for net metering, these numbers are typically subtracted to result in the "net," which is used for the Source-Equal method above.) Renewable energy that can be used instantaneously on site directly reduces imported electricity; this results in on-site renewable energy having a higher value in the building than does exporting the same energy. This method is a technique to model the grid as a non-perfect storage device.

For all methods, natural gas has a site-to-source ratio of 1.09 to include extraction and transportation to the site (ASHRAE 2014).

Absent from the analysis were the California Time Dependent Valuation (TDV) factors. As this study was national in scope, values dependent on California alone were not considered. These values provide good insight and inform policy related to new construction in California, but are difficult to apply to an operational metric, such as a ZEB definition. In addition, California recently has adopted the DOE methodologies (State of California, 2016).

The objective is to examine and compare the results of these four methods as building elements are changed, which impacts the building's energy performance. To do this, a qualitative evaluation of the building variants must be done, considering the following guiding principles:

1. **Improve building energy efficiency:** To reduce energy use in buildings, simple energy efficiency strategies are the most cost-effective and result in long-term building performance. Building owners and managers should make energy efficiency strategies their first priority. These strategies minimize energy transfers, including heat moving in and out of the building's systems. The fewer the energy exchanges, the less opportunity for efficiency losses and the more robust the efficiency measure.

2. **Reduce power system demand:** Variations in building power consumption result in additional utility infrastructure and generation inefficiencies. Conversely, a building with a flat-load profile increases the efficiency of the electrical grid. The shape of the profile is important to increase power system efficiency and buildings; therefore, identical load profiles from building variants should be considered to have equivalent value, independent of how the profile was created. This guiding principle also includes reducing the maximum peak demand of the building.

3. **Use non-renewable fuels efficiently*:*** Use of fossil fuels will continue for a long period of time, and the efficient use of these fuels both on the utility grid and in the building should be maximized.

Calculation Evaluation

For this analysis, the U.S. Department of Energy (DOE) commercial reference building was used (Deru 2011), with 54,000-ft^2, three -story, medium office building. The building was located in Chicago, Illinois, so that both heating and cooling loads could be evaluated. The building meets the envelope, lighting, and HVAC requirements of ASHRAE 90.1-2004 (ASHRAE 2004). The functions of the building, including schedules and plug loads, were fixed for all scenarios. Delivery and energy efficiency strategies were varied and included a heating system (including fuel type), building-level efficiency measures, cogeneration, daylighting, and energy storage. Hourly site energy loads were calculated. For each site-to-source calculation method, the amount of PV was determined in order to achieve a zero energy building in alignment with the DOE definition.

Figures 1 through 6 show the results of changing a building variable. A positive response from a calculation method is indicated by a curve that slopes downward toward the right. This represents "increasing" the guiding principles or increasing the efficiency of the building, which should reduce the amount of PV required to achieve a zero energy building. A curve that exhibits a different behavior is not consistent with the guiding principles. In addition, the amount of PV required can be compared using the various methods. Large variations between the methods in a particular comparison also indicate that one or more of the methods may not be appropriate in the context of a calculation method for a zero energy building.

Electric HVAC Efficiencies

The coefficient of performance (COP) of the heat pump supplying the heating and cooling to the building was increased starting with modeling electric resistance heat (COP_{heat}=1.0) and ending with a high-efficiency heat pump.

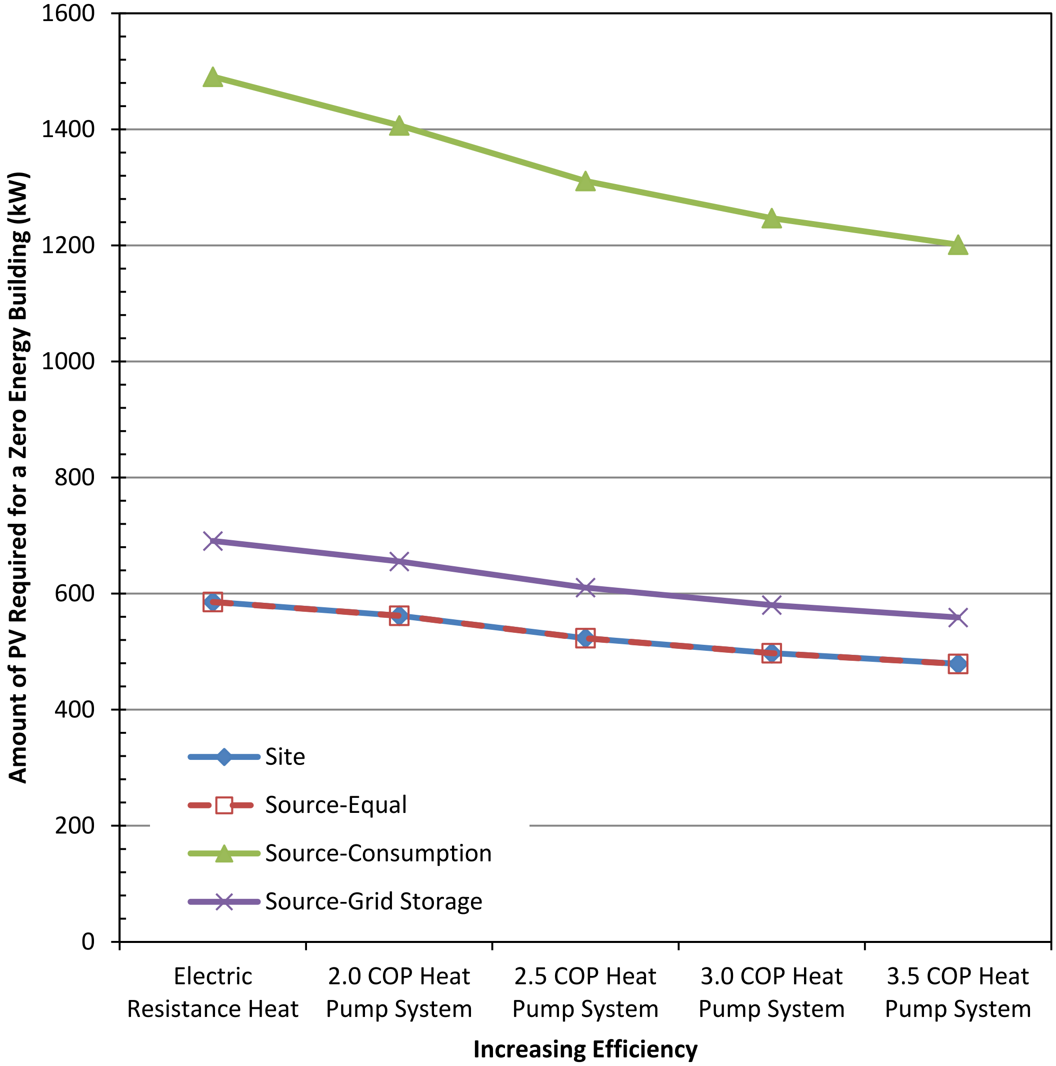

Figure 1. Parametric analysis of different HVAC efficiencies for an all-electric building

The amount of PV required to create a zero energy building is the same for the Site and Source-Equal methods. This was a result of the fixed multiplier for the electricity crossing the boundary in both directions and the fact that there was only one fuel source. The Source-Grid Storage method required slightly more PV because electricity exported has less value than imported electricity to account for losses in exchanging electricity with the grid. Source-Consumption required more than twice the PV as did the Source-Equal method because PV is exported at a ratio of 1.0 and all imported electricity has a ratio of 3.15. Roughly one-third of the PV energy can be used instantaneously in the building. In all cases, the slope of the lines is negative, implying that all methods meet the guiding principles.

Gas Heating

The efficiency of a natural gas furnace was varied from 70% to 95%. Because it is a non-renewable resource, renewable energy must be exported to account for the natural gas import.

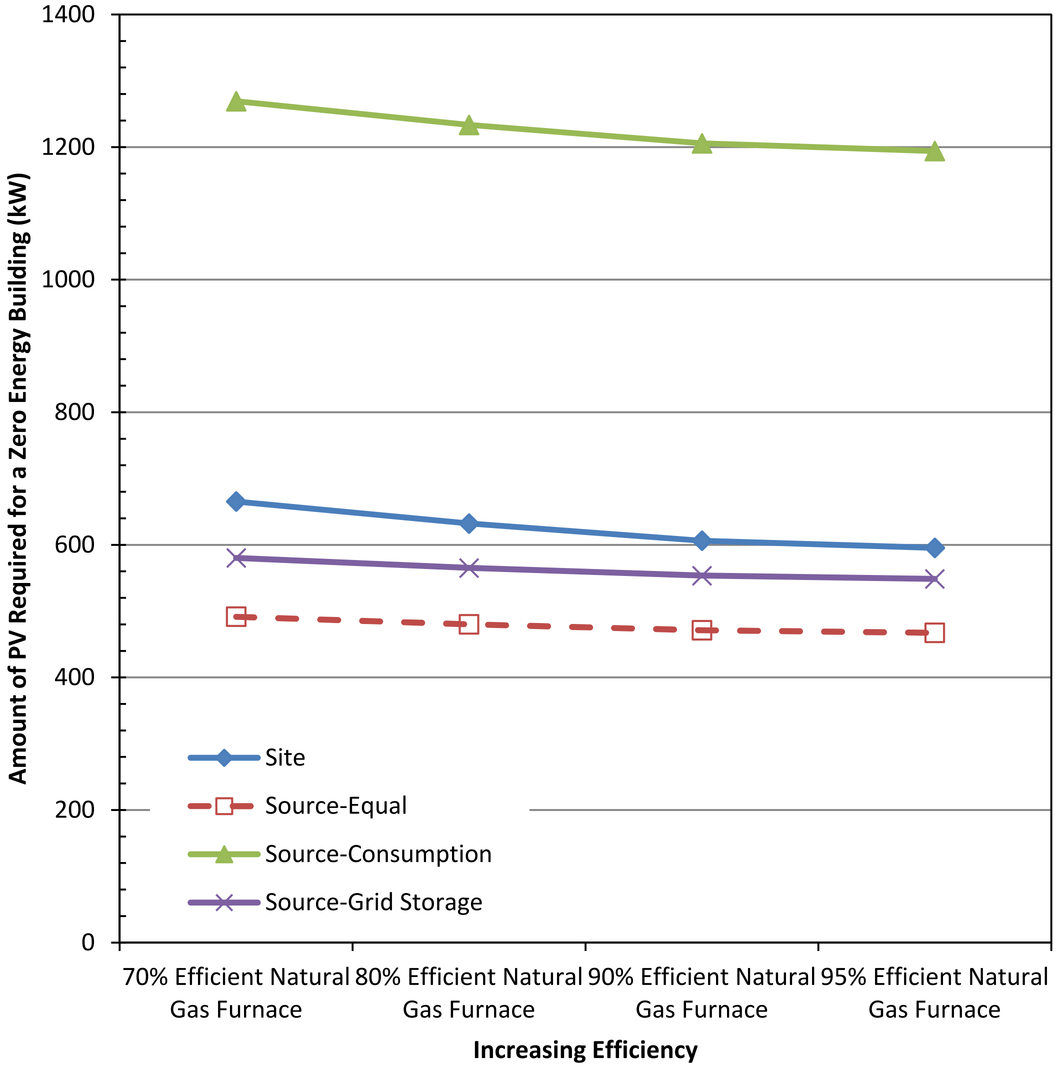

Figure 2. Parametric analysis of different efficiencies of gas heating

For this analysis, all the calculation methods met the intent of the guiding principles as the slopes of the curves are negative. The Source-Equal calculation required approximately 20% less PV than the Site calculation. This is because using natural gas at the site required less natural gas than using natural gas to generate electricity at a central power plant that is then used to perform the same work at the building.

Comparing Figure 1 and Figure 2, the Site method requires more PV because the natural gas is less efficient at the site than electric resistance heat. The site-to-source ratio accounts for the inefficiencies in the power generation system that produces the secondary energy source of electricity.

Storage Size Comparison

The size of building-level energy storage was also varied. Energy storage makes better use of the PV energy in the building and minimizes the import and export of that energy, thereby reducing variations in power consumption. Storage tends to smooth out load profiles. The energy storage was modeled with a round-trip efficiency of 80%, and could represent batteries, flywheels, or thermal storage including cold water, hot water, or ice storage.

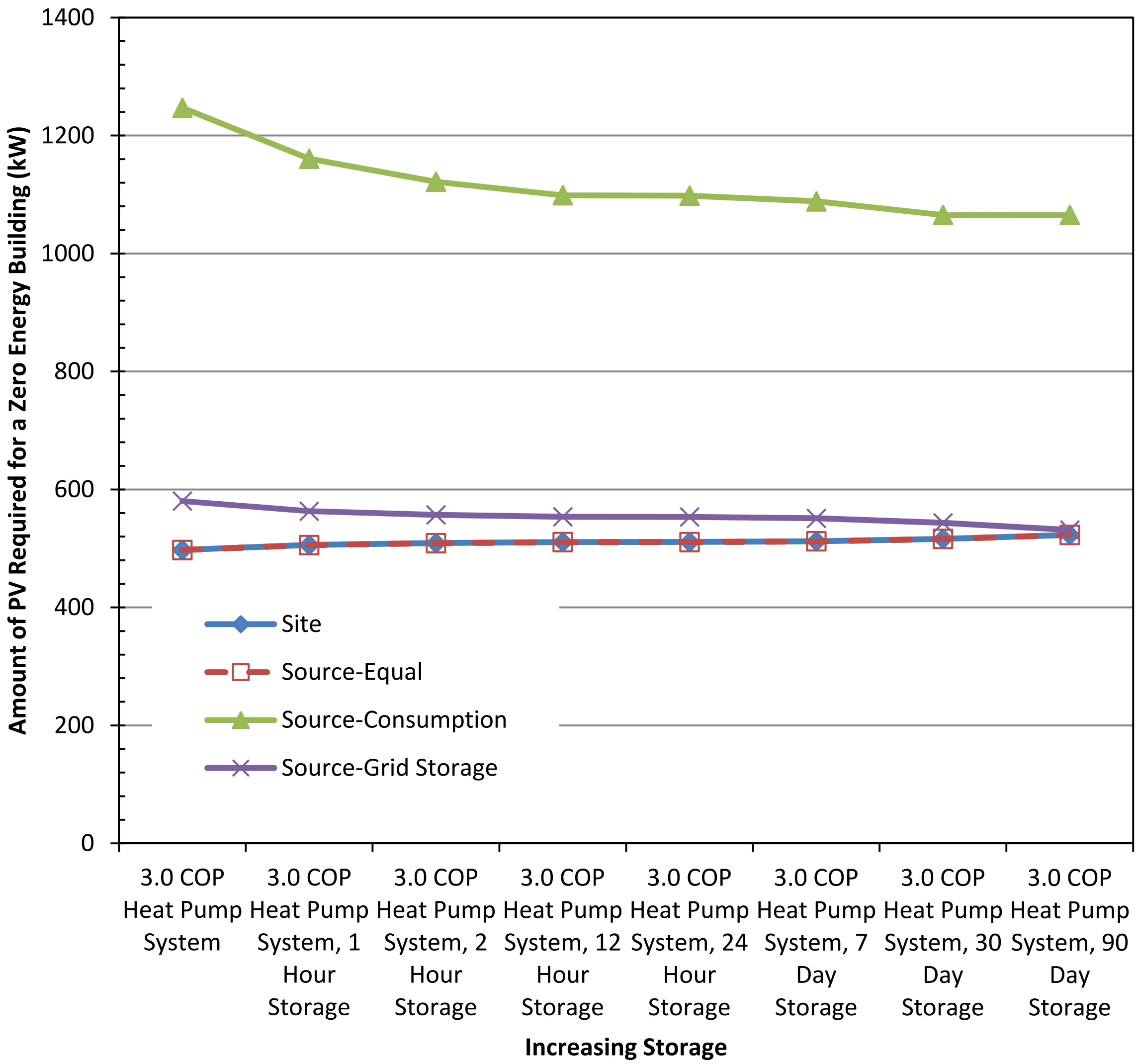

Figure 3. Parametric analysis of different storage levels (all-electric)

Figures 3 and 4 show that increasing the storage for the Source-Equal and Site calculation methods slightly increases the amount of PV required. This is because the storage efficiency of the grid (100%) is higher than the storage efficiency of the building-level storage (80%) in these calculation methods. This inefficiency is small compared to the total amount of energy moved across the boundary.

For an infinite battery, the building would be off-grid as a zero energy building. At this point, Source-Equal, Source-Grid Storage, and Site calculation methods come together. With this scenario, the Source-Consumption method is not valid, because the PV is assigned a source energy value of 1.0 that cannot be replaced with grid power. The other calculation methods have a source energy of 0.0 attributed to the PV that can be used on site, resulting in a grid-independent building. With Source-Consumption, there is a limit to the value of the storage.

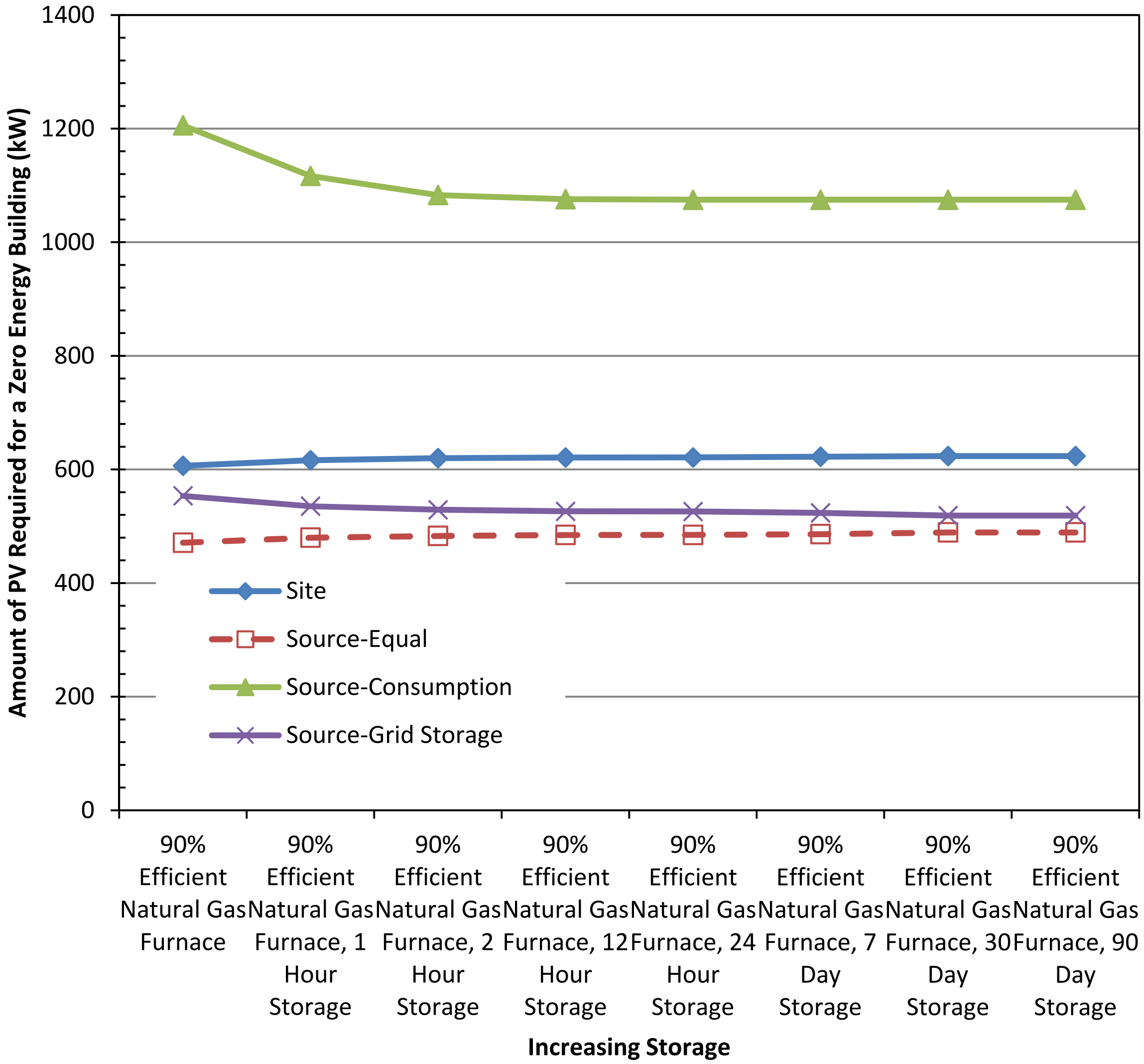

Figure 4. Parametric analysis of different storage levels (natural gas heating)

Cogeneration

Cogeneration was modeled such that it followed the heating load. Infiltration was varied to change the effective energy efficiency of the building. When more heat is needed by the building, more electricity can be generated from the cogeneration system because the heat is a byproduct of the electrical generation process.

Figure 5 indicates that when the guiding principle of increasing building efficiency is followed, it decreases the amount of PV required. Note that for the Source-Equal calculation, the heating load increases faster than the amount of electricity produced; this yields a curve that is consistent with the guiding principles. It may be possible to export electricity and decrease the source impact, because electricity has a high source value compared to natural gas. However, many local utility jurisdictions limit the export of power from non-renewable generation systems.

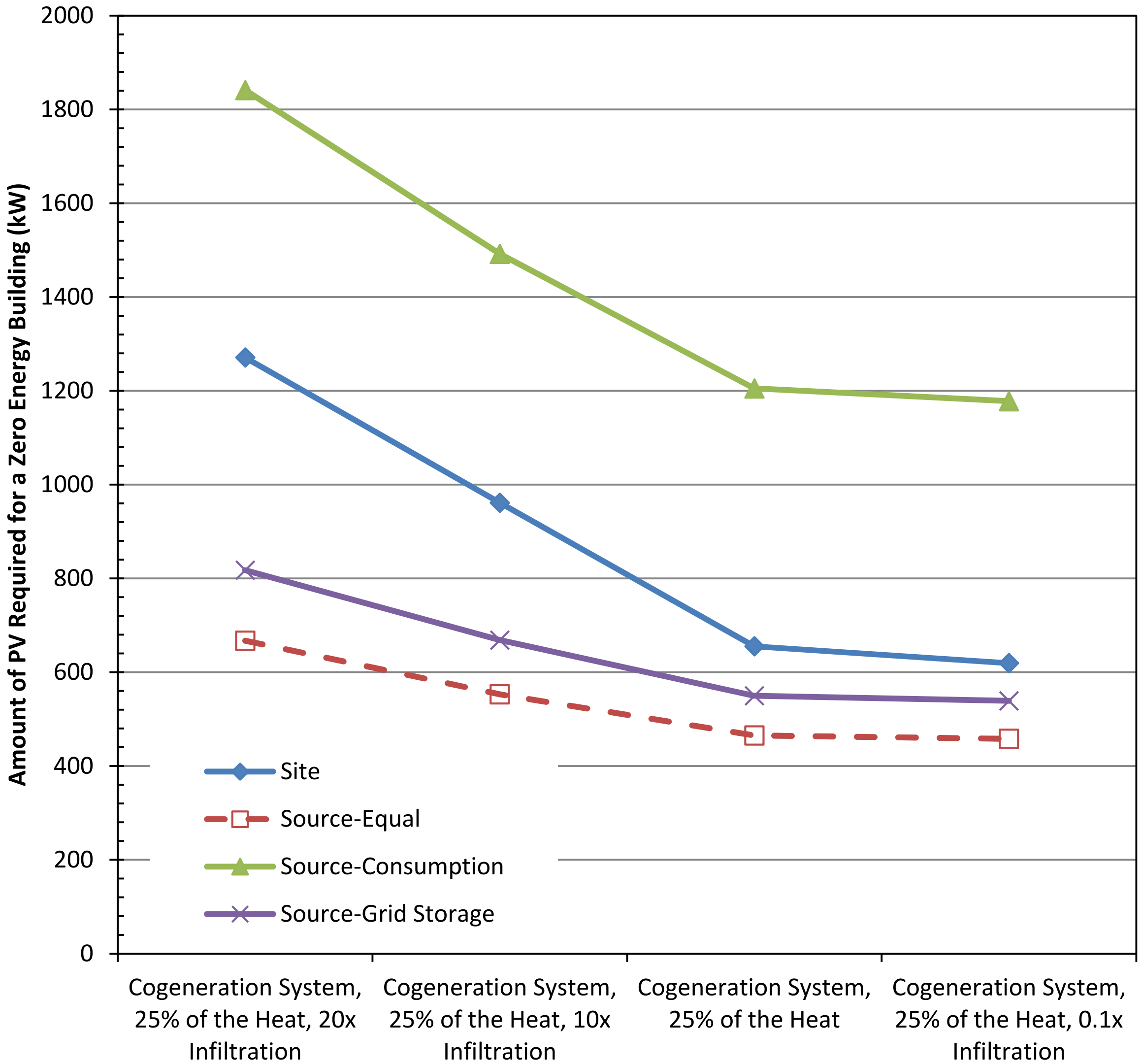

Figure 5. Parametric analysis of cogeneration meeting the heating load while infiltration rates are decreased as an energy efficiency measure

Figure 6 shows how changing the size of the cogeneration system provided a fraction of the heating required. No limits were placed on excess electricity placed into the grid from the cogeneration system in this analysis. The Site metric increased because the efficiency of the natural gas cogeneration system was less than 100%, the efficiency of site-delivered electricity. For the Source-Equal, Source-Consumption, and Source-Grid Storage metrics, the exported electricity had higher value than the natural gas input. Taking this to an extreme, additional cogeneration would continue to reduce the amount of PV to achieve a zero energy building to the point of having a zero energy building without renewable energy. From this, non-renewable energy produced by the cogeneration system should not be exported to the grid, which is consistent with many current utility regulations.

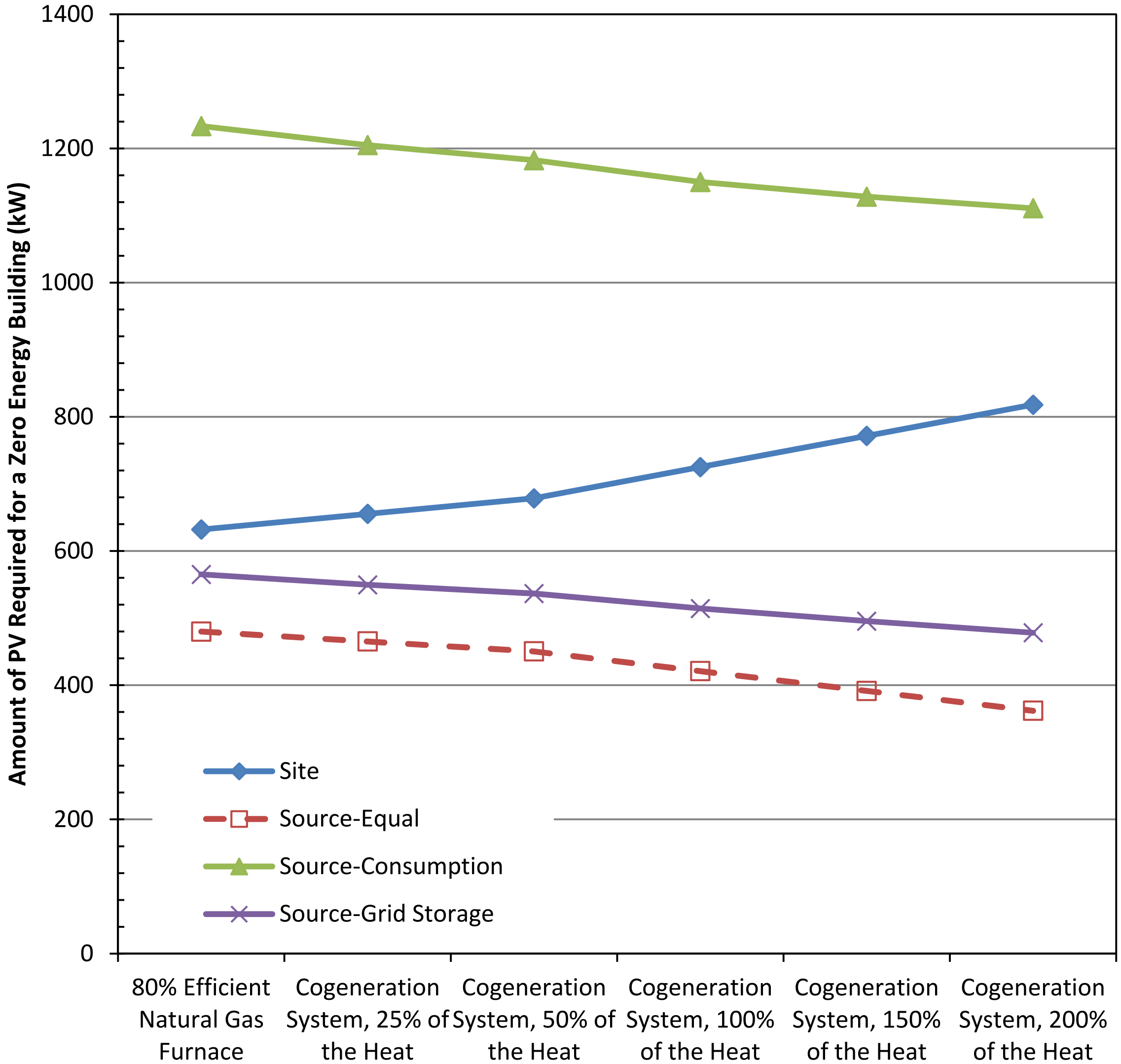

Figure 6. Parametric analysis of cogeneration meeting a fraction of the heating load; percentages of more than 100% are overproduction of heat

Conclusions

Table 1 provides a summary of the benefits and weaknesses of each of the methods along with references to the figures that highlight these points.

The Source-Equal calculation method follows the guiding principles in most scenarios, with a weak exception for on-site storage. The Source-Equal parameter is easy to calculate based on annualized data, and requires the same or slightly less PV when compared to the Site calculation. Buildings that meet a Site zero energy building definition will also meet the Source-Equal definition. The weakness appears in buildings with storage systems, because these are beneficial to the grid. However, the function is weak. In addition, complications of needing an interval meter.

Table 1. Benefits and weaknesses of calculation methods for source energy determination

Calculation Method	Benefits	Weaknesses	Reference
Site Energy	• Easy to measure and understand; commonly applied metric by the industry.	• Overvalues electric over gas on site even though gas is more efficient when considering the power generation efficiencies • Local energy storage penalized.	Figs 1 and 2 compared Figs 3 and 4.
Source-Equal Method 1 (3.15 ratio in/out)	• Commonly accepted definition as a method of balancing fuel sources and their relative environmental impacts • Economics of cogeneration typically prevent oversizing for production of electricity without a heating load • Because of typical net metering, provides a framework for Source-Grid Storage, if desired • Requires the least amount of PV to achieve ZEB • Same as Site for all-electric buildings.	• Cannot export excess electricity from cogeneration to avoid becoming a power plant where exported energy has a higher value than the fuel sources imported • Local energy storage shows a slight loss, even though it can improve grid efficiency, especially with high renewable penetration.	Figs 3 and 4
Source-Consumption (1.00 on all PV)	• Strongly encourages energy efficiency • Only values PV energy used in the building and not exported. If electricity is stored on site vs. exporting, this increases the PV penetration and value • Storage systems encouraged at small scale.	• Large renewable contribution required to achieve zero energy (more than two times the other methods); at scale, would create excess PV electricity on the grid • Does not effectively balance efficiency technologies that are cost-competitive with on-site PV systems • Hard to implement on a multi-metered system because instantaneous demand must be calculated.	Figs 1-4
Source-Grid Storage (import at 3.15, export at 2.34)	• Values efficiency and building efficiency at the building level • Encourages local energy storage • Follows guiding principles for parameters tested.	• Hard to implement on a multi-metered system because instantaneous demand must be calculated • Hard to explain • Cannot export cogeneration electricity.	.

data across a campus or portfolio (multiple meters) would make this calculation difficult even if it more accurately represented a grid and encouraged on-site usage of renewable energy with storage. As renewable energy and storage continue to advance, pricing models could account for this slight weakness, and a market determination could be used to decide whether storage is better located locally or at the utility scale.

References

ASHRAE. 2004. *ANSI/ASHRAE/IESNA Standard 90.1-2004: Energy Standard for Buildings Except Low-Rise Residential Buildings*. Atlanta, GA: ASHRAE.

ASHRAE. 2014. *ANSI/ASHRAE Standard 105-2014: Standard Methods of Determining, Expressing, and Comparing Building Energy Performance and Greenhouse Gas Emissions*. Atlanta, GA: ASHRAE.

DOE. 2015. *A Common Definition for Zero Energy Buildings.* Washington, DC: Prepared by the National Institute for Building Sciences. https://buildingdata.energy.gov/cbrd/resource/1938.

EPA. 2013. *Energy Star Portfolio Manager Technical Reference: Source Energy*. Washington, DC: U.S. Environmental Protection Agency. https://portfoliomanager.energystar.gov/pdf/reference/Source%20Energy.pdf.

State of California. 2016. *Definition of Zero Net Energy (ZNE) for California State Agency Compliance with Executive Order B-18-12.* May 16. Sacramento, CA: State of California.