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INVESTIGATING THE IMPACT OF COST-BASED AND CARBON-BASED RENEWABLE ENERGY GENERATION AND STORAGE SIZING STRATEGIES ON CARBON EMISSIONS FOR ALL-ELECTRIC BUILDINGS

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ABSTRACT

Current renewable energy system, and storage, sizing and optimization designs typically focus on technoeconomic modeling. This paper proposes sizing and optimization based on greenhouse gas emissions as a metric as opposed to energy costs, as a method more in line with the intent of installing grid-integrated clean energy systems. Using a combination of simple energy models and results derived from a spreadsheet based tool, the authors discuss the benefits and limitations of both approaches, and the applicability of each in present as well as future scenarios.

INTRODUCTION

It is widely recognized that building energy use results in significant greenhouse gas emissions and high performance design presents a significant opportunity to reduce energy use and carbon dioxide emissions. As we move towards an all-electric future with zero or low carbon buildings through decarbonization of the electric supply grid, it becomes imperative to evaluate on-site renewable energy and storage systems based on a sophisticated time of use optimization approach instead of simplified annual calculations.

Over the past few years, several tools have been developed for optimization of on-site renewable energy technologies. System Advisory Model and HOMER Energy (DiOrio et al. 2015) are designed for techno-economic modeling of grid-integrated energy systems and platforms like REopt (Simpkins et al. 2014, Elia et al. 2016) are capable of simulation and optimization of renewable energy systems. The authors believe that optimizing grid-connected renewable generation and storage configuration to reduce energy costs is a reasonable way of approaching this problem, but may be limited in prioritizing environmental benefits.

Mitigating climate change effectively should involve an approach that demonstrates optimization based on time of use carbon emissions instead of cost. While some of the aforementioned tools have the capability of sizing and optimization based on minimizing carbon impact, prioritizing carbon over cost isn't the norm.

The authors hypothesize, given the increased penetration of renewable energy in the grid and the current utility rate structures in place, that cost-based sizing and optimization of renewable energy systems and storage may be inadequate at achieving the original intent of designing a Zero Net Energy (ZNE) building i.e. climate change mitigation.

Although the methods of accounting for the externality represented by carbon emissions, in the form of Carbon offsets and Renewable Energy Certificates (REC), are volatile and insubstantial at present; the authors' belief is that since carbon isn't represented as a financial metric in typical cost-benefit calculations, a method based solely on operating energy cost optimization is inadequate in minimizing the impact of climate change. As "cost of carbon" becomes increasingly relevant through adoption of command-and-control regulations like carbon tax and cap-and-trade schemes, results from cost-based and carbon-based optimization may align with one another.

Using in-house tools, the issue has been explored in detail and the merits and demerits of both approaches have been addressed. The paper discusses the results of a cost-based analysis and a carbon analysis, and indicate where they align and differ. While the former approach prioritizes optimization based on minimizing the annual energy cost and is heavily influenced by the applicable utility rate structure, the latter prioritizes minimizing the carbon footprint of the building and depends more on the energy mix of the electricity generated at any given hour.

STUDY PROJECT

Overview

The objective of this analysis is to study the impact of using carbon as a metric as opposed to cost on two parameters for an all-electric building:

- Sizing of renewable energy and batterystorage;
- Operation optimization to minimize chosen metric

The study project is assumed to be grid-connected with on-site photovoltaics. An underlying assumption is that there are no net-metering cap and tariffs are identical for electricity purchased from and sold to the grid.

Description of energy model inputs

A building with typical academic occupancy, internal loads, and usage profiles, has been chosen. Table 1 lists key features that define a detailed energy model used to generate hourly load profiles for a year of operation.

Table 1 Energy Model Inputs

PARAMETER	INPUT
Building type	Academic
Conditioned area (ft^2)	87,500
Number of floors	4
Weather file	Merced, CA TMY3
Simulation tool	eQuest v3-65 (DOE 2.2)
Principal heating source	Electric heat pump
Principal cooling source	Central chiller plant
Utility rate structure	PG&E Electric Schedule E-20

Building energy use profile

Figure 1a shows building specific loads highlighting the hours of peak demand during midday in the summer months, in the form of a heat map.

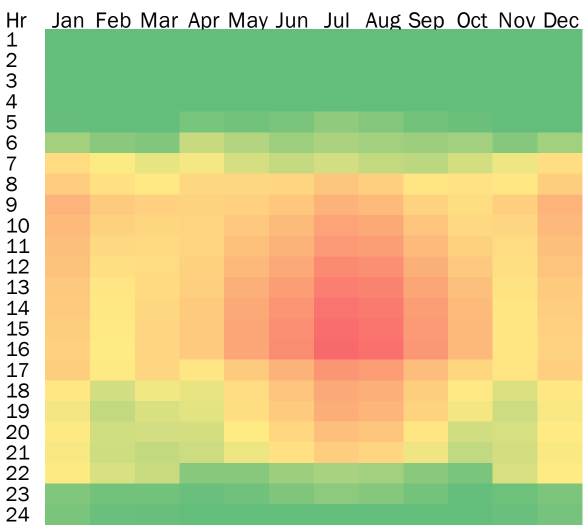

Figure 1a Average day heat maps (red:high-green:low) Building kWh

Grid electricity characteristics

The project falls under the jurisdiction of the California Independent System Operator (CAISO), with complex utility rate structures and a unique carbon intensity profile due to high photovoltaic penetration in the grid. Figure 1b qualitatively illustrates two grid related factors that affect energy cost and greenhouse gas emissions associated with building energy use. Each chart presents, the relative hourly distribution of a parameter for an average day of each month. The carbon emission intensity heat map is developed using emission profiles provided by WattTime. The maps show that hours of peak electricity cost coincide with the hours of maximum building energy demand, highlighting the significance of offsetting peak loads to achieve energy cost savings. Finally, it is important to note that the hours of maximum grid-based greenhouse gas emissions intensity during late afternoons, visibly different from the hours of peak electric costs.

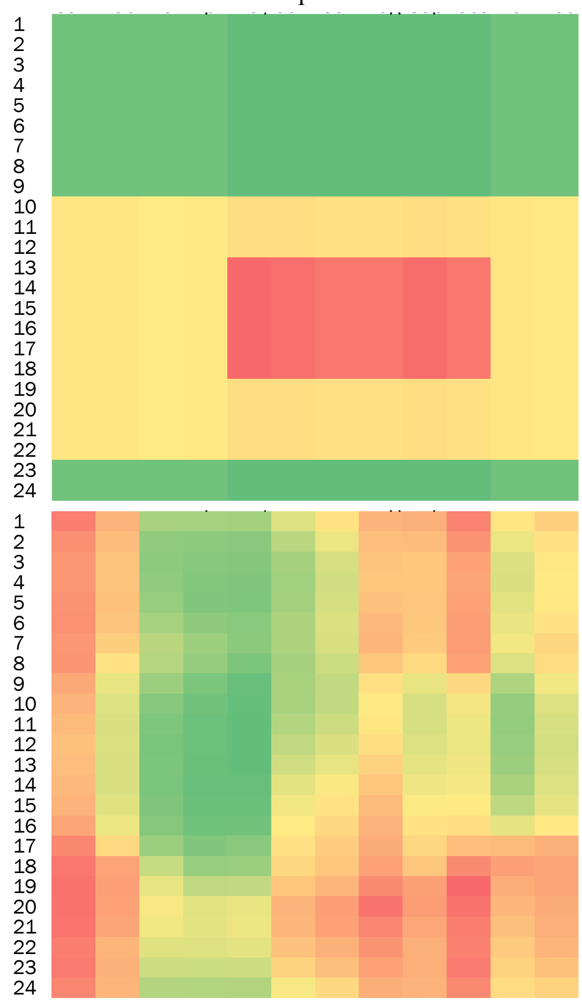

Figure 1a Average day heat maps (red:high-green:low) Top: Grid \$/kWh, Bottom: Grid CO_2e lbs/kWh

Carbon intensity calculator

A quick visual comparison of charts in Figure 1 clearly establishes that design strategies that solely target energy cost reduction by reducing the energy use during hours of peak electric rate, will not necessarily be most effective for greenhouse gas emissions reduction, and vice versa. This highlights the significance of carefully selecting appropriate renewable energy generation, storage, and dispach control sequences that offer the desired results. To enable the design of an optimally sized and controlled photovoltaic and battery system, a spreadsheet tool was developed that reads hourly building load profile, calculates the associated cost and emissions for each hour based on a user-selected optimization scenario and outputs the site energy use, operational energy costs and greenhouse gas emissions on an annual basis for each of the studied scenarios.

Optimized dispatch

In order to implement real-time optimization, the building automation system must have access to live energy use and data, energy use profile from the previous day, the previous year's energy profile for that day, or a profile for that day simulated by an energy model. Based on the parameters of optimization, the algorithm would require information regarding the applicable utility rate structure or the estimated grid carbon intensity profile. The control logic employed for the simulations in this study involve predicting durations when the penalty associated with either cost per unit energy consumed, power drawn, or grid carbon emissions will be the the most and the least, and operate the system accordingly. Based on the user-selected scenario, the function decides whether the building should draw electricity from the grid, from the photovoltaic system, or from the battery bank. Similary the control logic decides whether photovoltaic generated electricity for each hour is sold back to the grid, utilized by the building directly, or stored in the battery bank for future dispatch.

Sizing for net zero

In addition to the control logic, the capacities of energy generation and storage systems determine the proportion of building electricity demand that can be offset during either the peak-cost or the peak-emissions hours, depending on the performance goal of the studied scenario. The spreadsheet tool calculates the daily electricity demaind that needs to be offset for each scenario, sizes the photovoltaic system to generate that much electricity on a daily basis, and the battery system capacity based on the building demand during hours when grid purchased electricitiy should be avoided.

STUDY SCENARIOS

Several scenarios, designed to optimize different performance metrics, are simulated. This section presents the design configuration and resulting energy costs and greenhouse gas emissions for three distinct control logics; the first two rely on net-metered onsite renewable energy generation to ensure net-zero energy and net-zero energy cost respectively, and the third incorporates battery storage during late afternoons to achieve net-zero greenhouse gas emissions.

Net zero energy cost

This approach optimizes renewable energy generation such that, on an annual basis, the cost of grid purchased eletricity is equal to the cost of electricity sold back to the grid through net-metering. For the studied project and location, the hours of the highest electricity rate overlap considerably with the hours of photovoltaic generation. This implies that the renewable electricity can by utilized directly on site without the need for energy storage. Additionally, any surplus generated electricity can be sold to grid at a higher cost than the price to purchase from grid during off-peak cost hours.

Net zero site energy

This approach optimizes renewable energy generation such that, on an annual basis, the units of grid purchased electricity are equal to the units of photovoltaics generated electricity, regardless of its cost. Since all electricity is assumed to be net-metered, this scenario also does not require onsite battery storage, but requires additional photovoltaic capacity compared to the previous scenario

Net zero greenhouse gas emissions

Unlike the previous approaches, this scenario cannot rely solely on a renewable energy system since the photovoltaic generation does not coincide with the hours of highest grid emissions. In addition to a photovoltaic sysem sized for net-zero site energy, this scenario requires that renewable energy is stored in onsite battery banks during hours of low emissions intensity, and dispatched during polluting hours. In addition, the battery system needs to be designed with enough capacity to be able to offset the building energy demands during these hours.

Figures 2-4 show the hourly profiles for building electricity use, greenhouse gas emissions as well as energy costs for an average annual day with and without photovoltaic generation and battery storage; and summarize the performance of each scenario as percentage reductions in each of the studied metrics. The following section discusses these results in detail.

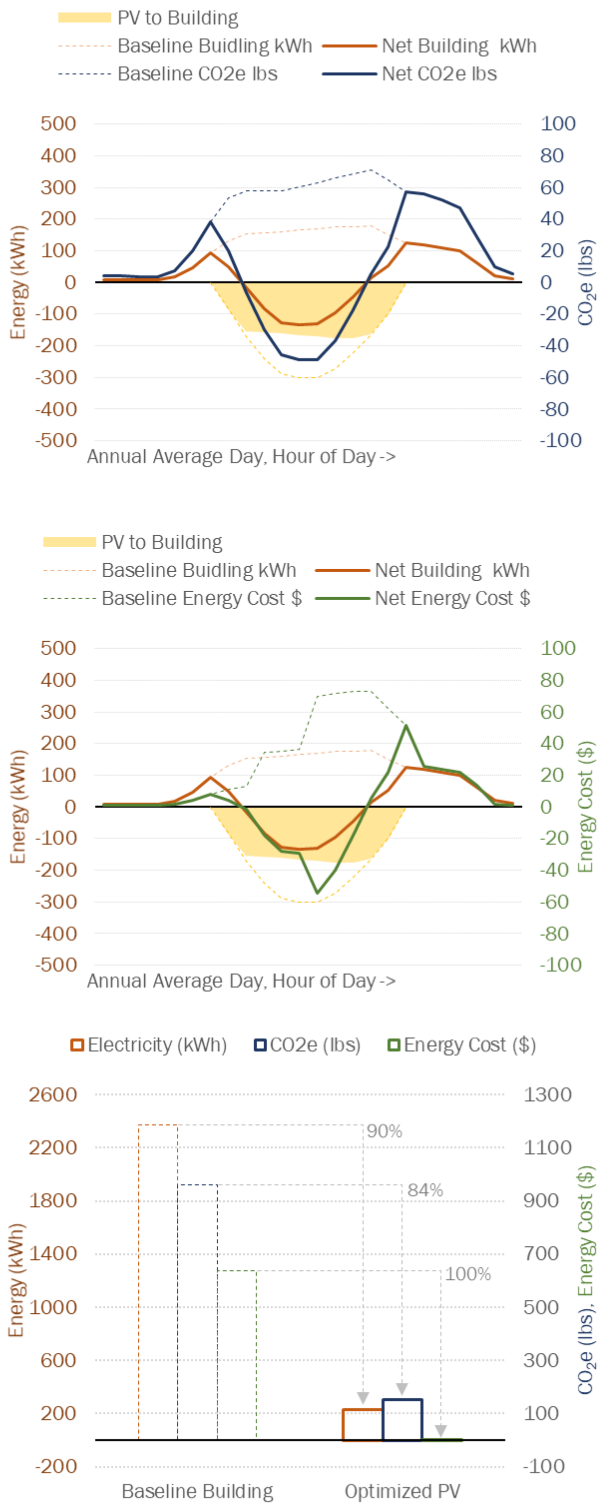

Figure 2 Control sequence for net zero energy cost showing energy use and CO_2e profile (top), energy use and energy cost profile (middle), and savings over baseline (bottom) for an average annual day

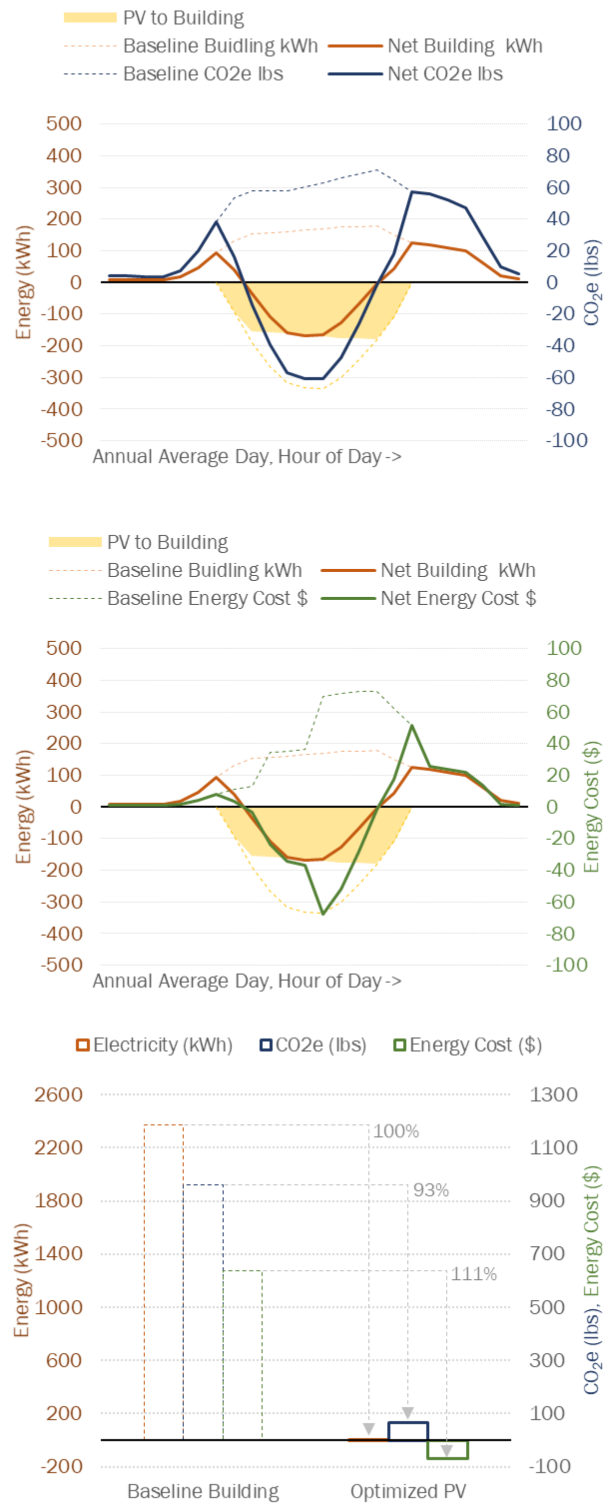

Figure 3 Control sequence for net zero site energy showing energy use and CO2e profile (top), energy use and energy cost profile (middle), and savings over baseline (bottom) for an average annual day

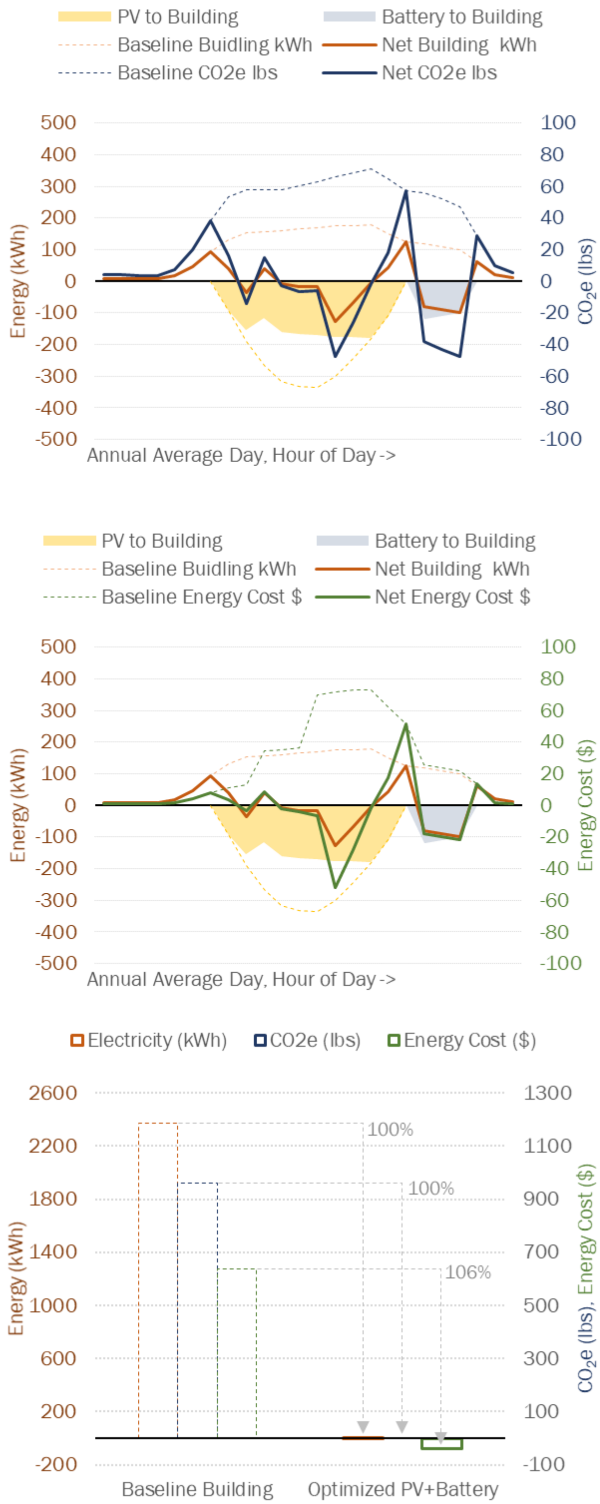

Figure 4 Control sequence for net zero CO2e emissions showing energy use and CO2e profile (top), energy use and energy cost profile (middle), and savings over baseline (bottom) for an average annual day

SUMMARY OF RESULTS

Table 2 sumarizes the results for all studied scenarios. The first step of optimizing for energy cost has the largest impact on greenhouse gas emissions, with each incremental step offering diminishing savings in both energy cost and greenhouse gas emissions.

The results suggest that the initial 84% reduction in CO_2e emissions (from 350,000 lbs to 56,000 lbs) comes with an onsite photovoltaic 525 kW_p photovoltaic array and results in an associated energy cost savings of \$233,000. The next step of increasing the photovoltaic capacity to 585 kW_p reduces the CO_2e emissions by additional 9% (56,000 lbs to 24,000 lbs) and the energy costs by \$10,000.

However, the last 7% reduction (24,000 lbs) required to achieve net-zero CO_2e emissions requires a 600 kWh battery storage capacity and results in an energy cost penalty of almost \$10,000.

Table 2 Summary of Results

BASELINE BUILDING	
Annual electricity use	865 MWh
Annual energy cost	\$ 233,000
Annual CO_2e emissions	350,000 lbs

DESIGN FOR NET-ZERO ENERGY COST	
Photovoltaic capacity	525 kW_p
Battery bank capacity	-
Annual electricity use	85 MWh
Annual energy cost	-
Annual CO_2e emissions	56,000 lbs

DESIGN FOR NET-ZERO SITE ENERGY	
Photovoltaic capacity	585 kW_p
Battery bank capacity	-
Annual electricity use	-
Annual energy cost	-\$25,000
Annual CO_2e emissions	24,000 lbs

DESIGN FOR NET-ZERO CO_2e EMISSIONS	
Photovoltaic capacity	585 kW_p
Battery bank capacity	600 kWh
Annual electricity use	-
Annual energy cost	-\$15,000
Annual CO_2e emissions	-

It is important to note that the estimated financial burden to achieve net-zero CO_2e emissions is conservative since it does not take into account the first cost of required battery storage.

DISCUSSION

Increased adoption of renewables across the electric grid has created an imbalance in electric demand and the time of solar energy generation and risk of over-generation. As the solar energy generation falls during evening hours, utilities ramp up flexible gas powered plants that can react quickly to adjust electricity production. This translates to a disconnect between the hours of peak electric rate hours and the peak electric emissions hours.

Consequently, projects that incorporate renewable energy generation and storage systems need to consciously design the systems' control sequences to minimize either the the energy costs, or greenhouse gas emissions. Ideally, these two performace goals should not be mutually exclusive.

Carbon pricing must play an important role in the transition to a decarbonized electric grid and, as such, should be considered as a financial metric in typical cost-benefit calculations. California Cap-and-Trade program for greenhouse gas emission allowances, launched in 2013, currently applies to large electric power plants, large industrial plants, and fuel distributors . In the future, as carbon pricing become increasingly relevant in curbing greenhouse gases and as these programs cover the building sector, it becomes imperative to include "cost of carbon" in evaluating on-site renewable energy and storage alternatives.

The current analysis shows a clear cost penalty associated with carbon-based optimization for on-site renewable energy and storage systems. Even after incorporating the prevalent cost of carbon between US\$80-120/tCO_{2e} (Kossoy et al. 2015), the monetary penalty for emitting a metric ton of carbondioxide is almost ten times smaller than the penalty of taking the most environmentally responsible approach.

An important factor as to why the penatly of carbon mitigation is so immense is the high utility rates appliable during times of battery charging. The duration when the grid is the cleanest is therefore the duration when power should be drawn from the grid. Similarly, the building receives electricity from the battery instead of the grid when the grid is the dirtiest, which coincidentally is also the off-peak period as per the utility rate structure. The utility rate structure doesn't align with the intent to minimize greenhouse gas emissions.

averaged grid emissions intensity and electricity cost profiles of one specific utility operator, demonstrates that control sequences for optimization of renewable energy systems and storage that are designed to maximize energy cost savings are inadequate in maximizing the potential impact of these technologies on climate change mitigation.

As we move towards higher renewable penetration into the grid and therefore quick-response peak load gas-powered plants, the grid emissions profile across the board will increasingly begin to resemble what is studied here, and prioritization of greenhouse gas emissions reduction over energy cost savings will become increasingly important.

The authors' belief is that the externality of greenhouse gas emissions needs to be better accounted for in economic decisions. On incorporating an appropriate cost of carbon that accurately accounts for the cost of emissions mitigation, designing from cost-based optimization and carbon-based optimization will be one and the same thing.

ACKNOWLEDGMENT

The carbon emissions instensity calculation is derived from hourly emission profiles shared by WattTime. http://watttime.org/

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