Why is My Zero Energy Home Not a Zero Carbon Home?

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For years, carbon calculations were done very simply. The method of calculation was to take annual totals of energy consumption and multiply by an average emission factor, either for the grid serving a project or for a larger region (e.g., an EPA eGRID subregion). The level of accuracy of this approximation was reasonably good, although the issue of accuracy was not, to our knowledge, tested. And the data required were minimal—just a year's worth of bills for each fuel and one lookup factor.

But this method ensures that a net zero energy home is automatically a net zero carbon home because zero times any possible emission factor is still zero.

Things changed starting in the early 2010s—grids were starting to rely more and more heavily on renewables, and the difference was showing up on aggregate load curves. This was perhaps noticed first in California, where aggressive renewable policies led to significant renewable power generation large enough to affect the overall shape of the diurnal load curve for independent systems operators. *Figure 1* shows how predicted net generation required after renewables dips more and more precipitously during the day as time progresses.

The analysis shows that net zero carbon is a more ambitious goal than net zero energy almost everywhere. The assumption of a constant emission factor is no longer accurate and now, and certainly in the future, emissions are strongly dependent on time of day and season of the year.

Long-run marginal emission rate (LRMER) methods have been incorporated into the Carbon Rating Index (CRI) prescribed in ANSI/RESNET/ICC 301, *Standard for the Calculation and Labeling of the Energy Performance of Dwelling and Sleeping Units Using an Energy Rating Index*. This standard provides a repeatable methodology for calculating emissions using long-run marginal emissions, which vary by time of day and month of the year. The rationale is discussed in Fairey, et al.,[1] and Kruis and Goldstein.[2]

ANSI/ASHRAE/IES Standard 90.2-2018, *Energy-Efficient Design of Low-Rise Residential Buildings,* recently adopted requirements to limit operational carbon emissions in homes and multifamily dwelling units. Standard 90.2-2018 sets a relative carbon emission performance or Carbon Rating Index (CRI) of 45, where 100 is the reference case and 0 is net zero operational CO_2e emissions. Standard 90.2-2018 uses a similar energy

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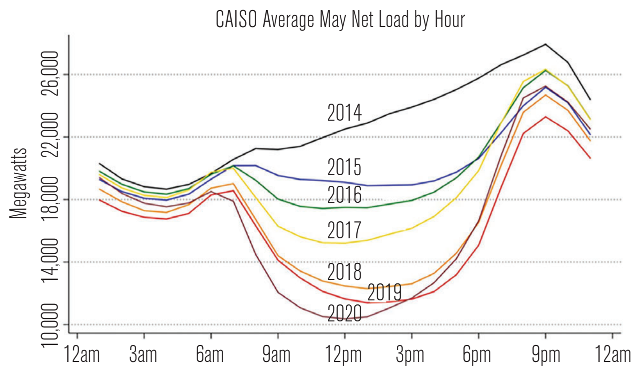


FIGURE 1 So called "duck curve" showing how typical spring day utility power demand changed substantially between 2014 and 2020.

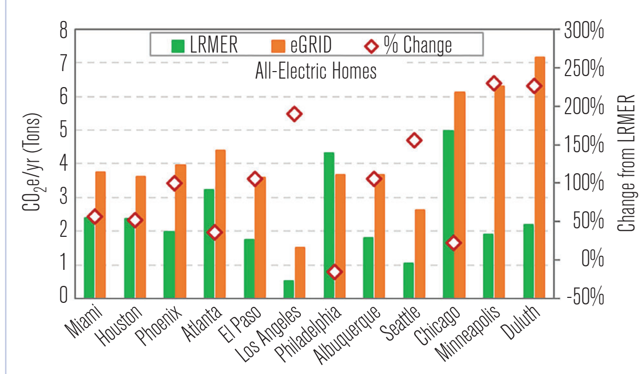


FIGURE 2 Projected annual CO_2e emissions in 12 U.S. climates showing the difference between LRMER and eGRID-2022 emission projections.

performance limit called the Energy Rating Index (ERI). In both cases the reference case is the 2006 International Energy Conservation Code standard reference design with 2006 federal minimum standard heating, cooling and water heating equipment, lighting and major appliances.

The concept of net zero energy homes is rooted in research on residential energy efficiency. When renewable energy is expensive, buildings use efficiency first and then renewable energy. That was the original concept behind net zero energy homes and still is. Russel[3] provides a synopsis on how the concept matured over time; Parker and Dunlop[4] discuss the first efforts toward achieving the goal of net zero energy in the field.

Gagnon and Cole[5] have demonstrated that, of the available carbon metrics, long-run marginal emission rate (LRMER) is better correlated to observed changes in utility emission rates than either short-run marginal emission rates (SRMER) or average emission rates (AER). This column shows how substantially the results differ.

The Standard 90.2-2018 definition of net zero energy (NZE) homes is based on RESNET/ICC 301. A NZE home is capable of producing all its annual energy needs using renewable energy resources.

But energy demand does not need to match renewable generation. During the day PV produces more power than needed by the home; it is returned to the home when the PV is not producing energy. This net metering process is assumed by default in NZE home projections.

Online Figure 1 presents an example.[6] While this Atlanta NZE home has a net electricity use of –33 kWh, it is not a net zero carbon home because it matters when that kWh of electricity is generated. Grid emissions are heavily dependent on time of day and month of the year. Emissions are significantly smaller when utility generation is using renewable resources and larger when utility generation is using conventional fuels.

Utility grids are expected to become much cleaner over time. Buildings constructed today will last through 2050, so built environmental planning and design need to be cognizant of how the grid will change to be responsive to building decarbonization needs.

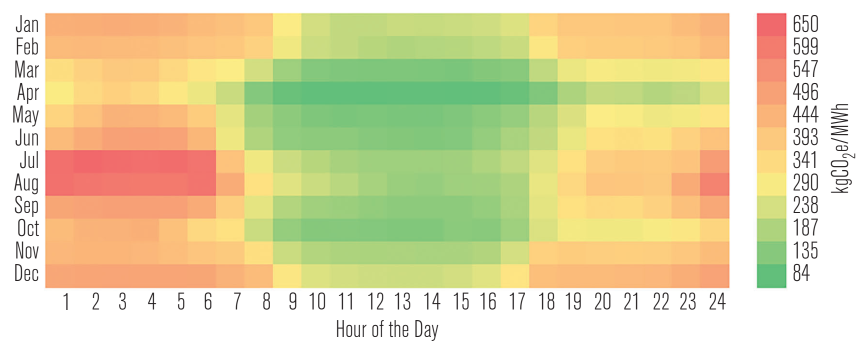
The National Renewable Energy Laboratory (NREL) developed an extensive database of utility generation and emission assessments based on a publicly available utility capacity expansion model[7] that projects the evolution and operation of the electric sector in the contiguous U.S.[8] This database, named Cambium, contains forward-looking generation and emission data based on different metrics and economic scenarios across 134 balancing areas. The data are also presented as generation and emission assessment (GEA) regions that mimic the U.S. EPA eGRID subregions.[9] *Online Figure 2* illustrates how the Cambium regions are virtually identical to the eGRID subregions.

The very large difference between the two data sets is eGRID data are historical data that do not reflect how the grid will change in response to changes in demand for electricity, either in real time over the course of the day and the seasons of the year or in the future.

Economists call these marginal emissions and distinguish them from average emissions. The whole foundation of economics is based on the recognition that for the economy to produce optimal results, not just for energy but for everything, decisions on current and future actions must be based on marginal calculations.

The Cambium data are based on marginal emission rates. They include projections of how the grid is likely

FIGURE 3 Levelized LRMER data for Atlanta's Cambium GEA region.



to change in response to demand, both immediately and in the future. The Cambium data are presented for two-year periods from 2022 through 2050. The results presented in this column use the levelized 2021 Cambium LRMER data for the 25-year period from 2025 to 2050 with a 3% social discount rate.[10]

Use of Cambium's LRMER data to make emission projections over the next 25 years yields substantially different results than use of eGRID[11] data to make projections over the same time period. Fairey, et al.,[6] evaluated very efficient homes that comply with the high-performance energy requirements of Standard 90.2-2018 in 12 U.S. climate locations. These 12 homes also comply with the standard's carbon requirements. *Figure 2* (page 21) presents the results of this analysis.

These results show that where eGRID data are used to project CO_2e emissions, the result is more than two times greater than the LRMER result in some cases (Minnesota cities).

These results also illustrate a basic difference between carbon accounting techniques. The eGRID technique assumes there will be no change from past data. This method of carbon accounting is called attributional accounting. The levelized, LRMER carbon accounting technique is referred to as consequential accounting, because it measures the consequences of specific actions to decarbonize.

In consequential accounting, the fact that policy and cost decisions are driving increasing electrification and a cleaner grid over time changes the value of the metric being used to assess the carbon emissions.

Why is my net zero energy home not a net zero carbon home? *Figure 3* provides a heat map of the CO_2e emission rates from the Cambium LRMER database for the levelized emissions in the region containing Atlanta (SRSOc).

Figure 3 shows that emissions during the hours of 9 through 16 will be significantly smaller during most of the year than emissions during the night and evening. The differences in emission rates in the Atlanta GEA vary by almost an order of magnitude, from 84 kg/MWh to 650 kg/MWh.

According to *Online Figure 3*, the Atlanta NZE home produces 1.45 tons of CO_2e emissions—a good deal more than net zero. Can we simply add battery storage to offset the remaining 1.45 tons of carbon from this home? The answer to this question is also no. The PV system that makes this Atlanta home a NZE home has a 6.75 kWdc capacity. It produces sufficient power to achieve net zero energy, but at the exact times of the day when the electric grid is the cleanest (*Figure 3*). Battery storage will not get the home all the way to net zero carbon because the PV system is not large enough.

Online Figure 4 shows the PV production, the net energy use after accounting for the PV production and the Atlanta grid emission rate for the first week of the year. The first week of the year was selected because it represents one of the periods during which CO_2e emissions are larger than normal (see *Online Figure 3*). These emission rates vary from a low of about 0.45 lb/kWh (204 kg/MWh) at around noon to a high of about 1.0 lb/kWh (454 kg/MWh) at around 3 a.m.

Where a 21 kWh battery storage system with very simple charge and discharge control algorithm is added to this home, it reduces total annual emissions from 1.45 tons to 0.61 tons. For this simplified control algorithm, the battery is charged whenever PV production is greater than the home energy demand and the battery capacity has not been reached. Where the battery capacity is exceeded, the excess power is returned to the grid. The battery is then discharged whenever house energy demand is greater than PV production until the battery has been fully discharged.

Figure 4 shows the hourly CO_2e emissions for this home after the 21 kWh battery storage system is added. Much of the CO_2e emissions during the middle of the year are reduced, but the winter emissions of the home are not altered very much. This is likely due to high weighting of nighttime heating requirements when emission rates

FIGURE 4 Carbon emissions for Atlanta NZE home with 21 kWh battery system.

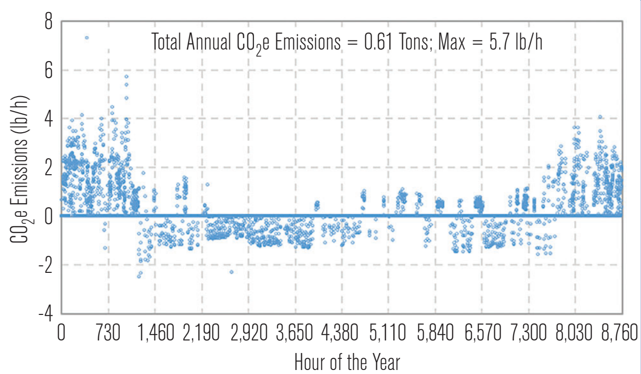


FIGURE 5 Impact of battery storage capacity on CO_2e emissions with simple battery storage controls in an Atlanta net zero energy home.

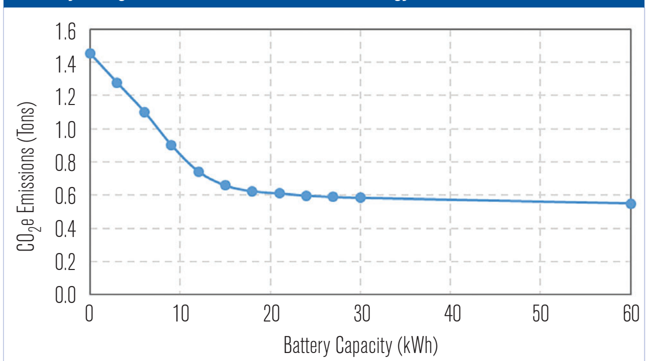
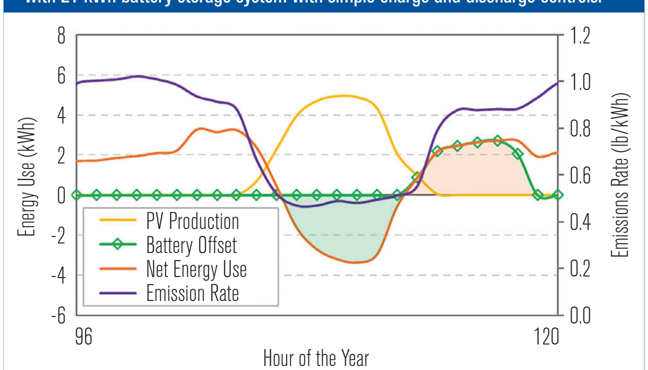


FIGURE 6 Battery energy charge and discharge integrals for Atlanta NZE home with 21 kWh battery storage system with simple charge and discharge controls.



are large (see *Online Figure 3* for comparison).

For simple battery charge and discharge control, if we add more battery storage than 21 kWh, the emissions are not reduced accordingly. The impact of battery capacity for this home is shown in *Figure 5*.

First, the net energy used to charge the battery storage for the home is not sufficient to overcome the home's full 24-hour energy demand. Second, the PV power production is offsetting home energy use during the time of the day when the CO_2e emission rate is smallest.

Figure 6 presents battery storage results from the most productive solar energy day during the first week of the year (see also *Online Figure 4*). The integrated battery energy storage (highlighted in green) offsets the integrated home energy demand (highlighted in orange) for less than seven hours on this day. Battery charging occurs during the period when CO_2e emissions are the smallest, while battery discharge is occurring during periods when CO_2e emissions are almost twice as large.

Figure 6 shows that simplified battery control algorithms may not be the optimum solution for building decarbonization. If all of the PV production shown in *Figure 6* is used solely for battery charging when emissions rates are small, total battery storage would be larger, and a much larger portion of the periods with large emission rates could be offset by the battery.

Standard 90.2-2018 requires that homes in Atlanta achieve an ERI less than or equal to 47. Standard 90.2-2018 also requires that homes achieve a Carbon Rating Index (CRI) less than or equal to 55. Simulation analysis[6] shows that the Standard 90.2-2018–compliant Atlanta home shown in *Online Figure 1* without PV achieves an ERI of 45 and a CRI of 47. With the addition of 6.75 kWdc PV, this home achieves the hourly energy use results shown in *Online Figure 1*—an ERI of 0 but a CRI of 21.

Net zero carbon can be achieved in two ways: by increasing PV capacity without battery storage or by increasing PV capacity and adding battery storage. Achieving a CRI of 0 with only PV capacity will require a 12.225 kWdc PV system. Increasing the PV system size to 9.6 kWdc coupled with a 19 kWh battery storage system will also achieve a CRI of zero.

Table 1 shows that net zero energy is not net zero carbon—by 21 points in this case. It illustrates that energy storage increases energy use, resulting in an increase in ERI—so net zero energy is no longer NZE. Finally, it shows that there are multiple ways to achieve net zero carbon. Net zero carbon can be achieved using increased renewable energy plus battery storage or with more substantially increased renewable energy alone.

Results shown here are determined using the energy and carbon calculation methods specified by Standard 90.2-2018, which relies on RESNET/ICC 301.

Analysis for the 12 locations shown in *Figure 2* includes an estimation of the cost-effectiveness of achieving net zero carbon using PV power production and an $80/ton social cost of carbon.[12] Cost-effectiveness was estimated following Duffie and Beckman.[13] Analysis, presented in terms of savings to investment ratio plotted against the mean LRMER for each location, are shown in *Figure 7*. It indicates that for extremely clean grids (mean LRMER ≤0.25), adding the PV capacity in excess of NZE to achieve net zero carbon is not cost-effective. However, for all other grids, the savings to investment ratio is greater than unity. For the dirtiest grid examined (Chicago), savings are more than three times the investment. Additionally, climates with very abundant solar resources stand out with respect to cost-effectiveness.

The study also includes a multivariant regression analysis as to the quantity of PV that is required in each of these locations to reach net zero carbon. *Online Figure 5* presents the results of this multivariant regression analysis. It shows that the correlation between installed PV power and predicted PV power is quite good with a correlation coefficient of almost unity.

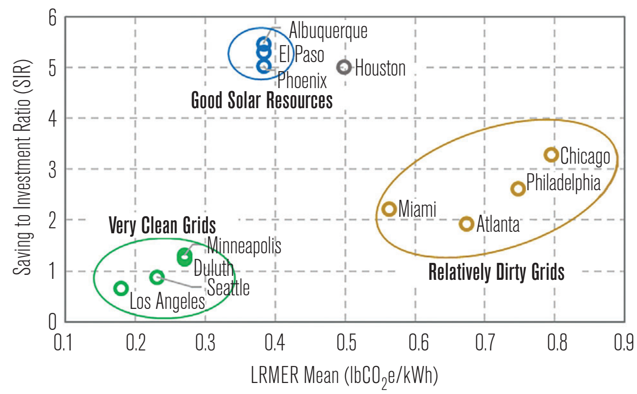
In conclusion, Standard 90.2-2018 through reliance on RESNET/ICC 301-2022 has established a consequential carbon accounting methodology that supports life-cycle analysis of operational CO_2e emissions, encouraging residential decarbonization.

Standard 90.2-2018 is also well aligned with International Standards Organization (ISO) standards in this regard. ISO/PAS 50010:2023[14] provides guidance on improvement of operation and maintenance based on NZE and net zero carbon principles for the planning for facilities, systems, equipment and processes to implement NZE and net zero carbon. ISO 50010 strongly recommends the use of hourly, long-run marginal emission rates (LRMER) for carbon accounting, recommending consequential carbon accounting rather than attributional carbon accounting. Standard 90.2-2018 aligns very well with the energy and carbon guidance provided by ISO 50010.

TABLE 1 Getting to net zero carbon with the Standard 90.2-2018 home in Atlanta.

STANDARD 90.2-2018 ATLANTA HOME CASES	ERI	CRI
Minimally Compliant Home	45	47
NZE Home with 6.75 kWdc PV	0	21
Home with 6.75 kWdc PV and 21 kWh Battery Storage	2	10
Home with 9.6 kWdc PV	-19	10
Home with 9.6 kWdc PV and 19 kWh Battery Storage	-17	0
Home with 12.225 kWdc PV	-37	0

FIGURE 7 Cost-effectiveness of adding sufficient PV power production beyond NZE to achieve net zero carbon.



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