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An assessment framework to quantify the interaction between the built environment and the electricity grid

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HIGHLIGHTS

- A metric to assess building interaction with the electricity grid is proposed.
- The GCS assesses electricity variability daily and seasonally.
- The GCS could inform building design decisions.
- The GCS could be used in building standards and rating systems.

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ABSTRACT

Electricity consumption in buildings is highly variable on time scales of seasons, hours, minutes, and even seconds. Yet, energy performance in building sustainability standards and rating systems is typically assessed in terms of total annual energy use, cost, and/or GHG emissions. Given that in North America buildings account for between 45 and 75% (depending on the region) of total electricity consumed, it is relevant to define an assessment framework to quantify the impact of variability in building electricity demand on the electricity system. This study proposes "Grid Compensation Scores" (GCS) that assess the contribution of a building electricity demand profile to increasing or decreasing the variability in the system electricity demand profile.

The GCS are applied to two building types (single family house and office building), located in two different electricity systems (Alberta and Ontario), and with a variety of building energy technologies (building variants). Results show significant differences in the GCS of different technologies depending on the building type, the electricity system, and the time scale (seasonal vs. daily). The grid compensation scores provide a quantitative assessment of the impact of building variants on the electricity grid at different time scales, which allow for a systematic comparison among building variants.

The results demonstrate that annual metrics can hinder decision making by obscuring variability that can alter the competitiveness of different building energy technologies. A multi-metric approach is therefore recommended for future assessments.

1. Introduction

Buildings (residential, commercial, and institutional) are responsible for approximately 73% of total electricity demand in the United States [1], and 56% of total electricity demand in Canada (with noticeable variations across provinces, e.g., 45% in Alberta, 65% in Ontario) [2]. Electricity demand in buildings vary seasonally, daily, hourly and even on a second time scale depending on a wide range of factors including but not limited to: building use type (e.g., residential vs. commercial), climate, efficiency and controls of lighting and appliances, availability of electricity generation technologies (e.g., solar photovoltaics), and energy source/carrier (electricity vs. natural gas) used for space heating, domestic hot water, or cooking.

Energy performance in building sustainability standards and rating systems is typically assessed on an annual basis in terms of energy costs [3,4], primary energy consumption [5], and GHG emissions [6]. These indicators, widely used to assess building energy and environmental performance, intrinsically assume that (1) the electricity grid

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environmental and cost performance is constant throughout the year, and (2) that the load (electricity demand) of a building does not affect the performance of the electricity grid. However, both these assumptions are inaccurate.

As the load of individual components in the grid change over time, the overall demand in the system varies. The periods of highest electricity demand are known as demand peaks. On an annual basis, high peaks of total system electricity demand lead to both economic and environmental costs because:

1. Generally speaking, more costly and less efficient power generation units are brought on-line as total system demand increases [7].
2. Transmission and distribution losses increase during peak demand periods.
3. The magnitude of the annual electricity peak demand drives the capacity requirements for electricity generation, transmission, and distribution systems. Hence, higher electricity peaks translate into higher infrastructure requirements and higher costs.

In turn, short term variability (on a minutes to hours scale) in total system electricity demand makes marginal generation units operate with lower efficiencies (than if they were operated constantly) due to frequent ON/OFF cycling or ramp-up/ramp-down. Therefore, short term variability also translates into increased economic and environmental costs (e.g., additional fuel being burned).

Strategies to reduce peaks and variability in electricity demand have been an objective of research [8–12] and policy programs [13]. At the same time, methods to effectively and sustainably integrate large scale variable renewable electricity sources (wind and solar) into the electric system has received much research focus of late [14,15]. However, assessment methods and standards used to aid in decision making related to building design largely disregard the impacts of variability introduced by electricity demand patterns in buildings.

Variations in electric load of an individual building are, indeed, insignificant to the electricity system. However, given that the aggregated load of the built environment dominates the overall electricity system load, an assessment framework that reflects the impact that different building demand patterns have on the electricity grid is needed.

1.1. Existing indicators to assess building interaction with the electricity grid

With the expected increase of distributed renewable generation systems as part of the transition towards net zero energy buildings (Net ZEBs), grid impact indicators [16] and grid interaction indicators [17,18] for Net ZEBs have been developed. Net zero energy buildings (Net ZEBs) are high performance buildings that, while connected to the electricity grid, generate as much energy as they consume on an annual basis. Policy commitments towards Net ZEBs [19,20] have triggered research initiatives [21] on the Net ZEB definition framework [22,23] as well as their design and performance characteristics [24,25]. Net ZEBs that use electricity as the only energy carrier have, by definition, a net zero electricity input from the grid on an annual basis. However, they can exchange large amounts of electricity with the grid on an hourly basis [26]. As Lund et al. put it, "from the viewpoint of the electricity supply system, a mismatch (between energy use and generation in Net ZEBs) is not necessarily negative. (…) a mismatch that decreases demand during the night (off-peak) and increases it during the day (peak) is negative. Such mismatch will increase the demand capacity and increase production of expensive units during peak hours and only save less expensive units during base load hours. However, for the same reason, a mismatch resulting in the opposite, i.e., a decrease during peak load and an increase during base load, creates a positive change for the system" [26]. Indicators of interaction between electricity supply and demand (in buildings) developed to date mainly address distributed generation systems and Net ZEBs due to concerns of distribution grid reliability. Distribution grids are usually sized to satisfy peak load [17], but this does not guarantee that they can handle the peaks of electricity production surplus when distributed generation is installed. In residential Net ZEB neighborhoods (which would typically have low electricity use and high electricity generation around noon on a sunny work day), excess electricity generation could result in unacceptable feeder voltage fluctuations and transformer overloads [27]. Experience in Germany suggests that high penetration of solar PV and wind can require costly reinforcements of the distribution grid [28].

Grid interaction (GI) indicators describe the resulting import/export interaction of a building with the energy grid. "The objective of computing grid interaction factors is to measure how a building or a cluster of buildings utilize the grid connection" [17]. Grid interaction indicators assess the exchange of electricity between a building and a grid based on total electricity exchange over a year, peak power demand (by the building, from the grid), and peak power supply (by the generating energy systems in a building, to the grid) [17]. GI indicators assess the net flow of electricity (imports/exports) between a building and the electricity grid, however, they do not take the variability on the supply side of the electricity system into account (that is, GI indicators do consider the characteristics and temporal performance of the electricity system).

The mismatch compensation factor (MCF) is another indicator defined as the ratio between the capacity of the renewable system for which the economic value of annual electricity import and export is the same and the capacity of the renewable system that makes the net annual electricity exchange with the grid equal to zero. It "shows the difference between the capacity (of the renewable electricity system) that meets the annual demand and the same capacity if one also has to compensate for the mismatch. If the mismatch compensation factor is 1.2, then the mismatch has a negative influence on the system and has to be compensated for by increasing the capacity of the renewable energy system by 20%" [26]. Unlike the GI indicators, the MCF accounts for the variability in the electricity supply system (by using hourly data of electricity price). However, it carries the implicit assumption that electricity price and total electricity system demand are linearly correlated, to which there are reported exceptions (such as Alberta) [29] and depends on electricity market pricing mechanisms. Additionally, the mismatch compensation factor can mislead users to think that a building with a MCF of 1 has no mismatch between demand and generation, or that if a building with a MCF of 1.2 increased renewable energy supply by 20% there would no longer be a mismatch. The logic of these assertions is generally not true, since the MCF is a ratio of renewable system capacities, and does not directly assess the magnitude of electricity exchange between the building and the grid. The mismatch compensation factor is only applicable to net zero energy buildings (i.e., that generate as much electricity as they use on an annual basis).

The recent work by Stinner et al. [30] has developed a framework for the assessment of flexibility measures in building energy systems (i.e., measures that allow buildings to shift electricity load over time). These assessment methods allow a consistent comparison among flexible options in the building energy systems themselves (e.g., heat pumps combined with thermal storage of different capacities) and storage technologies such as batteries. However, they are only relevant for buildings with energy flexibility measures, and are not meant to assess the interaction between buildings and the electricity grid.

Another recent paper [31] explores the potential for load shifting using the heating and cooling system of an office building. However, this research focuses on developing a control concept with specific storage options.

A method to incorporate electricity GHG emissions intensity variability into building environmental assessment was recently developed [29]. By accounting for the dynamics in both the supply (electricity grid) and demand (building) sides, this method provides a more