How New Metrics for Time-of-Use Carbon Can Help (and not Hinder) Decarbonization Goals

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ABSTRACT

Widely used metrics for energy ratings and energy code compliance are based on the ratios of modeled energy consumption of the proposed design to the consumption of a comparable building that meets an older and weaker energy code. These metrics provide factors for comparing electricity consumption to fuel consumption, and typically are single numbers computed by the rating or code agency or by the user. As the electric and gas supply systems evolve, these factors should not be constants over the year, but vary substantially based on time of use. This is true whether the factors are based on marginal carbon emissions, utility supply-side investment costs, or marginal source energy. Several organizations are working on developing such time-of-use factors and algorithms for controls that improve building performance, product capabilities, and whole-building networks required to reduce consumption at the desired times.

These ratings standards can include time-of-use energy comparison factors without creating unintended or unjustified barriers (or incentives) to shifts in how buildings and vehicles use energy. Large-scale changes in energy markets and policy frameworks today risk making energy codes and current program approaches obsolete, due in large part to the legacy metrics used by energy codes, ratings, standards, and efficiency programs. The paper recommends a framework for future metrics to rectify the problem, ensuring that building energy codes can remain relevant and useful in tomorrow's energy paradigm.

Introduction

Metrics of energy efficiency are used to establish single-parameter definitions of energy efficiency that can be used for code compliance or for demonstration of beyond-code performance. Examples of such metrics include the Energy Use Intensity (EUI), the Energy Rating Index (ERI) for homes used in the International Energy Conservation Code (IECC) and in ASHRAE 90.2, the Home Energy Rating System (HERS index) provided by the Residential Energy Services Network (RESNET), the Energy Design Index used in California's Title 24 energy code, and the Performance Cost Index used in ASHRAE 90.1. All of these standards consider a facility's energy consumption from multiple energy sources and weight them in specified ways. In this paper, we use the term "metrics" to describe the methodology and results of how these weighting factors are chosen.

These metrics historically have been used to add the levels of consumption of different types of fuels in a defensible way. One could just add the energy consumption of each fuel at the building boundary with a weighting factor of 1. But this method, called "site energy," is hard to defend: One Joule of electricity is not the same as one Joule of gas, for example, because electricity has lower entropy and thus can do more. Also, one Joule of energy from burning gas onsite has resulted in considerably less fuel use from a societal perspective than one Joule of electricity. This has been true because the great majority of electricity is traditionally supplied by centralized fossil fuel fired power plants with typical thermal efficiencies in the 30%-40% range, whereas the efficiency of onsite gas combustion is above 90% in some applications. Accounting for these conversion efficiency factors is called “source energy” One can also compare fuels in terms of their cost or their pollution impacts. All these issues are explained in Fairey 2016.

Today, an array of policy and market drivers is disrupting this paradigm. First, policy makers increasingly are concerned with limiting the impacts of greenhouse gas pollution, which can best be done if the metric is tied to this pollution. Second, the rise of renewables is decreasing the source energy content of electricity. The specific impacts of these changes vary widely both temporally and geographically, so the factors themselves will need to vary with place and over time. This paper explores how and why this need can be met.

When these comparison metrics were introduced in the 1970s, their impact was often incorrectly seen as a way of encouraging electric heating over gas heating, or vice versa. But this has never been an outcome of energy codes because the codes have chosen, in most cases, to be fuel-neutral by their structure. Thus, the ERI/HERS score uses metrics that are structured such that a gas heated home and an electric heat pump heated home will have the same score whenever the insulation levels, duct sealing, etc., are the same. The IECC similarly requires the assumption that a base case house uses the same envelope and same heating source – either a gas furnace or an electric heat pump – as the proposed design. Rather than encouraging fuel switching, these metrics mainly affected tradeoffs – for example, when the addition of south-facing windows reduced heating loads (usually gas consumption) but increased cooling loads (usually electricity).

As we enter the 2020s, the key driver of energy policy is no longer source energy but rather the reduction of greenhouse gas emissions. This shift drives follow-on policy issues including not only which fuel to choose for heating, but what time of the year electricity, and to a lesser extent gas, is used. Different designs of buildings will yield significantly different social impacts in terms of carbon emissions, and in terms of cost, even when their annual energy consumption is identical. Code metrics must evolve to remain relevant tomorrow.

This paper addresses how the metrics used in code and beyond-code energy ratings can be modified to encourage the societal goals of minimizing climate impacts of energy use. It also explores what additional changes in the energy modeling ruleset (e.g., the California ACM Manual, ASHRAE 90.1 and 90.2, and ANSI/RESNET/ICC Standard 301).

Background

Current codes tend to be neutral with respect to heating fuel choices, considering electricity and gas to be about equal in terms of their performance. But this near-equality has become untrue due to two distinct trends:

1. The dramatic and accelerating growth of distributed and utility-scale renewables is significantly reducing the marginal emissions associated with electricity usage.
2. The efficiency, performance, availability, and affordability of heat pumps for both space and water heating has improved significantly in the last decade.

These two trends are considered in more detail below.

Electricity's Falling Emissions Impact

For many decades, the source energy and emissions impact of marginal (additional) energy consumption at the building level was relatively constant across North America and across the year: 1 kWh of end use consumption required about 3 kWh of fuel input at a power plant. Some grids were more heavily reliant on hydro or nuclear than others, but this difference did not matter because hydro and nuclear plants were used as base load: their output did not depend on demand. Even if a region relied on these zero-emission sources for most of its electricity, each additional unit of energy consumed at a building did not—could not—affect hydro or nuclear generation. Instead that marginal unit of energy was provided by combustion of fossil fuels: the marginal resources on the grid.

But this began to change as more states adopted Renewable Portfolio Standards (RPS). These standards require that a certain percentage of all electricity generation must come from new renewable sources. Under this legal/policy structure, what happened at a building site DID affect the choice of generation: if the RPS is 50% then half of all electricity must be renewable. This has driven, and will continue to drive, significant investment in new renewable generating capacity, and incrementally more as buildings use more electricity to replace other fuels. The overall grid resource mix is changing – especially at the margin but also across the board.

Improved Heat Pump Performance

This change was compounded by the improved performance of heat pumps. As space and water heat pumps have become more efficient, they have disrupted the 3:1 ratio between site and source energy.

Let us consider an illustrative example: water heating. An electric resistance water heater is about 100% efficient: nearly all energy in the incoming electricity is delivered to the water. If the power plant is 33% efficient, 3 kWh of primary source energy (fuel at the power plant) were needed to provide 1 kWh of heated water. However, heat pump water heaters can achieve efficiencies of 300% or greater (DOE 2020). Therefore, 1 kWh of electric energy input could provide 3 kWh of hot water. A total of 3 kWh of primary energy is still required to deliver 1 kWh of energy, but 3 kWh of hot water energy is delivered. The ratio of primary energy to end use energy is now 1:1, not 3:1.

The picture is broadly similar for a gas water heater. Typical natural gas storage water heaters are about 70% efficient, so about 1.4 kWh are required to deliver 1 kWh of hot water energy. The heat pump water heater uses 40% less primary source energy than the gas water heater.

The Combined Outcome

Building energy codes do not account for electricity's falling emissions impact. They do account for efficiency gains at the appliance level, because performance-based compliance allows the designer to take credit for the rated efficiency of the installed heat pump. Since the potential savings from heat pump efficiency is higher as a percentage than the potential saving from a better gas furnace or boiler, this already allows a small incentive for beneficial/efficient electrification. But the codes still do not account for the ability of the water heater to change the timing of electric power demand and allow greater integration of variable-output renewables into the grid. This problem—and its solution—is discussed next.

The Growing Importance of Time of Energy Use

As renewable energy provides an increasing share of electricity on the grid, time of use becomes increasingly important. The marginal carbon content of the grid can vary by about an order of magnitude over the course of a typical day, and to an even greater extent over the course of a year. This temporal variation will increase under building, grid, and vehicle electrification scenarios, although it may be moderated if strategic efficiency measures (e.g., deep building envelope improvements) are part of retrofit electrification programs.

Figure 1 shows current (2019) and future (2030) predicted variability in the ***average*** hourly emissions impacts by month associated with electricity consumption in California.

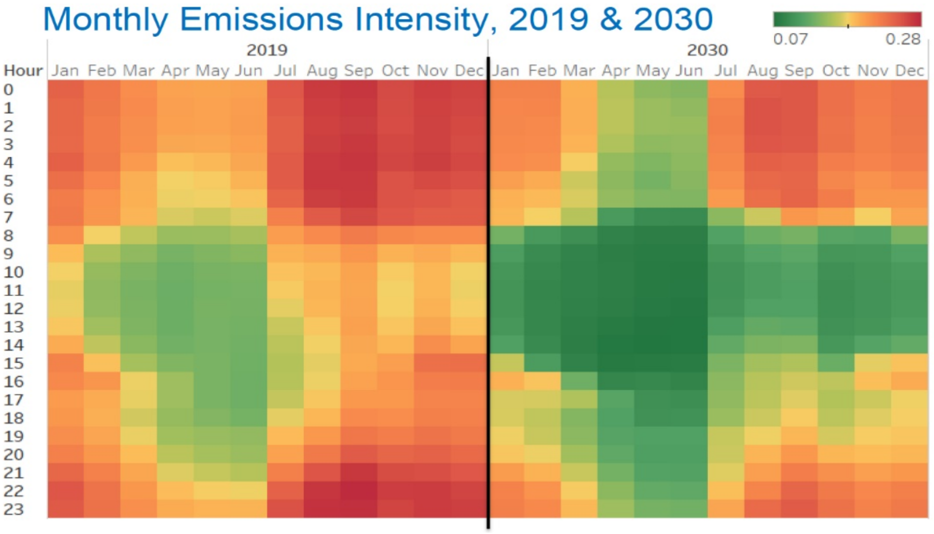

Figure 1. California Current and Future Monthly Emissions Intensity (Brook 2018).

This strong time-dependence of emissions impacts is a result of the high and increasing market share of variable renewable energy (solar and wind) in the generation mix. To effect such a large change in ***average*** hourly emissions in just 11 years requires ***marginal*** emissions to vary by a much larger proportion.

At some times of the year, the marginal resource on the California grid is predicted to be solar by 2030. During these times, saving energy does not result in significantly reduced emissions. These times include the mid-morning hours in spring when solar generation is high and electricity demand is relatively low. For some wind-dominant grids, the low-impact hours are overnight. For example, in Texas, wind energy provided a record-setting 55% of total system demand around midnight in December 2018 (St. John 2019).

For most grids, the highest marginal pollution impacts are just after dark in cooling season when air conditioning loads are high and lights are still on. In such hours, more of the energy on the grid is provided by relatively inefficient fossil fuel fired “peaker” generation.

Natural gas systems also have time-of-use variation: gas distribution systems store gas for use when weather conditions are adverse, and the provision of storage costs substantial money and can cause methane leaks. One such distribution system leak, at Aliso Canyon in Southern California, had a climate impact similar to the annual emissions of 600,000 cars (Warrick 2016).

Building designers can use their knowledge of time-of-use impacts to deliver facilities that maximize energy use during low-carbon periods and minimize use during high-carbon periods, in part by utilizing automatic systems that shift the time of use in response to utility signals, real time prices, or other inputs. Operators can utilize the demand flexibility capabilities designed into the building and its equipment stock to optimize the timing of consumption if such controls are present and enabled. A variety of initiatives are underway to provide new metrics and tools to the buildings industry, including the GridOptimal Buildings Initiative (GridOptimal 2020), which is led by author Alexi Miller. But these capabilities will be encouraged to a greater extent if codes and building rating systems account for their effect on greenhouse gas emissions and/or cost.

The Building Energy Codes Context

At present, building energy code metrics do not provide a mechanism to optimize building emissions impacts in this way. If, however, energy efficiency metrics were based on time-of-use impacts and/or if code metrics leveraged time of use emissions impacts directly, buildings could get credit for unlocking grid-scale emissions benefits through behind-the-meter demand flexibility and time of use energy efficiency strategies. This would offer the buildings community strong incentives to address the timing as well as the amount of energy consumption.

Building energy efficiency measures that can shift load or enhance demand flexibility, allowing the option of increasing or decreasing demand by design, such as grid-connected smart devices and controls, could be modeled for code compliance as saving emissions through their ability to defer or advance the time of energy consumption to minimize simulated emissions. The degree of savings would depend on the type of controls and the algorithms used by the controllers, among other factors. These approaches can be modeled for energy codes and specified or commissioned to ensure that their operation co-optimizes emissions and economics while maintaining services and comfort. New energy simulation modeling and building commissioning protocols will need to be developed.

These technical issues are not entirely new to the energy codes world. California has used “time dependent valuation” (TDV) as the metric for code compliance since 2005 (PGE 2002). California’s code specifies 8,760 separate factors (one for each hour in the year) with which to weight energy consumption as a function of climate and as a function of time. Gas and electricity have different TDV factors. They are based on the marginal cost of providing energy service at that hour, looking separately at generation costs, transmission costs, and distribution costs.

Generating these numbers is not a cheap or easy exercise, as it involves analyzing and modeling the grids for each of 16 climate zones (climate being important because the most expensive hours tend to be in the late afternoon several days into a hot spell, so the weighting factors have to correspond to the weather files used for energy simulation). Extending them to other regions would involve considerable effort.

Demand response is also not a new idea. Many large utilities have had such programs for decades. But what is new is the level of sophistication that is now possible with the Internet of Things. In the past, industrial customers were asked to cut power use on a day-ahead or similar basis by the utility when high peak loads were expected. This was carried out by a telephone call from utility staff to the plant operators. Residential customers were asked to sign up to a program that would allow the utility to cycle their air conditioners off for typically 15 minutes out of an hour based on a radio signal to a utility-installed controller retrofitted onto their air conditioner. In both types of programs participants received a financial concession.

New technology allows such controls to be much more comprehensive: rather than simply turning off specific equipment for a set time based on a signal, buildings can proactively adjust their load shape while simultaneously achieving deeper demand flexibility through whole-building level controls as well as at the equipment level through smart appliances and devices, often utilizing variable speed operability. For codes and ratings, we will need additional thought and analysis concerning how to model the energy impacts of specific control algorithms. This paper attempts to begin this process.

Getting Codes to Respond

The goal of efficiency efforts such as codes, standards, and ratings include both consumer protection and the advancement of societal goals[1] such as climate stabilization. Current codes provide insufficient incentives for electrification compared to the emissions reduction benefits and contain almost no mechanisms for incentivizing the harmonization of demand curves over time with the availability of clean energy resources over time. In order to ensure that building energy codes remain relevant and continue to deliver the significant societal benefits they have delivered for decades, policymakers should consider these questions:

What is the Purpose of Building Energy Codes Today?

This question gets at the fundamental *raison d'être* of energy codes. While ostensibly codes regulate energy consumption, today there are virtually no stakeholders in the business or nonprofit world that care about energy *per se*. Stakeholders care about the *consequences* of energy use: economic costs and pollution. Historically these metrics have tracked each other reasonably closely: source energy, consumer costs, and carbon emissions have remained generally proportional.

This is no longer true. Low natural gas prices have resulted in much lower consumer cost impacts from gas use, even while pollution impacts have remained relatively high. Meanwhile, retail electricity prices have risen steadily while emissions associated with electricity are falling.

If the purpose of energy codes is cost savings, then the time of use factors should be based on cost. If the purpose is climate stabilization, then the factors should be based on emissions. These two choices will tend to track seasonally: at times of low grid emissions impacts, there will be plenty of renewables available and costs will be low[2]. Conversely, at times when peaking plants that burn fossil fuels at low efficiency are heavily used, costs will be higher.

But the overall (yearly average) emissions metric will give results that diverge radically from those of the overall cost metric on the value of electrification. Here is a real-world example:

An electric heat pump water heater (HPWH) that is relatively efficient as defined by meeting the Northwest Energy Efficiency Alliance's Advanced Water Heating Tier 3 specification gets roughly the same TDV score in the California 2019 score as a tankless non-

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[1] Energy codes for homes were first established in the 1950s to reduce the likelihood of homeowners'' defaulting on mortgages due to high energy bills; energy codes for commercial were first undertaken in the 1960s to reduce the likelihood of mass blackouts such as the one that hit the regions around New York in 1965; legislative action on codes started after the oil crisis of 1973 and used energy consumption directly as the metric because of the perception that America had an energy shortage that was independent of price or environmental impact.

[2] This discussion is oversimplified because it ignores the difference between marginal costs to society and consumer costs. California's TDV methodology is based on societal marginal costs. Consumer costs are based on rates approved by the utility regulatory commissions. They tend to track marginal costs eventually, but time of use rates are not common for buildings and even when they exist their structure and the amount of variation understates the marginal value.

condensing gas water heater. However, it reduces carbon emissions by 50 to 70 percent. These emissions reduction benefits are not valued by the 2019 building code because the TDV metric is purely focused on energy costs instead of carbon emissions (Brockway and Delforge 2018).

Given this divergence, policy makers must choose which objective(s) they wish to best achieve. Jurisdictions seeking to design an energy code must first decide on the purpose of the code: whether it is intended to reduce cost, emissionsource energy, or a combination of these (Leslie and Goldstein 2019). A code could require compliance based on meeting two metrics individually or by a weighted average.

To What Extent Should Building Energy Codes Encourage Buildings to Address Grid Issues?

What is the extent to which codes should encourage load shifting and energy storage as ways of increasing efficiency (measured at the grid level)? This decision is independent of whether the code is regulating energy based on cost or on emissions: the algorithms needed to model the impact of changing the time of consumption are the same, and the structure of weighting factors is the same; only the numbers are different.

This paper argues that codes and ratings should encourage grid-level efficiency because as the world moves to an all-renewables future as required to meet climate goals (IPCC 2018), it is likely to find that the last 20% or so of decarbonizing the grid will otherwise be very expensive (Gowrishankar and Levin 2017). None of the studies on future emissions reductions potential has taken account of the dramatic savings that the authors think will be possible from grid-responsive buildings, which are not expensive at all.

How Energy Codes Can Remain Relevant and Useful in the Future

The authors have attempted to list selected key action areas to ensure that energy codes, standards, and ratings remain relevant and useful given the trends and developments discussed herein. In some cases, progress has already been made. The authors have included some examples to make these concepts more concrete.

These topics could be tackled one a time or as a comprehensive project. This is not a comprehensive list of needed action items; rather, it is intended to serve as a starting point.

1. **Develop and Implement Time of Use Metrics:** Codes should weight site energy impacts on an hourly basis in order to measure building-scale contributions to grid efficiency[3]. This action requires the generation of values for these factors based on the regional grid. These factors may be dependent on the weather files used for energy simulation, such that the highest impact could occur on the fourth day of a heat wave on the weather file. The development of these factors may require consideration of grid efficiency impacts based on historical and/or projected data.
   Current Progress: Time of use energy rates are common across the country and are the default rate structure for an increasing number of utility customers. However, time of use metrics are less common in energy codes. California's Time Dependent Valuation framework values energy savings based on energy cost during hours of the year when savings occur. This and other applications are summarized in a paper published

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[3] In this list, "grid efficiency" is shorthand for grid-scale cost and/or emissions improvement.

contemporaneously with this one (Edelson et al. 2020, also coauthored by Alexi Miller). A conceptual energy codes framework called Load Credits, which centers around a formula to award credits for building-scale load shifting (kW savings) weighted by hour was proposed by author Alexi Miller in a previous paper (Edelson and Miller 2018).

1a. **Develop Grid Efficiency Factors:** Grid-scale cost and carbon factors should be developed for both electricity and natural gas across all hours of the year. These factors should be weather-normalized and the methodology should be consistent so that implementing jurisdictions have the ability to focus on cost, emissions, source energy, or a blend of the three, while achieving minimum performance thresholds in each category. *Current Progress:* In some limited applications, grid efficiency factors already have a role in energy codes. As mentioned above, Time Dependent Valuation is used in California, and while it currently focuses on cost exclusively, this conceptual framework could be used to more accurately reflect grid efficiency considerations (cost and/or emissions); some thinking along these lines has been published in the ZERO Code for California (Architecture 2030 2018).

1b. **Locational Adjustments:** Codes should take into account the variability in grid efficiency between locations (utility territories, balancing authorities, weather, etc.) *Current Progress:* Grid-scale emissions, costs, and constraints vary from place to place. A few national databases are available to provide a single point of reference for this information. One forthcoming source that will be very useful is the National Renewable Energy Laboratory's Standard Scenarios (Cole et al. 2019): a structured data set of hourly data forecasts for the electric power sector, covering the contiguous US, for a range of scenarios extending out biennially to 2050. The data will include system total and net (minus variable generation) load, marginal and average CO_2 emission rates, and marginal electricity costs (separable into energy, capacity, ancillary services, and policy costs). The tool should be released in late 2020. Other data sources are discussed in Edelson et al. 2020.

2. **Define Standardized Requirements for Grid-Integrated Devices and Controls:** Leveraging the Internet of Things to improve grid efficiency at scale will rely on interoperability, security, and other key aspects; standardization is necessary for code/ratings applications. But to do this in a repeatable way suitable for an energy code requires standards on communications. An example of such a standard is presented next. *Current Progress:* The private sector has made some progress in this area. For example, the Consortium for Energy Efficiency (CEE) has gathered feedback from its members to develop a specific set of Consensus Principles for Connectivity, including:

    - Establish multiple pathways to connect;
    - Use open, nonproprietary, communication standards to achieve interoperability;
    - Understand the location of connected products;
    - Establish the minimum necessary communication pathways;
    - Secure customer data and adequately protect privacy;
    - Accommodate both price signals and reliability signals;
    - Disclose the equipment's ability to accept and respond to a grid signal;
    - Be able to share basic energy data with customers or an authorized third party.

3. **Develop and Publish Standardized Simulation Modeling Algorithms for Demand Flexibility Measures:** While California has developed methods for modeling battery storage, to the authors' knowledge standardized modeling algorithms have not been developed and published for demand flexibility measures.
   Current Progress: Some limited progress is being made but this is very much an area of emerging work. Pacific Northwest National Laboratory is working to model the impacts of commercial building load shape modification and demand flexibility strategies and expects to document its work; this documentation could form the foundation of standardized modeling approaches.

This is a large, complex problem. Detailing current efforts to solve these challenging issues is beyond the scope of this paper. However, one of the authors (Alexi Miller) has published two papers concurrently that delve deeper into recommended code metric frameworks and outline a range of recommended new metrics for designers (Edelson 2020 and Miller 2020).

This paper, and the two cited above, propose a framework for action plans that can be attempted for codes and rating standards. We anticipate that this framework will facilitate discussion and experimentation to find the best solutions that can encourage grid flexibility and credit it in ways that make sense. This experimentation and discussion is critical. The goal of new metrics is to encourage new efficiency measures that co-optimize the performance of the building and the grid. If they are effective, the grid will become more efficient over the years, and there will be a feedback loop between the methods discussed here and the results in terms of pollution and cost impacts.

How Carbon Metrics in Codes Will Support Climate Policy Achievements

This paper discussed some ways in which the buildings may substantially reduce the GHG emissions associated with their energy use, for example the electrification of space and water heating results in substantial reductions in carbon emissions in California[4]. However, current codes typically do not recognize such outcomes. Current code structures constitute a barrier to meeting goals of carbon reductions.

Regardless of how general the conclusion is about electrification helping reduce carbon emissions, the locally-specific right answer can be derived when the actions suggested in this paper are followed and real buildings can be compared based on a carbon metric.

Use of the carbon metric as the code compliance technique or as one of two (or more) required demonstrations of compliance will help provide the appropriate environmental signals concerning the extent to which electrification is beneficial. This will be important in jurisdictions where electrification aligns with the policy objectives. The foregoing discussion assumes that the compliance metric in the code or rating system is emissions-based. This may be a bridge too far for some codes or jurisdictions.

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[4] While California is a special case in some ways, it is typical of North America, and indeed of almost anywhere, in the future. To meet climate goals and comply with RPS requirements, the rest of North America will need to install far more variable renewable resources such as wind and solar, and the grid characteristics in these other locations will likely look more like California's grid does today as they approach similar penetrations of those variable resources. California has a large RPS, but other regions are close behind or even slightly ahead. And while many utility grids still rely on coal, natural gas is the marginal resource most everywhere to first approximation because it can load-follow more easily than coal or nuclear.

When does it make sense to electrify? This is a complex question that goes beyond the scope of this paper. The Regulatory Assistance Project (Shipley et al. 2018) states that “for electrification to be considered beneficial, or in the public interest, it must satisfy at least one of the following conditions, without adversely affecting the other two:

1. Saves consumers money over the long run,
2. Enables better grid management, and
3. Reduces negative environmental impacts.”

Conclusions

With the current and predictable grids for both electricity and gas, a critical part of increasing efficiency is to use a code metric that reflects the consequences of operating a building. These consequences, in terms of aggregate carbon emissions and in terms of the cost of the utility system, are no longer proportional to annual energy use, or even to a combination of peak power use and energy use. Instead they vary in both space and time, due in large part to weather (both in terms of renewable energy production at an appropriate location and a specific time, and in terms of how weather affects the demand on the grid).

To make defensible and appropriate decisions, we require building performance metrics that account for time of use, not just annual energy consumption. This paper has discussed key considerations for these metrics and outlined at a high level how they may be developed.

Some organizations are already embarked on this task. The California Energy Commission has been using time of use metrics for over a decade, and RESNET has decided to extend this work integrate time of use into the calculation of whole-house energy performance. A range of specific code metrics have been described in a paper published concurrently with this one (Edelson et al. 2020). The GridOptimal Buildings Initiative has developed a set of eight building-grid interaction metrics, which are described in a paper also published concurrently (Miller and Carbonnier 2020). This paper is intended to serve as an invitation to further research and consensus building on the details.

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