The Use of Time-Dependent Greenhouse Gas Emissions Factors in High Performance Building Design

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Abstract

Existing building performance programs addressing carbon emissions typically use energy as a proxy for carbon or use a single carbon emissions factor to convert annual energy use to an annual carbon value. In reality, the magnitude of emissions associated with electrical power generation varies with time and grid region. This study compares the use of an annual emissions factor to hourly marginal operating emissions rates (MOERs) in building carbon emissions calculations. Measured energy performance data from a case study net zero energy building is used to compute carbon emissions with and without the building's on-site PV production using both calculation methods. The results show that calculation with MOERs produces a greater magnitude of annual carbon savings from PV, but a minimal difference in carbon savings ratio. Examination of hourly data suggests the latter result is due to a low correlation between this particular building's time of use and the MOERs, and that a different result might be observed for a more grid-responsive building. These results have two implications for the use of MOERs in building carbon calculations. First, MOERs facilitate examination of a building's time of use impacts on the grid, but more work is needed to develop building carbon performance metrics that capture these effects. Second, MOERs allow the high performance building design process to expand beyond traditional energy efficiency measures and assess the impacts of fuel switching and shifting time of use through energy storage or demand control, and should be incorporated into building simulation tools.

Introduction

The need to decarbonize the building sector is necessitating a shift away from energy performance metrics and toward the use of carbon-based metrics in building design and operation. As a climate change mitigation strategy, focusing on and improving building energy performance has long been used as a proxy for reducing building carbon emissions. While commonly used energy performance metrics such as annual site energy use intensity (EUI) enable improvements in energy efficiency, they don't allow assessment of strategies such as fuel switching and shifting time of use through demand control and storage that will play a critical role in decarbonizing the building sector.

Recognizing the importance of using carbon-based metrics, many organizations and local jurisdictions are adopting these into their building performance policies and programs. New York City's Local Law 97, passed in May 2019, sets carbon emissions intensity limits for energy use in commercial and multifamily residential buildings greater than 25,000 square feet, with penalties for noncompliance (New York City Council 2019). The latest version of the International Living Future Institute's Living Building Challenge includes a net positive carbon imperative, requiring projects to offset both operational and embodied carbon and prohibiting on-site combustion (International Living Future Institute 2019).

The method these programs use for converting energy consumption to carbon emissions uses a location-specific single annual average emission factor and does not reflect the time-dependent nature of carbon emissions from the electric grid. In reality, carbon emissions vary with both location (grid region) and time, as different types of generators (e.g., nuclear, coal-fired, natural gas-fired, photovoltaic) are brought on- and off-line in response to changes in load and in an order reflecting the marginal cost of generation. Consequently, avoided carbon emissions associated with building electricity savings or use of on-site renewable energy will also vary based on the location and time of savings (Siler-Evans, Azevedo, and Morgan 2012).

The goal of this paper is to compare the use of an annual average emissions factor to hourly emissions factors in building carbon emissions calculations using a case study building. In short, we ask: What are the benefits of using hourly emissions factors over a single average annual carbon value in calculating operational emissions? A net zero energy (NZE) building was selected as the case study because NZE buildings represent the epitome of current high performance building design and allows us to explore the extent to which a NZE building is also net zero carbon. The methodology and results from this paper can inform policy and programs addressing building carbon emissions, as well as the design of high performance buildings.

Data and Methods

In this study, we use three datasets to compute building energy and carbon metrics: hourly building energy consumption and on-site renewable energy generation for our case study building, annual average carbon emissions factors, and hourly marginal operating emissions rates for the relevant balancing authority (i.e. the entity responsible for balancing electricity supply and demand in real time for each specific grid region).

Case Study Building

The Kohler Environmental Center (KEC) at Choate Rosemary Hall is a 29,325 square foot academic and residential facility located in Wallingford, Connecticut (International Living Future Institute 2020). Completed in 2012, the building contains laboratories, classrooms, and a research greenhouse, as well as residential facilities for up to 20 students. From the outset, the building was designed to achieve net zero energy performance, and it incorporates a variety of passive design strategies to reduce demand: highly insulated roof and walls, overhangs and shading, daylighting, and operable windows.

Heating and cooling are provided by a ground source heat pump system; earth ducts and energy recovery ventilators are used to pretreat outdoor air. When it originally opened, the building used a waste oil boiler to heat the greenhouse, fueled by cooking oil or biofuel; this was removed in March of 2016 and replaced with an electric boiler to eliminate on-site combustion (J. Scanio, program director, Kohler Environmental Center, pers. comm., March 5, 2020). A 294 kW grid-connected ground-mounted photovoltaic (PV) array and roof-mounted evacuated tube solar thermal panels provide over 100% of the building’s operational energy needs. This net positive energy building is a certified LEED Platinum building, and is also certified under the

Living Building Challenge. The building provides information and feedback to the occupants for teaching and learning purposes through an energy management system (EMS).

The KEC was selected as a case study for this paper due to its exemplary energy performance and the availability of operational energy data for the project, provided by the building owner to the authors. In the context of this study, it provides a benchmark example of a grid-connected net zero energy building operating on the U.S. power grid.

Metered interval data from the local utility was not readily available for this building, which is served by a small municipal utility. In lieu of this, the building owner provided the authors with hourly whole-building electricity consumption and PV production data downloaded from the building's EMS. Data for both variables was provided from July 2012 through December 2019.

The energy consumption and PV production data contained missing values due to data collection errors in the EMS, and each variable had different patterns of missing data. Table 1 shows the number of pairwise complete observations (i.e., hours containing both electricity and PV observations), and number of observations for each variable by year; for comparison, a complete year would contain 8,760 hourly observations. To fill in (i.e., impute) missing data, data from the post-oil boiler removal period (i.e., April 2016 through December 2019) was averaged by month, hour, and weekend or weekday to produce a lookup table of average energy consumption and PV production over that period. Each missing hour was completed using the corresponding average value for its hour, month, and whether it was a weekend or weekday. While this method provides complete hourly data, it provides only limited assessment of the true year-to-year variation in building performance, as multi-year averaged values are used where values are missing.

Table 1: Count of EMS observations by variable and year

Year	Pairwise Electricity and PV Observations	Electricity Consumption Observations	PV Production Observations
2012	2,410	2,386	3,789
2013	6,430	7,960	7,161
2014	5,803	8,000	6,538
2015	6,498	7,241	7,150
2016	7,226	8,202	8,684
2017	7,174	7,182	8,631
2018	3,670	5,506	4,298
2019	6,539	6,656	6,539

To align with the dates of available marginal carbon emissions data, the years 2018 and 2019 are used as the period of performance for this analysis. Figure 1 plots post-imputation monthly building electricity consumption, PV production, and net electricity consumption for the analysis period. The plot shows higher electricity demand in the winter compared to the summer for both years. This trend is expected in an all-electric building, and the seasonal demand profile for the electric grid as a whole will likely change in response to widespread building electrification (Hewitt and Coakley 2019). The profiles are similar across both years, showing net positive energy in most months of the year, with net consumption occurring only in the winter months when building electricity demand is highest and PV production is lowest.

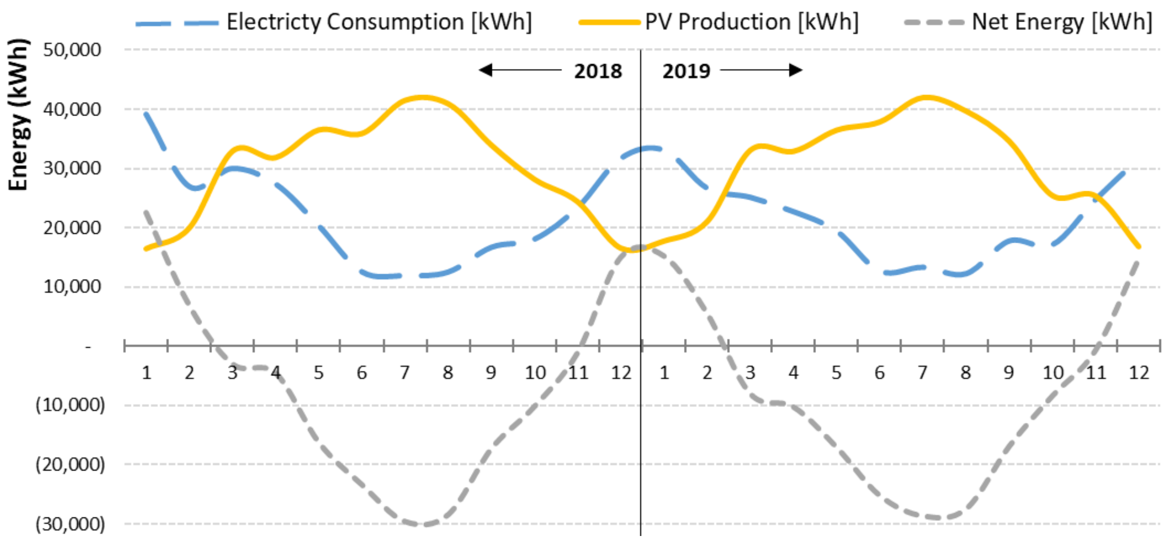

Figure 1: Post-imputation monthly building energy consumption and PV production for the KEC

Carbon Emissions Factors

Annual average emissions factors. Single annual average carbon emission factors are widely used by governmental, non-governmental, and for-profit organizations to convert building electricity consumption to CO_2 (or CO_2-equivalent) emissions for the purposes of carbon footprinting, benchmarking, and purchasing offsets. This is a single annual emissions rate representing average carbon emissions for all generators across the entire year.

For this study, we use annual average emission factors for the 2018 calendar year from the Emissions & Generation Resource Integrated Database (eGRID), developed by the U.S. Environmental Protection Agency (EPA) (U.S. Environmental Protection Agency 2020). eGRID provides total annual emissions and emissions rates for a variety of emissions types (e.g., CO_2, NO_x, SO_2) for the electric power sector. Emissions data are aggregated at several levels, including plant, state, balancing authority, and eGRID subregion (an EPA-defined area larger than a single balancing authority). The annual average emissions factor for the Independent System Operator New England (ISO-NE) balancing authority is 527.5 lbs. of CO_2/MWh and is the value used in this study.

To convert building electricity consumption to annual average carbon emissions, the annual net electricity consumption (i.e., electricity consumption less on-site renewable generation for the year) in units of MWh is multiplied by the annual average carbon emissions factor to determine lbs. of CO_2 per year.

Marginal operating emissions rates. Whereas annual average emissions factors represent the emissions from all generators on the grid, marginal operating emissions rates (MOERs) represent the emissions from the marginal generators only, i.e., the last generators to meet demand at a given time (Siler-Evans, Azevedo, and Morgan 2012). Because the marginal generators are also the first to respond to a reduction in demand, marginal emissions are the best measure of avoided emissions, and are therefore the best metric for evaluating the true impact of building demand reduction or net generation on the grid (DiStefano and Richardson 2019). MOERs change constantly as demand on the grid changes and different generators come online and go offline in response to changes in load and in an order reflecting the marginal cost of generation (Siler-Evans, Azevedo, and Morgan 2012); as a result, it is important to use sub-annual emissions factors to evaluate the impact of a building on marginal emissions.

For this study, we use MOER data for the ISO-NE Connecticut balancing authority sub-region provided by WattTime (WattTime 2020). WattTime uses a proprietary method to compute MOERs in real-time, expanding on the method developed by Silver-Evans, Azevedo, and Morgan (2012). MOER values were provided at 5-minute intervals from May 2017 through December 2019 and are in units lbs. CO_2/MWh of electricity. All values within a given hour were averaged to produce an average hourly MOER, which was used in this analysis.

To convert building electricity consumption to marginal carbon emissions, the net building electricity consumption at each hour (i.e., electricity consumption less on-site renewable generation for that hour) in units of MWh is multiplied by the MOER for that hour. This methodology captures the impact of changing grid emissions by giving more credit to a building implementing demand reduction measures or providing net generation to the grid during higher MOER times. Conversely, a building receives less credit for reducing demand or providing net generation during the lower MOER times. The MOERs effectively act as weights for a building's carbon emissions at a given hour.

For the purposes of visualizing trends in the MOER data, a heatmap of MOERs for each year in the analysis period is shown in Figures 2 and 3. The figures show hourly MOER values for each year, averaged based on month and weekday or weekend, as well as average values for the entire analysis period. The data indicates higher marginal emissions during summer months, especially July and August, and in the winter months, especially December and January. Marginal emissions are also higher during the day, particularly during the early evening hours.

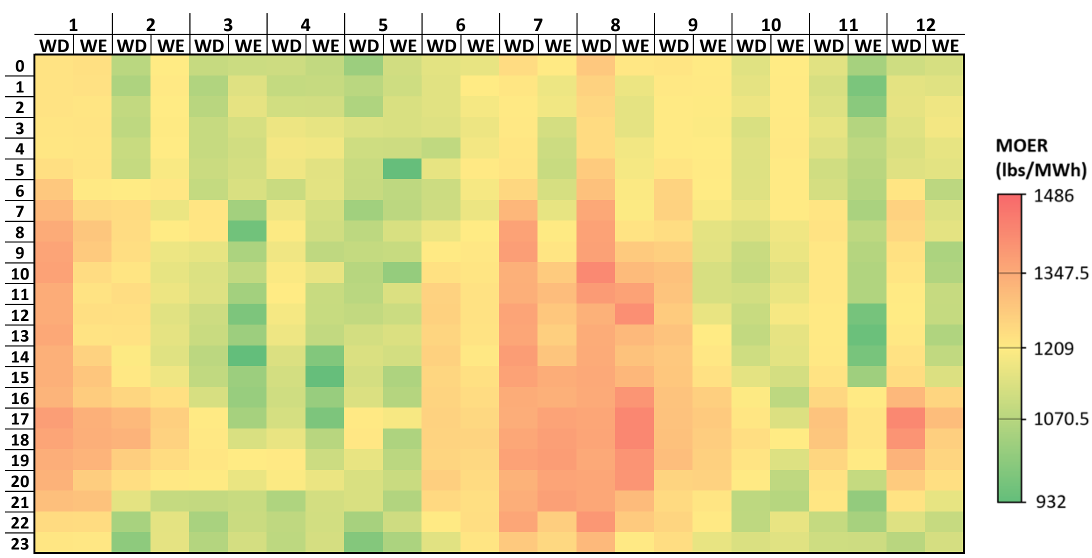

Figure 2: Heatmap of hourly marginal operating emissions rates (MOERs) for 2018

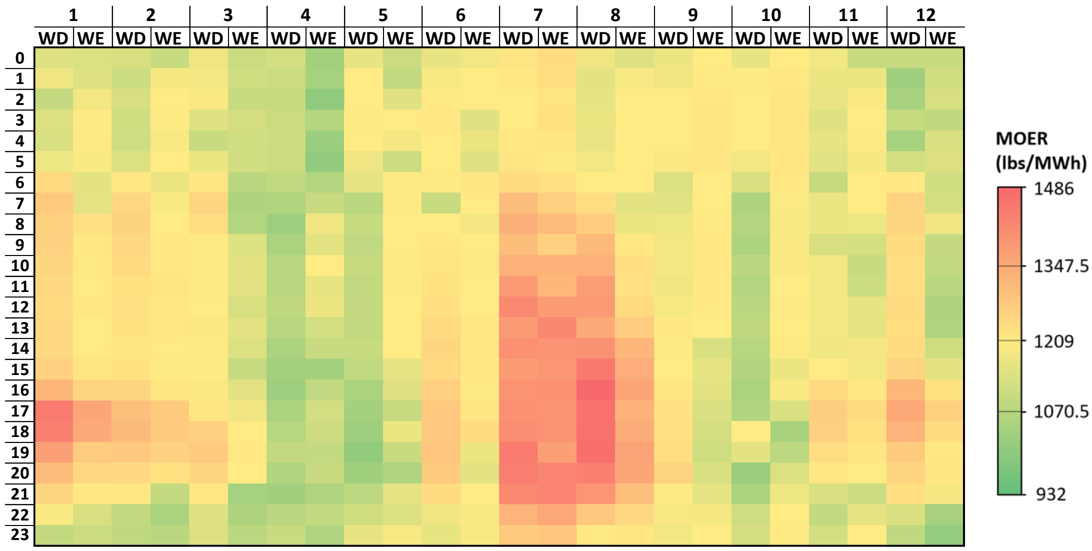

Figure 3: Heatmap of hourly marginal operating emissions rates (MOERs) for 2019

Figure 4 further illustrates the concept of marginal emissions compared to average emissions. A histogram of the MOERs for each year in the analysis period is shown, as well as the average annual emissions factor for ISO-NE balancing authority, provided from eGRID. Typical marginal emissions ranges for natural gas and coal power plants are overlaid for reference (World Nuclear Association 2011). The figure shows that the marginal generators for this grid region are primarily natural gas power plants with minor use of coal power plants. The marginal emissions rates for these generators are higher than the average annual emission rate of 527.5 lbs/MWh.

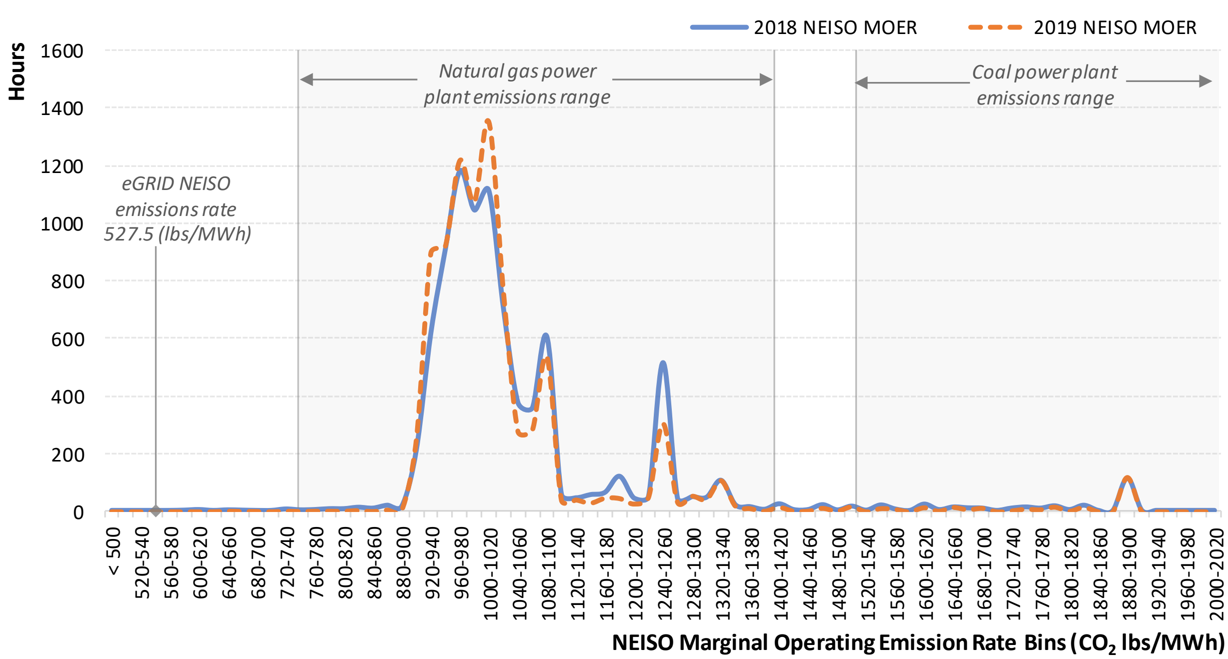

Figure 4: Histogram of hourly marginal operating emissions rates (MOERs) for the analysis period

Results

The results of the study are presented in Tables 2-4 and Figures 5-8.

Table 2 provides an annual summary of building electricity consumption, PV production, and net consumption for both years in the analysis period. Intensities (computed per square foot of building floor area) for each value are also provided, along with a savings ratio, computed as the ratio of PV production to electricity consumption (i.e., the energy savings provided by PV). Similar metrics have been used to evaluate the feasibility of net zero design (Eley 2016, 86-89). The results show that the KEC is a net positive building, overproducing electricity compared to its consumption in both years. The building's EUI of around 30 kBtu/ft^2 without PV is consistent with a typical high-performance building; its PV system is relatively large for its energy needs, with a PV production intensity of around 42 kBtu/ft^2 ensuring overproduction. The building has a savings ratio of 1.33 in 2018, meaning that the building produces 1.33 times the electricity it consumes; this value increases to 1.42 in 2019.

Tables 3 and 4 provide a similar summary, but for annual carbon emissions. Carbon emissions, emissions reductions, and net emissions are shown, along with carbon intensities for each metric and the savings ratio. Table 3 summarizes carbon emissions using an annual emissions factor, and Table 4 summarizes using hourly marginal operating emissions rates.

Table 3 indicates that the building achieves operational net zero carbon over the course of the year. The savings ratio using an annual carbon emissions factor is the same as the value for energy shown in Table 2; this is expected as this factor is a single multiplier.

Compared to Table 3, the magnitude of carbon emissions and emissions intensities in Table 4 are higher. This is expected, given that the marginal emissions for the ISO-NE CT subregion are higher than the annual emissions factor, as discussed in Figure 4. However, the savings ratio computed using marginal operating emissions is similar to the value computed using the annual emissions factor, suggesting that the building has equivalent annual energy and carbon savings under both carbon calculation methods.

While the savings ratio does not reflect a difference between the two calculation methods for this particular net positive building, the magnitude of the marginal operating emissions reduction does reflect a difference. Both metrics are important; savings ratio provides a comparative metric to reflect the relative effectiveness of carbon mitigation design decisions. Marginal operating emissions reduction captures the real world impact of carbon efficiency measures in terms of carbon emissions avoided.

Table 2: Annual summary of building electricity consumption

Year	Electricity Consumption (kWh)	PV Production (kWh)	Net Electricity (kWh)	EUI (no PV) (kBtu/ft^2)	PV Production (kBtu/ft^2)	EUI w/PV (kBtu/ft^2)	Savings Ratio
2018	270,284	359,487	-89,203	31.45	41.83	-10.38	1.33
2019	256,172	363,155	-106,982	29.81	42.26	-12.45	1.42

Table 3: Annual summary of building carbon emissions based on annual emissions factor

Year	Annual Emissions (lbs. CO_2)	Annual Emissions Reduction (lbs. CO_2)	Net Emissions (lbs. CO_2)	Emissions Intensity (no PV) (lbs. CO_2/ft^2)	Emissions Intensity from PV (lbs. CO_2/ft^2)	Emissions Intensity w/PV (lbs. CO_2/ft^2)	Savings Ratio
2018	142,575	189,629	-47,055	4.86	6.47	-1.60	1.33
2019	135,131	191,564	-56,433	4.61	6.53	-1.92	1.42

Table 4: Annual summary of building carbon emissions based on MOERs

Year	Marginal Operating Emissions (lbs. CO_2)	Marginal Operating Emissions Reduction (lbs. CO_2)	Net Marginal Operating Emissions (lbs. CO_2)	Emissions Intensity (no PV) (lbs. CO_2/ft^2)	Emissions Intensity from PV (lbs. CO_2/ft^2)	Emissions Intensity w/PV (lbs. CO_2/ft^2)	Savings Ratio
2018	284,855	383,831	-98,976	9.71	13.09	-3.38	1.35
2019	265,553	385,640	-120,087	9.06	13.15	-4.10	1.45

Hourly plots provide insight about why the savings ratio is the same for both carbon calculation methods. Figures 5-7 plot hourly building electricity consumption and PV production on the left y-axis, and hourly MOERs on the right y-axis for representative 24-hour periods in the spring, fall, and winter. These plots provide an hourly illustration of building electricity consumption and production relative to the MOERs; in a grid-responsive building, net production periods would align with the hours with the highest MOERs.

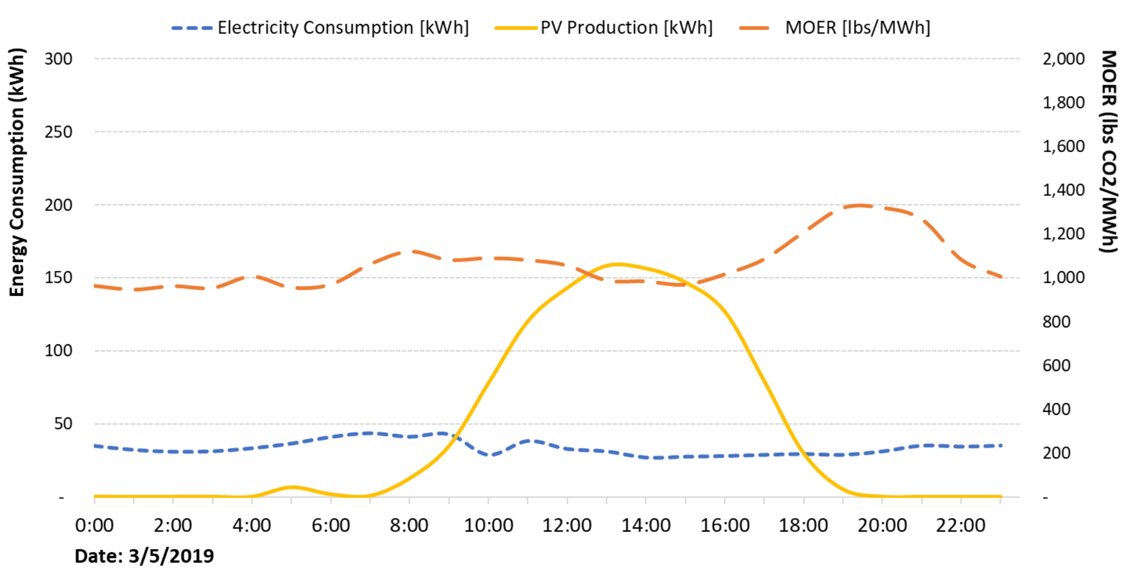

Figure 5: Hourly electricity and MOER profiles for a representative spring day

Figure 5 plots the hourly values for March 5, 2019. The building's consumption profile over this period is relatively flat, suggesting mostly passive conditioning of occupied spaces, and little need for space heating or cooling. PV production occurs during times of comparatively low marginal emissions, reducing marginal emissions less than if the production were shifted to later hours through energy storage. Due to overproduction from on-site photovoltaics in this particular project example, battery storage could be an effective carbon reduction measure, despite the round trip losses associated with charging and discharging.

Figure 6 plots the hourly values for July 11, 2019. Similar to the spring plot, the building's consumption profile during this fall period is relatively flat, suggesting energy use mostly for base loads. The MOERs show two peaks in the grid emissions, one around 11:00 AM and another around 8:00 PM. The PV production aligns fairly well with the first peak, but is unable to offset energy use in the evening hours during the second grid emissions peak.

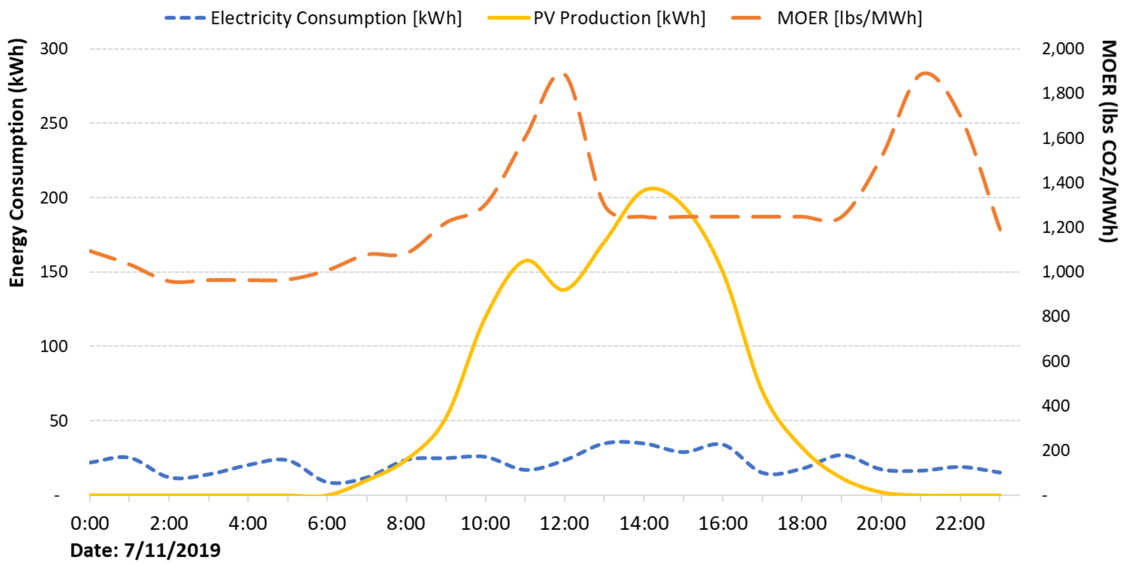

Figure 6: Hourly electricity and MOER profiles for a representative summer day

Figure 7 plots the hourly values for December 12, 2019. The building's consumption profile reflects the need for space heating during the early morning hours, decreasing during the day due to beneficial solar gains and internal loads, and increasing again in the late evening. The MOER peaks around 6:00 PM, which does not align with the peak PV production during the day. The building's peak heating demand and PV production periods are both offset from peak MOERs. Compared to the spring and fall, PV production in the winter is considerably lower, failing to offset net building energy consumption for that day. The seasonal difference in PV generation and MOER underlines the value of seasonal storage in considering how buildings can effectively respond to grid MOERs.

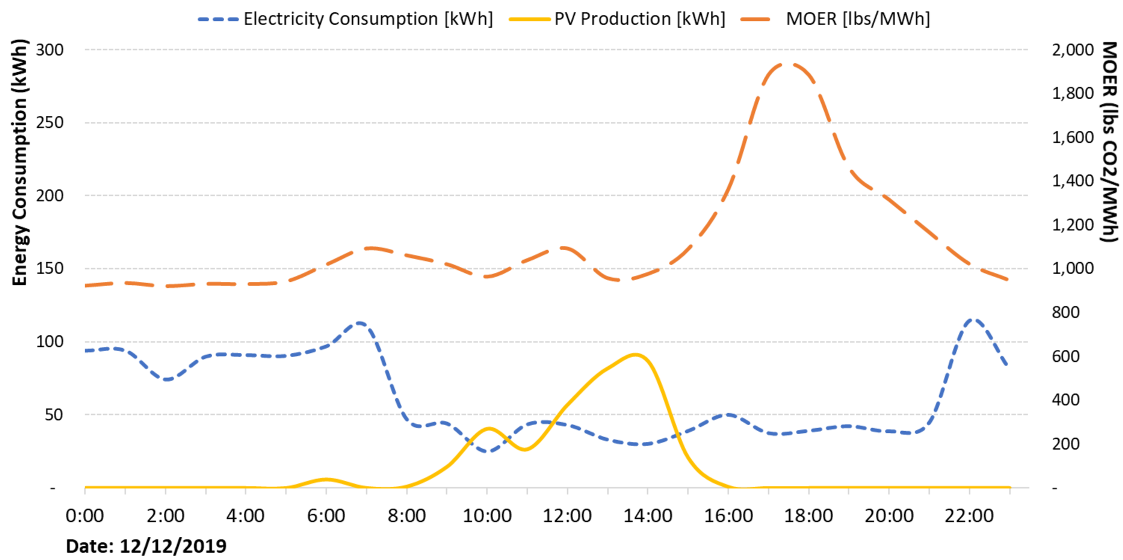

Figure 7: Hourly electricity and MOER profiles for a representative winter day

To further illustrate the misalignment between net building electricity consumption and MOERs over the entire analysis period, Figure 8 provides a scatterplot of hourly net building electricity consumption and hourly MOER. In a theoretical perfectly grid-responsive building, this plot would show a perfect negative linear correlation, with times of high MOER corresponding to times of low net electricity consumption (negative values indicate net generation to the grid). The data for the case study building shows a large amount of scatter, and no apparent linear trend. The correlation coefficient is r = -0.071, showing effectively no relationship between the two variables. With no correlation between the MOERs and energy use, the weighting effect of the MOERs effectively evens out over the course of the year, resulting in an annual savings ratio similar to that calculated using a single annual average emissions factor.

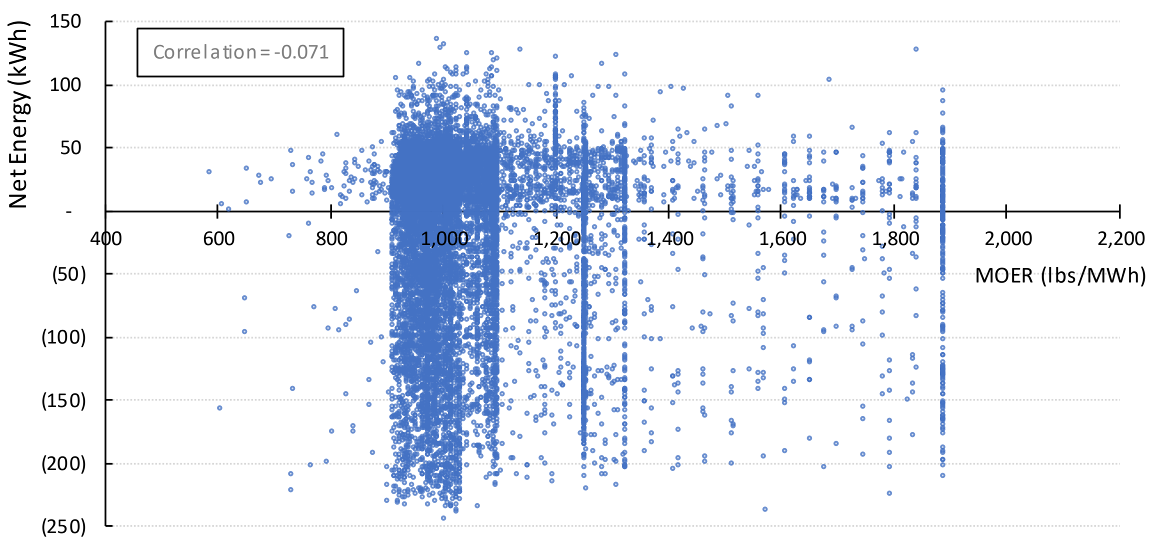

Figure 8: Scatterplot of hourly net building electricity consumption and hourly MOER

To examine the extent to which the MOER-based savings ratio would change with a more grid-responsive building, hypothetical data was generated with a stronger correlation with MOERs. Using the R package "fabricatr" (Blair et al. 2019), hypothetical data was generated with a correlation coefficient of -0.90 between net electricity consumption and MOERs (i.e., as MOERs increase, net electricity consumption decreases). The same annual metrics shown in Tables 2-4 were then computed using the correlated data. The results showed that the savings ratio for annual carbon was the same as for energy (1.69, a slight increase with the hypothetical dataset compared to the case study building), but that the MOER-based carbon savings ratio increased to 2.34 using the correlated dataset. This lends initial support to the idea that the savings ratio for the three metrics is similar for the case study building because it is not grid-responsive. Future work is needed to further investigate the use of MOER-based carbon metrics on grid-responsive compared to non-grid responsive buildings.

Discussion and Conclusions

The goal of this study was to compare the use of an annual average emissions factor to hourly marginal operating emissions rates in building carbon emissions calculations. The results for this particular case study show a greater magnitude of annual carbon savings but minimal difference in annual savings ratio computed using an annual average emissions factor compared to calculations using hourly MOERs. However, hypothetical correlated data provides initial evidence that a different result might be observed for a grid-responsive building, which shifts time of use in response to the emissions of the grid. More work is needed to examine how these results might change for non-net positive buildings, buildings in other grid regions, or buildings which are grid-responsive.

Unlike annual average emissions factors, MOERs allow examination of hourly carbon performance. Using MOERs is therefore advantageous compared to single annual average factors because it provides an understanding of the impact of a building's time of use patterns on the grid. This result has important implications for building carbon performance metrics and for high performance building design.

Building Carbon Performance Metrics

The use of annual emissions factors in most current building carbon emissions calculations reflects a focus on *how much* carbon buildings use, rather than *when* they use it. Fully decarbonizing the buildings sector will require buildings to be more responsive to their time of use impacts on the grid, and this should be reflected in the carbon performance metrics used in policies and standards, and by building designers and operators. Conceptually, marginal emissions are the best measure of a building's time of use impact on the grid, as the marginal generator is the first to respond to changes in demand. Building carbon performance metrics should therefore include the use of marginal emissions in addition to single annual average emissions factors.

In this study, we examine some possible marginal emissions-based metrics that might provide better guidance on a building's grid-responsiveness and which could be readily implemented into policy: net marginal operating emissions intensity, savings ratio (computed based on marginal operation emissions rates), and the correlation coefficient between hourly net electricity consumption and MOER. More work is needed to further develop metrics for grid-responsive buildings and examine how they might compare for other case study buildings and in other grid regions.

High Performance Building Design Implications

This study also illustrates the discrepancy between high performance building design and grid-responsive building design. The case study building is an excellent example of a high performance building, achieving net positive energy and zero net operational carbon on an annual basis. As shown in Figures 5-8, the building could achieve even further carbon emissions reductions through demand shifting or energy storage measures.

When designing a high performance building, energy efficiency measures achieved by prioritizing climate-appropriate passive design and efficient systems will always be the most effective carbon reduction measures. Energy or carbon-based metrics are appropriate to evaluate these strategies and will lead a designer to the same design conclusions. However once a design moves beyond efficiency to consider fuel switching, and shifting time of use through storage or demand control, time-dependent carbon metrics are critical to evaluate decisions. This study applied MOERs to post-occupancy measured data from a real building, but MOERs can and should be applied to hourly building energy simulations to give designers a common metric to evaluate the effectiveness of carbon efficiency measures and grid-responsive strategies.

Limitations

This study has several important limitations. First, only one case study building was used. This study should be repeated in different grid regions and with different high performance building designs (including buildings that are not net positive) to evaluate the extent to which these findings differ with different building demand profiles and grids. Second, while in principle the marginal carbon emissions calculation method used in this study is easily replicable, it is dependent on the availability and quality of hourly building energy data and marginal operating emissions rates. Similar to the KEC, many buildings still lack easy access to utility-metered interval electricity consumption and on-site generation data. While real-time and historical MOERs are available for many different locations in the U.S., they will undoubtedly change in future years as utilities move towards meeting mandated renewable portfolio standards; grid-responsive buildings should be flexible enough to respond to MOERs as a moving target. Finally, the need for grid-responsive building design and operation highlighted in this study requires tools that can support this shift. Despite recent advances in modeling demand shifting and energy storage measures, these have yet to be implemented in the most commonly used building energy simulation software.

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