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Incorporation of electricity GHG emissions intensity variability into building environmental assessment

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HIGHLIGHTS

- Current building assessment does not account for variability in the electric grid.
- A new method incorporates hourly grid variability into building assessment.
- The method is complementary with peak-shaving policies.
- The assessment method can affect building design decisions.

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ABSTRACT

Current building energy and GHG emissions assessments do not account for the variable performance of the electric grid. Incorporating hourly grid variability into building assessment methods can help to better prioritize energy efficiency measures that result in the largest environmental benefits. This article proposes a method to incorporate GHG emissions intensity changes due to grid variability into building environmental assessment. The proposed method encourages building systems that reduce electricity use during peak periods while accounting for differences in grid GHG emissions intensity (i.e., peak shaving is more strongly encouraged in grids that have GHG intense peak generation).

A set of energy saving building technologies are evaluated in a set of building variants (office, residential) and grid types (hydro/nuclear dominated, coal/gas dominated) to demonstrate the proposed method. Differences between total GHG emissions calculated with the new method compared with the standard (which assumes a constant GHG emissions intensity throughout the year) are in the 5–15% range when the contribution of electricity to total GHG emissions is more significant. The influence of the method on the assessment of the relative performance of some energy efficiency measures is much higher. For example, the estimated GHG emissions savings with heat pumps and photovoltaics can change by −40% and +20%, respectively, using the new assessment method instead of the standard. These differences in GHG emissions estimates can influence building design decisions. The new method could be implemented easily, and would lead to better decision making and more accurate estimates of the emissions from buildings and building technologies.

1. Introduction

Buildings use 40% of global primary energy [1], and energy efficiency measures in the building sector offer some of the most cost effective means of reducing energy use and GHG emissions [2–4]. In this context, building energy performance is a clear target for mandatory energy policies [5] as well as voluntary environmental standards and rating systems [6–8]. Building performance metrics used in standards and rating systems include total annual energy costs [6,9], primary energy consumption [8], and GHG emissions [7]. Even the definition of "net-zero energy building" refers to an annual energy balance (i.e., building total energy use relative to total renewable energy generation on an annual basis) [5,10–12].

Building energy standards and rating systems set a performance target for compliance (e.g., LEED v4 for new construction requires a

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5% reduction in annual energy cost relative to a reference building [13]), and building design teams are free to use any design strategy to meet that goal. Building energy simulation tools [14–16] are widely used to estimate energy use and assess environmental performance of building design alternatives and, ultimately, to aid design teams in making design decisions for new buildings and retrofits.

The standard building environmental assessment practice starts by running energy simulation tools to estimate the performance of buildings including their heating, ventilation and air conditioning systems at short time steps (typically less than 1 h) under varying conditions of weather and building use profiles (schedules). These tools then integrate the resulting hourly energy use values over a year to estimate the total annual final energy use. Practitioners typically convert the final energy consumption (kW h_{final}/yr) to annual primary energy use (kW h_{primary}/yr), annual GHG emissions (kg CO_2/yr), and/or annual energy cost ($/yr) by applying annual average conversion factors. National or regional energy agencies and standards organizations provide annual updates of these average values. For example, ASHRAE (in the United States) provides annual carbon intensity values to be used for Standard ASHRAE 189.1 [7], while DIN [17] and IDAE [18] provide annual factors for the mandatory building energy rating systems in Germany and Spain, respectively. However, the use of these annual average factors to describe the electricity grid neglects variations on the supply side (e.g., the electric grid) in the building energy simulation process and, therefore, in the derived environmental assessment of the buildings [19].

The term "grid variability" refers to the varying performance of the electric system over time (in this paper we focus on hourly variability). Total system electricity demand varies seasonally, daily, hourly, and even on the millisecond scale. The periods of highest electricity demand are known as peaks. The magnitude of the annual peak drives the capacity requirements for electricity generation, transmission, and distribution systems. In order to satisfy varying electricity demands electric power system operators dispatch (i.e., bring generating units on-line or adjust the output of on-line units) electric power generating units. The sequence of generators that are dispatched depends on a variety of factors, including the expected duration of the increase in demand, variable plant costs, plant start-up time, ramp rate, availability of renewable sources, and transmission constraints [20]. Variations in the power generation mix, for example type of fuel consumed and efficiencies of different generating units, lead to temporal variations in electricity emission intensity (e.g., kg CO_2/kW h). Electricity consumption of buildings also varies over time. For example, lighting is mostly used in the evenings and more so in the winter, while air conditioning use peaks around early afternoon on hot summer days. Therefore, energy efficiency measures for lighting and air conditioning will result in electricity savings at different points in time (e.g., hours of the day, different seasons). The environmental benefits associated with energy savings due to changes in lighting and air conditioning depend on the environmental performance of the electricity generation system at the corresponding points in time.

A better match between energy supply and demand through demand side management and the use of smart grids is the object of current technological and policy research [21–23]. Shaving peak power demand (i.e., lowering system demand at peak periods by using energy efficiency or displacing non-critical loads to off-peak periods) reduces the need to increase generation and transmission capacity of the electric system, and leads to a more efficient use of the available energy infrastructure and, generally, to a reduction of environmental impacts. Some jurisdictions have already implemented demand response programs and time-of-use pricing structures to shift some electricity use from peak to off-peak hours [24], and some building voluntary standards include requirements for annual peak power demand mitigation [7,8]. With the expected increase of distributed renewable generation systems as part of the move toward net zero energy buildings, load match and grid interaction indices have been developed to assess building interaction with the grid [25,26]. These indices quantify the energy exchange between the building and the grid, however, they do not account for variations in grid total demand, overall efficiency, or GHG emissions intensity. Load match and grid interaction indicators assess the variability of energy demand and supply at the building side, but do not include the associated variable environmental impacts at the supply side.

The assessment of energy-related building environmental impacts would be more accurate if supply side variability was incorporated into the assessment. Furthermore, incorporating grid variability can help to better prioritize energy efficiency measures that result in the largest environmental benefits. It can also help to enhance market penetration of "grid-friendly/peak-shaving" features in buildings by accounting for this variability in building environmental assessment at the design stage. Current building environmental rating systems are performance based; therefore, incorporation of grid performance into the assessment process would help design teams identify the sources of energy use with the highest impacts while still allowing them to find creative ways to reduce energy demand when it is most critical.

The objective of this study is to propose a method to incorporate GHG emissions intensity changes due to grid variability into building environmental assessment. The GHG emissions estimates using this method provide a more accurate representation of the actual GHG performance of buildings, accounting for the dynamics of both the supply (electricity system) and demand (building) sides. The development and rationale for the new method is described first. The method is then tested using 36 numerical scenarios (2 building types, 3 grid types, and 6 variants of energy technologies). The results of the numerical scenarios are then used to explore the implications and appropriate use of the new method.

2. Method

2.1. New method to incorporate grid variability into building environmental assessment

The current method to assess GHG emissions derived from building energy use (Eq. (1)) applies the annual average GHG intensity of the electric grid (CI_{EAvg}) to the total annual electricity use.

$$Total\ Annual\ GHG_{Current} = \left[\int_{yr} Electricity\ Use_t\, dt\right] CI_{EAvg} + \left[\int_{yr} Fuels\ Use_t\, dt\right] CI_{Fuels} \tag{1}$$

where:

t is time, usually discretized in hourly time steps
yr is year (i.e., the equation integrates over time t throughout one year yr)
$Electricity\ Use$ is the use of electricity in the building
$Fuels\ Use$ is the use of fuels in the building
CI_E is the GHG emissions intensity of electricity
CI_{Fuels} is the GHG emissions intensity of the fuels

Variability in the GHG emissions of the electricity grid can be incorporated into the assessment by multiplying electricity use (*Electricity Use*) and the corresponding GHG intensity (CI_{Et}) on an hourly basis (Eq. (2)). Eq. (1) is a particular case of Eq. (2).