Managing residential solar photovoltaic-battery systems for grid and life cycle economic and environmental co-benefits under time-of-use rate design

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Abstract

The residential time-of-use (TOU) rates have been increasingly discussed or implemented by the US power utilities. The TOU rate design can potentially promote residential battery installations targeting increased selling or utilization of solar energy during the on-peak hours. However, our understanding in terms of the design and management of solar photovoltaic (PV)-battery systems for economic, environmental, and grid co-benefits under the TOU design remains limited. This study integrated system dynamics modeling with life cycle assessment to investigate the peak load reduction, life cycle cost, as well as life cycle climate change, water depletion, and fossil fuel depletion effects of residential grid-connected PV-battery systems under a TOU rate design. A residential prototype house in the Boston-Logan area, MA was selected for model simulation. Our study found solar PV-battery systems that maximize the on-peak grid selling can achieve the highest on-peak load reduction and economic benefits. However, they may not result in the highest environmental benefits, as on-peak hours have lower carbon emission and fossil fuel depletion factors as compared with the mid-peak hours in the New England grid. This suggests a potential tradeoff between the need of on-peak load reduction, economic saving, and environmental protection. Installing a PV system alone presents relatively strong economic and environmental performances, but its on-peak load reduction is limited. Installing a battery system but without an effective control strategy might result in relatively weak peak-load reduction, economic, and environmental outcomes. This highlights the importance of effective battery control in the implementation of solar PV-battery systems.

Keywords

Solar photovoltaic-battery system; battery control strategy; time-of-use rate; system dynamics modeling; life cycle cost assessment; carbon footprint

1. Introduction

Managing the daily and hourly fluctuations in electricity demand has been a long-standing problem within the power utility sector (Gelazanskas and Gamage, 2014; Oconnell et al., 2014; Uddin et al., 2018). To meet the peak demand, excess generation with fast response capabilities have to be installed, and more expensive fuels, such as natural gas, are normally used (ISO-NE, 2018). These peaking resources require substantial capital and operational investment (Uddin et al., 2018), yet they are only used during the limited on-peak windows (IRENA, 2019). Residential solar photovoltaic (PV) systems have traditionally been viewed as a potential means to reduce peak load (Huang et al., 2017). Over the last decade, installations of residential PV systems have boomed, and these systems currently contribute to around 0.77% of the total generation in the US (EIA, 2019, 2020). However, recent studies indicate that the large penetration of residential solar PV systems might result in a steeper ramp-up after the sun begins to set and use rises (Alam et al., 2014; Sukumar et al., 2018), making it more difficult for the grid operators to accommodate (Eltawil and Zhao, 2010). One potential solution to this steep ramp could be expanding storage at the residential scale (Sukumar et al., 2018). Less than 5% of the residential and commercial PV systems in the US have energy storage capacities currently (SEIA, 2020a, 2020b). Even among this small number of storage installations, only about 15% are managed for load control (Nottrott et al., 2012; O'Shaughnessy et al., 2018).

To help alleviate peak load pressure, utilities in the US have started to explore or implement residential time-of-use (TOU) pricing rates (Newsham and Bowker, 2010). TOU pricing refers to a rate structure that establishes a higher electricity use/sell price during the on-peak and/or mid-peak hours, and a lower price during off-peak hours (Dufo-López and Bernal-Agustín, 2015; Haider et al., 2016). Implementation of TOU rates can promote residential battery installations by encouraging increased selling/utilization of solar energy during the on-peak hours (Zhang and Tang, 2019). The design and operation strategy for these systems can influence the economic, environmental, as well as the peak load reduction benefits. For instance, management strategies that target peak load reduction might also speed up battery degradation and hence increase replacement or maintenance costs (Martins et al., 2018). Our understanding regarding how to design and manage solar PV-battery systems for economic, environmental, and grid co-benefits remains limited. Such an understanding is especially important given the Federal Energy Regulatory Commission's recent Order 2222, which will result in promoting the participation of aggregated distributed energy resources in the organized electricity wholesale markets (FERC, 2020).

Many previous studies only focused on the technical performances of the solar PV-battery systems under TOU rate designs, which were often measured in terms of the ramp rate of the PV output (Sukumar et al., 2018), solar energy consumption (Alramlawi et al., 2018; Khoury et al., 2016), grid use and sell (Alramlawi et al., 2018; Khoury et al., 2016), and peak load reduction (Huang et al., 2017; Schibuola et al., 2017; Uddin et al., 2018). Particularly, peak load reduction was found to be up to 50% at a household scale when the PV-battery systems were managed according to the TOU rate designs (Huang et al., 2017; Schibuola et al., 2017; Uddin et al., 2018). Additional studies have investigated both the peak load reduction and economic performances of solar PV-battery systems under TOU rate, comparing different battery control strategies (Khalilpour and Vassallo, 2016; Martins et al., 2018; Zhang and Tang, 2019), demand load profiles (Linssen et al., 2017), battery types (Parra and Patel, 2016), and battery storage capacities (van der Stelt et al., 2018; Zhang et al., 2017). Some of these studies found the installation of solar PV-battery systems can provide synergistic benefits of both peak load reductions and economic benefits for users (Khalilpour and Vassallo, 2016; Linssen et al., 2017; van der Stelt et al., 2018; Zhang et al., 2017; Zhang and Tang, 2019), while others highlighted tradeoffs between peak load reductions and economic savings, especially when the batteries' initial and replacement costs were considered (Martins et al., 2018; Parra and Patel, 2016). Not many studies have investigated the environmental performances of solar PV-battery systems under the TOU rate design. Hiremath et al. (2015) and Sun et al. (2019) investigated the cumulative energy demand or carbon footprint of various solar PV-battery system designs (e.g., different battery types and storage capacities) considering grid mix changes during on- and off-peak hours. None of these studies, however, considered the influence of battery management strategies on the environmental outcomes. Fares and

Webber (2017) and Litjens et al. (2018) further investigated tradeoffs between the peak load reduction and the life cycle environmental impacts of residential solar PV-battery systems. While both studies consistently reported reduced peak load when battery is added to a solar PV system, no consensus was found on whether or not the battery additions can reduce carbon emissions. Only three studies further considered solar PV-battery systems' economic performance in addition to their peak load reduction and environmental performances under the TOU rate design (Mariaud et al., 2017; Nojavan et al., 2017; Yang and Xia, 2017). Nojavan et al. (2017) and Yang and Xia (2017) found peak load reduction, economic, and carbon benefits can be achieved simultaneously through optimized battery control strategies. However, Mariaud et al. (2017) found installation of a PV-battery system can provide peak load reduction and carbon benefits, but it might increase the overall cost. This discrepancy is potentially a result of the different incentive designs and PV-battery technology costs considered. None of these studies, however, took account of the carbon emissions associated with battery manufacturing and replacement.

To address this knowledge gap, this study integrated system dynamics modeling (SDM) with life cycle cost and environmental assessment to investigate the preferred design and operation strategies of PV-battery systems under TOU rate design. The modeling framework was applied to a 5-unit prototype house in the Boston-Logan area, Massachusetts of the United States as a testbed. The Boston area was selected because of its strong in-place solar incentive programs (MassCEC, 2020), and its active pursue of renewable energy and storage (Mass.gov, 2020a). Five performance measures were used to evaluate different PV-battery system design and management scenarios: peak load reduction, life cycle cost (LCC), fossil fuel depletion, carbon footprint, and water footprint. This study aims to evaluate and understand the tradeoffs among the peak load reduction, economic, and environmental performances of different solar PV-battery system design and management scenarios under TOU rates in support of future pertinent policy and incentive designs.

2. Methodology

2.1 System and scenario descriptions

The grid-connected polycrystalline silicon (poly-Si) PV panel and Li-Ion battery system was selected in this study given their popularity and cost competitiveness (Sharma et al., 2015). Figure 1 presents a schematic of the setup of the studied system. The PV-battery system was applied to a prototype low-rise multifamily house based on the US Department of Energy's House Simulation Protocol (Wilson et al., 2014). The hourly load profiles of this prototype house was collected from the Open Energy Information database for the Boston Logan area, MA for our simulation (NREL, 2014). The grid fuel mix was collected from ISO New England Inc. (ISO-NE), an independent and non-profit Regional Transmission Organization (RTO) serving the New England area (ISO-NE, 2018).

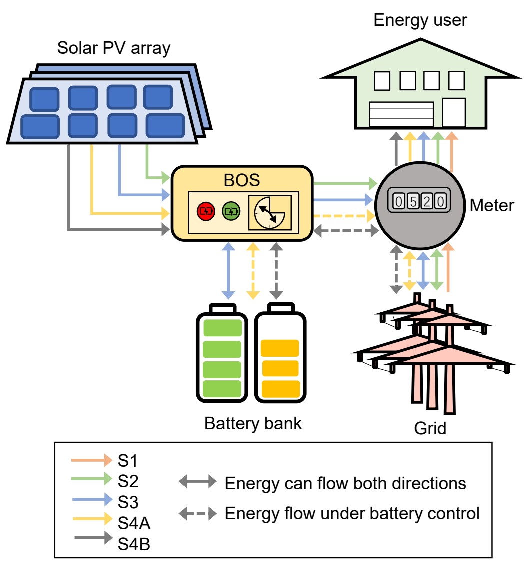

Figure 1. Schematic of the GC solar PV-battery system

The TOU rate structure adopted in this study came from a pilot study conducted by the Liberty Utilities in 2018 (Tebbetts, 2018), which includes an off-peak, mid-peak, and on-peak rate (Figure 2). For comparison purpose, a flat rate structure was also investigated, which utilizes a constant rate of 16 cents/kWh calculated as the average electricity rate in New England area from 2016 to 2017 (NREL, 2017). For simplicity, solar feed-in-tariffs were assumed to be the same as electricity retail prices under both TOU and flat rate structures.

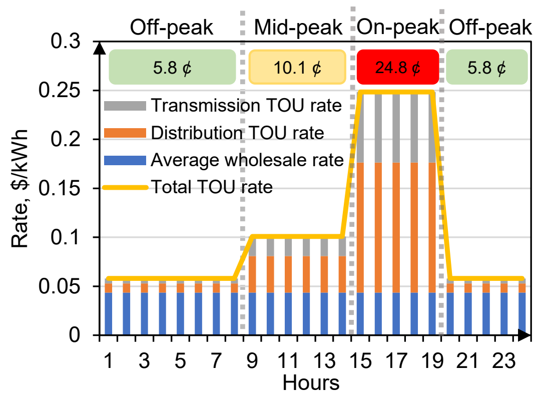

Figure 2. The TOU rate design that is utilized in this study

Five solar PV-battery design and management scenarios were investigated (Figure 1). Scenario 1 (**S1**) describes a baseline condition where no PV or battery was installed. The household relies entirely on the grid. Scenario 2 (**S2**) represents a condition where only PV panels were installed. The panel size was assumed to be 12.2 kW, which was designed to meet the peak load of the prototype house. The same panel size was also utilized in the following scenarios. Scenario 3 (**S3**) is when both PV and batteries were installed but the battery system was not managed according to the TOU rate structure. Only solar energy can charge the battery. Scenario 4A (**S4A**) is when both PV and batteries were installed and managed according to the TOU rate structure. Only solar energy can charge the battery. Scenario 4B (**S4B**) is similar to S4A except that both solar energy and the grid were allowed to charge the batteries. These scenarios are reflective of the typical residential PV system designs and/or operation strategies with consideration of potential user benefits and the developing policy initiatives in the energy industry. The rules of system control under each scenario were further discussed in Section 2.2.1.

2.2 Description of the modeling framework

Load reduction, economic, and environmental performances were assessed in this study by integrating SDM, life cycle cost assessment (LCCA), and life cycle assessment (LCA). SDM is a computational method applying a set of linked differential equations to simulate the behavior of complex systems over a certain time period and studying the interactions among system components through capturing system feedback loops and delays (Forrester, 1997; Sterman, 2000). LCCA adopts a net present value (NPV) method to account for all economic costs and savings that incur during the life span of a PV-battery system (Durairaj et al., 2002). LCA assesses the supply chain environmental impacts attributable to the entire life cycle of a PV-battery system (Rebitzer et al., 2004). In this study, the SDM was used to simulate the dynamic behavior of energy generation, storage, and grid sell on a thirty-minute step over a typical year (Peng et al., 2017; Reddi et al., 2013; Ren et al., 2020). Outcomes from the SDM were used to inform the off-, mid-, and on-peak load reductions, costs/savings, fossil fuel depletion, carbon footprint, and water footprint calculations over the 20-year use life of the solar PV-battery systems. The conventional LCCA and LCA methods were applied to the manufacturing, transportation, maintenance (i.e., battery replacement) phases of the solar PV-battery systems.

2.2.1 System dynamics modeling of the solar PV-battery system

The SDM was developed in Vensim DSS® software given its wide application (Ford and Ford, 1999). This section was intended to provide a brief overview of the SDM, while a more detailed model description can be found in Ren et al. (2020).

Solar energy generation was calculated following a method that was used in the HOMER software, adjusted to consider the cooling effect provided by wind (Section 1 in Supporting Information) (Ren et al., 2020). The amount of generation depends on three key time-varying input variables: incident solar radiation, ambient temperature, and wind speed. All three variables were obtained from the National Solar Radiation Database (NREL, 2015). Battery storage was simulated based upon battery charge, discharge, and energy loss at each time step. The initial battery storage was assumed to be zero. The charging and discharging rates depend on the total charging/discharging need and the existing battery storage at each time step, as well as the total battery storage capacity. These rates were constrained by the maximum charging and discharging rates calculated based upon the percent vacancy of the battery capacity at each time step (Eq. S4-8 in Supporting Information) (Energy, 2017). Energy loss during charging and discharging was calculated based upon the system round-trip efficiency, which was assumed to be 80% (around 10.6% of the charging and discharging rates was lost) (Dufo-López and Bernal-Agustín, 2015). In addition, battery replacement over the system lifespan was estimated through the ratio of the actual battery system throughput to the rated battery system throughput (HOMER, 2017).

The SDM contains an energy balance sub-model which controls the allocation of the generated solar energy to house consumption, battery charge, and grid sell as well as the timing and amount of battery charge and discharge. Grid sell was assumed to be unconstrainted considering the current Massachusetts Net Metering policy (Mass.gov, 2020b). Table 1 presents the rules of system control under the five scenarios.

Table 1. Prioritization of generated solar energy distribution

Peak time	S1	S2	S3	S4A	S4B
off-peak	No solar energy is generated.	Solar energy generated is prioritized for meeting household demand before grid sell.	Solar energy prioritization goes from meeting household demand, battery charging to grid sell. Battery storage is discharged whenever household demand cannot be met by the solar energy before the grid kicks in.	Solar energy prioritization goes from battery charging, meeting household demand to grid sell. Battery is not discharged during this period.	Solar energy prioritization goes from battery charging, meeting household demand to grid sell. Grid charge only kicks in if the battery is not fully charged by the solar energy 30 mins before the off-peak period ends. Thirty minutes were assumed to be sufficient to fully charge the battery system. Battery is not discharged during this period.
mid-peak					Solar energy generated during this period is prioritized for meeting household demand and then grid sell. The battery system remains fully charged and inactive.
on-peak				Battery is fully discharged for grid sell and then remains inactive. Solar energy generated is prioritized for meeting household demand before grid sell.	

Load reductions (kWh) during different time periods were calculated using Equation 1.

$$R_{load} = \int_{t_0}^{t} \left(E_{solar} + E_{sell,PV} + E_{discharge,g} \right) dt \quad \cdots \cdots \text{Equation 1}$$

Where,

R_{load} represents the load reduction of the grid, kWh;

E_{solar} is the household demand met by solar energy, kW;

$E_{sell,PV}$ is the direct grid sell from the PV system, kW;

$E_{discharge,g}$ is the grid sell from the battery storage, kW.

2.3 Life cycle cost assessment

The LCC of installing a solar PV-battery system was calculated as the NPV of the capital cost, operation and maintenance (O&M) cost, tax credit and rebate using Equation 2. The capital cost of the system includes the costs of panels and racking ($1/Watt of generation capacity) (McFarland, 2014), batteries ($209/kWh of storage capacity) (Curry, 2017), inverters ($300/inverter unit) (HOMER, 2018), permission ($450/system) (NREL, 2017), and labor (calculated based upon a tiered pricing; Figure S3 in Supporting Information) (HomeAdvisor, 2019). All future costs were discounted to the year of 2020 applying a discount rate of 5% (Ren et al., 2020).

$$C = C_c - C_r + \sum_{n=0}^{n=L}\left[\frac{C_{o,n} + r_{off}\int_{t_{off}}(E_{u,t}-E_{s,t}-E_{d,t})\,dt + r_{mid}\int_{t_{mid}}(E_{u,t}-E_{s,t}-E_{d,t})\,dt + r_{on}\int_{t_{on}}(E_{u,t}-E_{s,t}-E_{d,t})\,dt}{(1+d)^n}\right]$$

··· ··· Equation 2

Where,

C represents the LCC of a PV-battery system, $;

C_c is the capital cost of the system, $;

C_r is the tax credit (30% of the capital cost) (IRS, 2019), and rebate ($0.25/Watt of installed PV capacity) (NHMA, 2015);

L is the life span of the solar PV system, 20 years;

$C_{o,n}$ is the battery replacement cost in one year, \$;

r_{off}, r_{mid}, and r_{on} are the off-peak, mid-peak, and on-peak rates respectively, \$/kWh;

t_{off}, t_{mid}, and t_{on} are the duration of off-peak, mid-peak, and on-peak time in a year respectively, hours;

$E_{u,t}$ is the actual grid use, kW;

$E_{s,t}$ is the direct grid sell from the PV system, kW;

$E_{d,t}$ is the grid sell from the battery storage, kW;

d is the discount rate, 5%;

n is the year index;

$E_{u,t}$, $E_{s,t}$, and $E_{d,t}$ were obtained from the SDM model.

2.4 Life cycle assessment

Environmental impacts considering life cycle stages of manufacturing, transportation, and operation were assessed using Equation 3. The global average manufacturing impacts of the solar PV-battery system components obtained from the EcoInvent 3.0 were utilized in this study. The operation phase considers the environmental impacts related to the grid use and the replacement of batteries over the life cycle. The savings from solar energy consumption and grid sell were also considered in the operation phase. The disposal phase of the PV-battery system is not considered following (Bernardes et al., 2004; Grinenko, 2018). SimaPro 8.3 was used for charactering the environmental impacts. Specifically, the ReCiPe Midpoint (H) 1.12, Europe Recipe H was used for estimating the climate change, fossil fuel depletion, and water depletion impacts associated with each PV-battery system components. The SimaPro entries, unit costs, and environmental impacts of the PV-battery system components are provided in Table S1 of the supporting information.

$$I = I_m + I_t + \left[I_r + f_{off} \int_{t_{off}} (E_{u,t} - E_{s,t} - E_{d,t})\, dt + f_{mid} \int_{t_{mid}} (E_{u,t} - E_{s,t} - E_{d,t})\, dt + f_{on} \int_{t_{on}} (E_{u,t} - E_{s,t} - E_{d,t})\, dt \right] L \quad \cdots\cdots \text{Equation 3}$$

Where,

I represents the life cycle environmental impacts of a PV-battery system, kg CO_2 eq., kg oil eq., or L;

I_m is the environmental impacts associated with system manufacturing, kg CO_2 eq., kg oil eq., or L;

I_t is the environmental impacts associated with system transportation, kg CO_2 eq., kg oil eq., or L;

I_r is the annual environmental impacts of the replacement of batteries, kg CO_2 eq., kg oil eq., or L;

f_{off}, f_{mid}, and f_{on} are the unit environmental impacts during off-, mid-, and on-peak periods respectively, kg CO_2 eq./kWh, kg oil eq./kWh, or L/kWh;

t_{off}, t_{mid}, and t_{on} are the duration of off-peak, mid-peak, and on-peak time in a year respectively, hours;

$E_{u,t}$ is the actual grid use, kW;

$E_{s,t}$ is the direct grid sell from the PV system, kW;

$E_{d,t}$ is the grid sell from the battery storage, kW;

L is the life span of the PV system, 20 years.

f_{off}, f_{mid}, and f_{on} were calculated based upon the 2017 New England grid fuel mix profile (Figure 3a) obtained from the Independent System Operator-New England (ISO-NE) database (ISO-NE, 2018). Particularly, f_{off} was calculated based on the utility fuel mix profile of the off-peak period during 2017. f_{mid} was calculated based on the additional load in GW provided by different fuel types during the mid-peak period as compared to the off-peak period (Figure 3b). f_{on} was calculated based on the additional load in GW provided by different fuel types during the on-peak period as compared to the mid-peak period. As such, our calculations reflect the "actual" fuel mix that is replaced as a result of the installation of solar PV-battery systems. Figure 3c presents the unit environmental impacts associated with carbon emissions, water consumption, and fossil fuel depletion during the off-, mid-, and on-peak periods. Unit environmental impacts associated with each fuel type are provided in Table S2 of the supporting information.

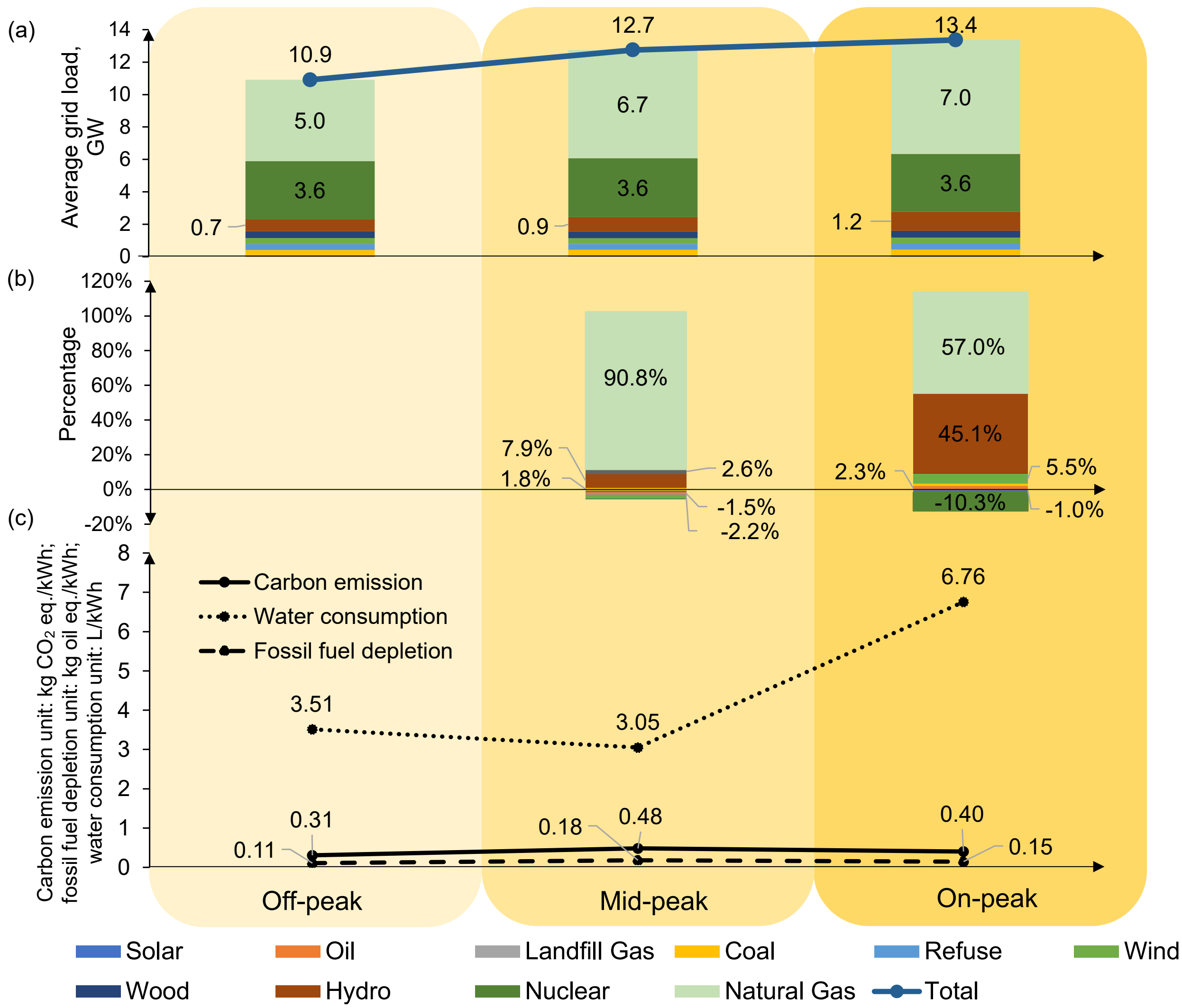

Figure 3. (a) Average annual grid load during the off-, mid-, and on-peak periods obtained from the Independent System Operator-New England (ISO-NE); (b) percentages of grid fuel mix that were used for calculating carbon emission, water consumption, and fossil fuel depletion factors during the mid- and on-peak periods; and, (c) estimated unit carbon emission, water consumption, and fossil fuel depletion per kWh of electricity consumption during the off-, mid-, and on-peak periods

2.5 Sensitivity analysis

A sensitivity analysis was performed to investigate the influence of TOU rate structure, discount rate, on-peak grid fuel mix, and duration of on-peak period on the economic and environmental performances of a typical PV-battery system with 50 panels and 50 batteries installed on the prototype house. Particularly, the model's sensitivity to changes in the on-peak grid fuel mix was investigated by changing the hydropower and natural gas contributions in the grid during the on-peak hours, given their significance. We investigated scenarios where the increase in the percentage of on-peak hydropower grid contribution was associated with a corresponding decrease in the natural gas contribution, and vice versa. Hence, the total on-peak grid demand remained the same under these scenarios. We also assumed the change of on-peak period duration is associated with equal changes in both off- and mid-peak durations (Table S3 of the supporting information). For instance, a 2.5-hour increase in the on-peak period is associated with a 1.25-hour decrease in the mid-peak period immediately preceding the on-peak period, plus a 1.25-hour decrease in the off-peak period that immediately follows. Each of the selected input variables were varied by ± 50%. A sensitivity index (D) was calculated for each input change using Equation 4 (Ren et al., 2020; Song et al., 2019).

$$D = \frac{\frac{d_i - d_b}{d_b}}{\frac{I_i - I_b}{I_b}} \quad \cdots \cdots \text{ Equation 4}$$

Where d_i is the output value after the input was changed; d_b is the base output value; I_i is the altered input value; and I_b is the original input value. Inputs were considered "highly sensitive" if $|D|$ >1.00.

3. Results and Discussion

3.1 Solar and grid energy utilization and peak load reduction

Figure 4 presents the daily solar energy generation and utilization, battery charge, and grid sell/use patterns of the prototype building with 50 panels and 50 batteries during a typical winter (left) and a typical summer (right) day. The building's peak electricity usage periods (6-8 AM and PM) only slightly overlaps with the on-peak period (2-7 PM) designated by the TOU rate structure, indicating a potential need of energy storage systems. Overall, the studied building uses 1.75 times more energy on the winter day as compared to the summer day, which can be attributed to the higher heating demand in winter.

Installing a 50-panel PV system in the prototype building (Scenario S2) can provide load reductions both during mid-peak and on-peak hours (Figures 4a and 4b). The on-peak load reduction is much higher on a typical summer day mainly due to the seasonal changes in solar energy generation. Adding an "uncontrolled" 51-kW battery system (Scenario S3), however, may decrease the peak load reduction benefits (Figures 4c and 4d). The total load reductions during the mid- and on-peak periods are around 91.8% and 49.9% of those associated with Scenario S2 in winter and summer, respectively. This is because the large amount of solar energy generated during the mid- or on-peak hours, especially in summer, may be stored and used during the off-peak hours as compared to Scenario S2. While Scenario S3 has limited peak load reduction benefits in a grid-connected setting, it might appeal in a standalone system that is not grid-connected. When the on-peak load reduction is considered alone, Scenario S3 can potentially provide increased load reduction during winter but decreased load reduction during summer, indicating the importance of seasonal variations of solar energy generation patterns. When the battery system is controlled for peak load reduction (Scenario S4A), the total mid- and on-peak load reductions are 87.9% and 94.4% of those associated with Scenario S2 in winter and summer, respectively; and the on-peak load reductions are 2.7 and 1.6 times of those associated with Scenario S2 in winter and summer, respectively (Figures 4e and 4f). This shows battery control can effectively increase on-peak load reduction, but its charging and discharging losses might slightly reduce the total mid-and on-peak load reduction benefit. When the grid is allowed to charge batteries (Scenario S4B), peak load reduction benefit is the highest (Figures 4g and 4h). The total mid- and on-peak load reductions are 2.6 and 2.0 times of those associated with Scenario S2 in winter and summer respectively, while the on-peak load reductions are 10.0 and 3.0 times of those associated with Scenario S2 in winter and summer respectively.

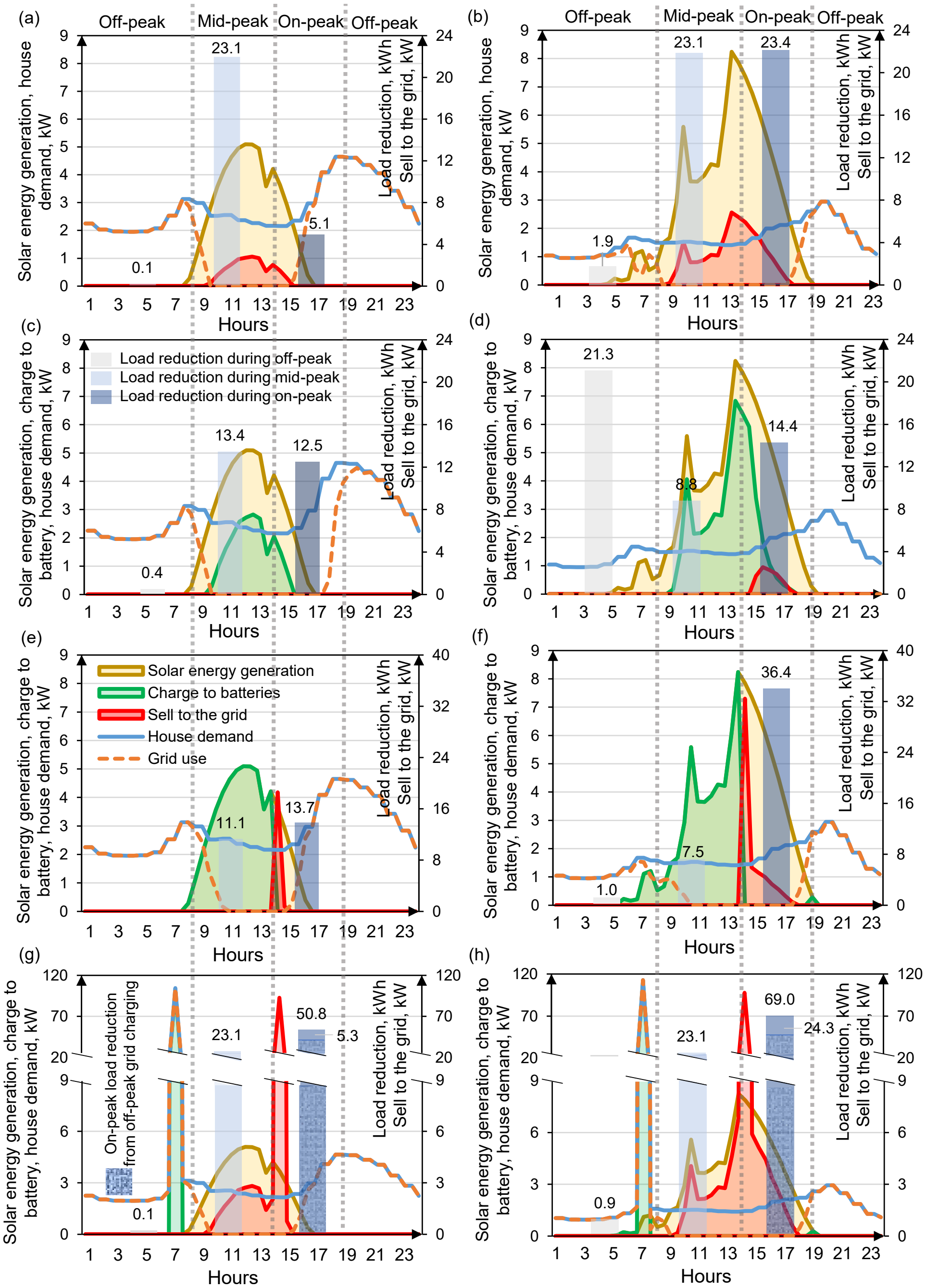

Figure 4. Solar energy and grid electricity utilization of the typical solar PV-battery system in Scenarios S2 (a and b), S3 (c and d), S4A (e and f), and S4B (g and h) on a typical winter day and a typical summer day. Figures on the left-hand side (a, c, e, g) correspond to a typical winter day and figures on the right-hand side (b, d, f, h) correspond to a typical summer day.

Figure 5 further presents annual load reductions under the simulated scenarios. Scenario S4B provides the highest peak load reduction benefit considering either on-peak hours alone or on-peak and mid-peak hours combined, 5.2 and 3.3 times of the lowest counterparts. However, around 80.7% of the on-peak load reduction is provided by the grid energy from off-peak hours rather than solar energy generated. Scenario S2 has the lowest on-peak load reduction, while Scenario S3 has the lowest load reduction when mid- and on-peak hours are combined.

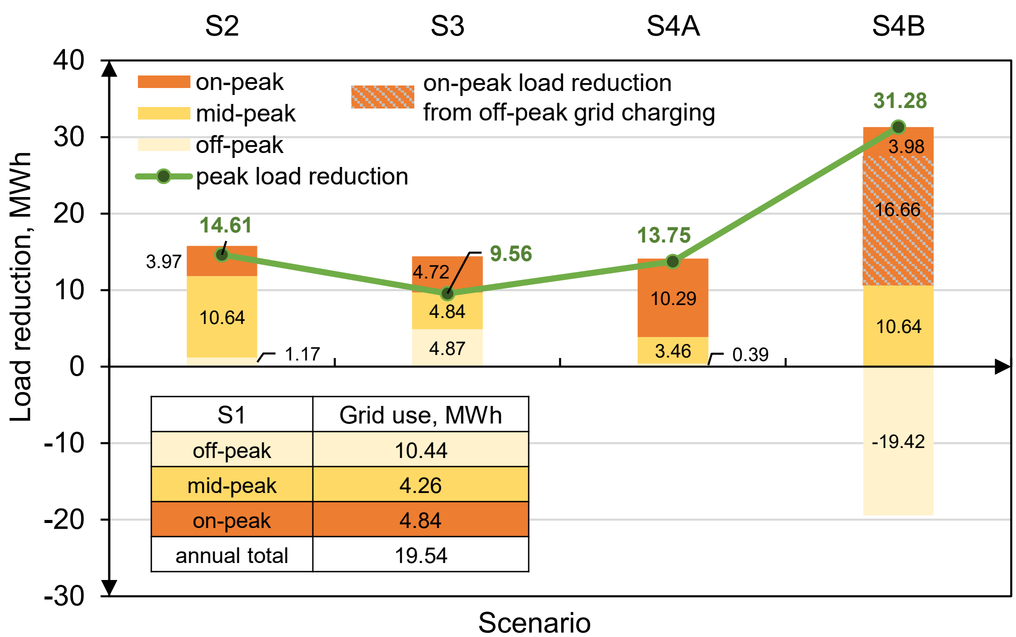

Figure 5. Annual total load reductions in the simulated scenarios. The green line plot shows the sum of load reductions from mid- and on-peak hours.

3.2 Life cycle cost assessment

Figure 6 presents the LCCs of the simulated scenarios considering different battery sizes. Under the TOU rate design, Scenario S4B consistently presents the lowest LCC regardless of battery size, by taking advantage of the price difference between off- and on-peak hours. It is also the only scenario that is able to achieve net cost saving when the battery size is sufficiently large. However, this might be subject to policies including caps on residential charge from and resell to the grid. The ranking of the other scenarios change based on battery size. When the battery size is relatively small (5-20 batteries), Scenarios S2 and S4A present similarly low LCC, followed by Scenario S3, while Scenario S1 presents significantly higher LCC compared with the remaining scenarios. When the battery size is relatively large (80-160 batteries), Scenario S2 has the second lowest LCC, followed by Scenarios S4A and S1, while Scenario S3 has the highest LCC. This indicates the importance of matching battery sizing and control strategies to achieve the lowest LCC. Compared with the current flat rate structure, the TOU rate design results in an economic benefit for the prototype house. Under the flat rate design, Scenario S2 always presents the lowest LCC regardless of battery size, indicating a potential lack of economic incentive to install battery storage systems.

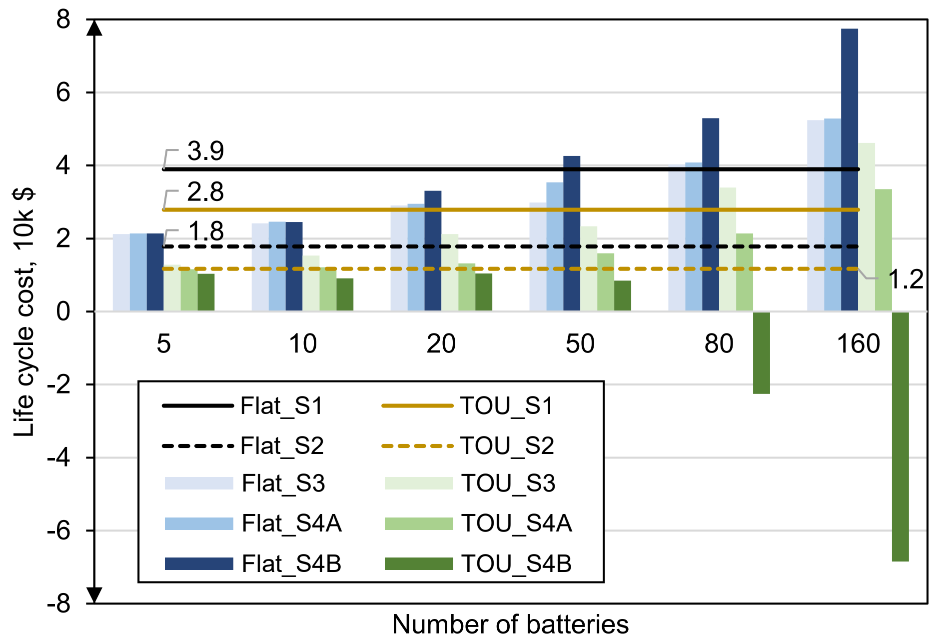

Figure 6. LCCs (discount rate: 5%) of the solar PV-battery systems under TOU and flat rate designs considering different management (Scenarios S1-S4B) and battery sizing scenarios

3.3 Life cycle environmental assessment

Figure 7 presents the life cycle climate change, water depletion, and fossil fuel depletion effects under varied battery sizing and control strategies for the prototype house. The life cycle climate change, water depletion, and fossil fuel depletion effects of the typical 50-panel PV system (no battery) in this study are 61.9 g CO_2 eq., 2.54 L, and 0.0165 kg Oil eq. (0.69 MJ based on 1 kg Oil eq. = 41.9 MJ (UJ, 2016)) per kWh of solar energy generated, respectively, all of which are within the previously reported range of 50-800 g CO_2 eq./kWh, 0.73-7.2 L/kWh, 0.22-1.04 MJ/kWh for roof-mounted solar PV electricity generation, respectively (Fthenakis and Kim, 2010; Kim et al., 2014; Stamford and Azapagic, 2018; Stolz, 2017; Stoppato, 2008). Scenario S4B generally performs the best environmentally regardless of battery sizes, while Scenario S1 performs the worst. Scenario S4A presents the second highest life cycle climate change and fossil fuel depletion effects following Scenario S1, although it provides a relatively large on-peak load reduction. This is because Scenario S4A shifted load reductions from mid-peak to on-peak period, while the on-peak period has lower carbon and fossil fuel intensities compared to mid-peak hours, due to a higher contribution from hydropower. This indicates the importance of the daily grid mix patterns in determining the environmental performance of battery control strategies that maximize on-peak load reductions. Scenario S4A also presents an optimal battery sizing at 50, which aligns with the default battery size calculated based on maximum daily electricity use. This indicates the engineering rule-of-thumb used in this study is effective in achieving the minimized household climate change, water depletion, and fossil fuel depletion effects. On the other hand, the installation of solar PV-battery systems (Scenarios 3 and S4A) does not present a significant benefit in terms of water depletion as compared to the climate change and fossil fuel depletion impacts, expect for Scenario S4B at relatively larger battery sizes. This is because of the high initial water demand associated with PV and battery productions.

Overall, our results show that while installing a solar PV system clearly provides environmental benefits, adding a battery storage does not necessary provide additional carbon, water, or energy benefits. The solar PV-battery system also does not provide essential water benefits except when a large battery capacity is installed and the battery system is allowed to charge from and resell to the grid in Scenario S4B. When peak load reduction, economic, and environmental impacts are considered together, Scenario S2 presents relatively good economic and environmental performances, although its on-peak load reduction is limited.

Scenario S4B presents excellent peak load reduction, economic, and water benefits, but its carbon and energy benefits are relatively limited as compared to Scenario S2. However, this result may differ for regions with a more fossil fuel dependent grid. Scenario S4A has relatively good on-peak load reduction and economic performances, but it does not provide effective carbon emission and fossil fuel use reductions as compared to Scenario S2. Installing a solar PV system without an effective control strategy, such as in Scenario S3 might lead to sub-optimized peak load reduction, economic, and environmental outcomes.

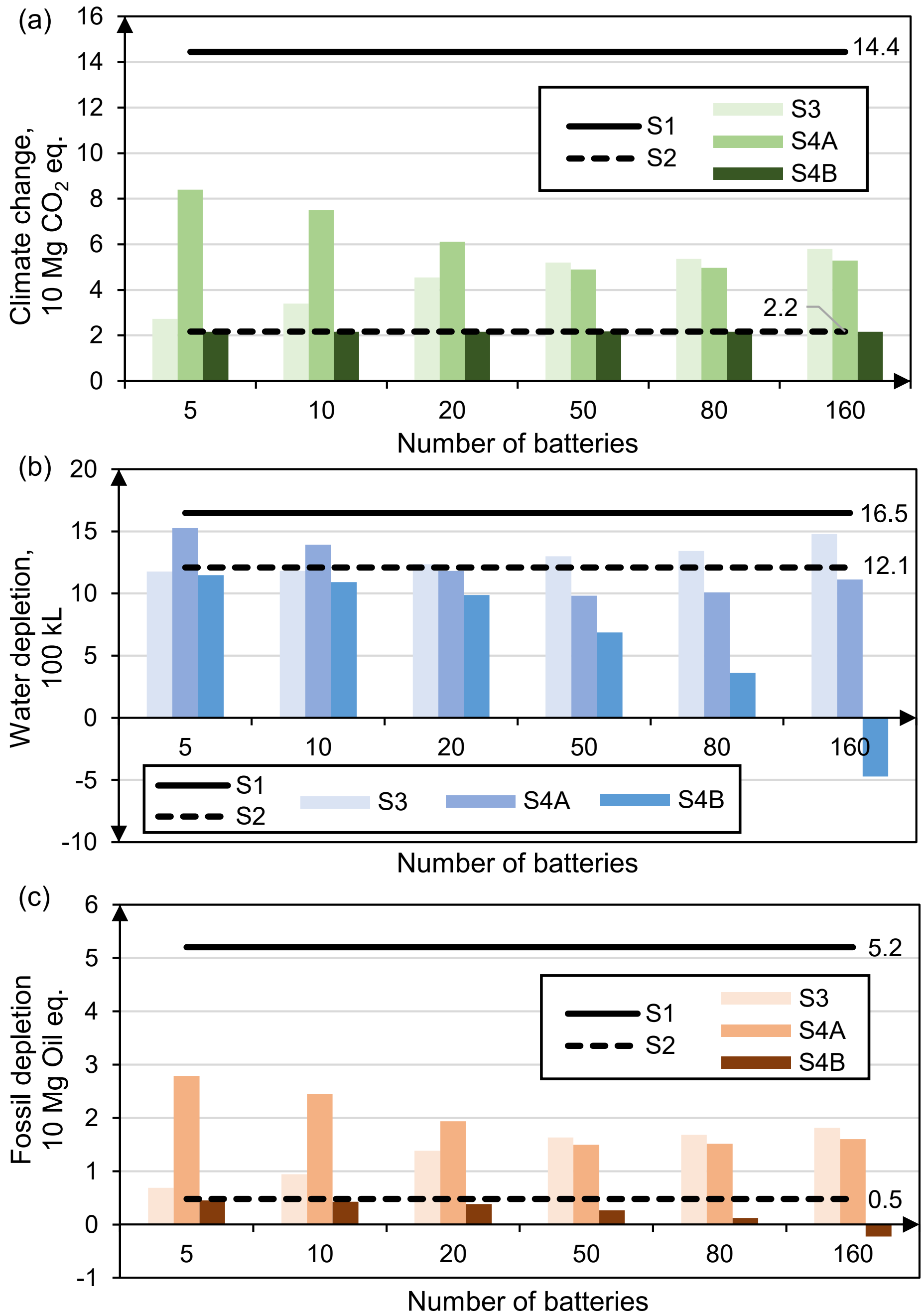

Figure 7. Life cycle (a) climate change, (b) water depletion, (c) fossil fuel depletion of the solar PV-battery systems under different management (Scenarios S1-S4B) and battery sizing scenarios

3.4 Sensitivity analysis

Figure 8 presents the percent changes of LCC of a typical 50-panel 50-battery solar PV-battery system in response to changes of the discount rate, TOU rates during off, mid, and on-peak periods, and the duration of the on-peak period. The LCC outcomes of Scenario S4B are highly sensitive to changes in on- and off-peak electricity rates as well as the discount rate. This can be explained by the scenario's high dependence on the difference between the electricity rates between on- and off-peak hours. Scenario S4B is also highly sensitive to changes in the discount rate. In contrast, Scenario S4A is only sensitive to the on-peak rate. This is because the economic saving in this scenario largely relies on the on-peak grid sell. All the remaining scenarios are not sensitive to ±50% change of the five input variables. Particularly, Scenario S3 presents the lowest sensitivity. This is because of the limited solar energy use during the mid- and on-peak hours under this scenario.

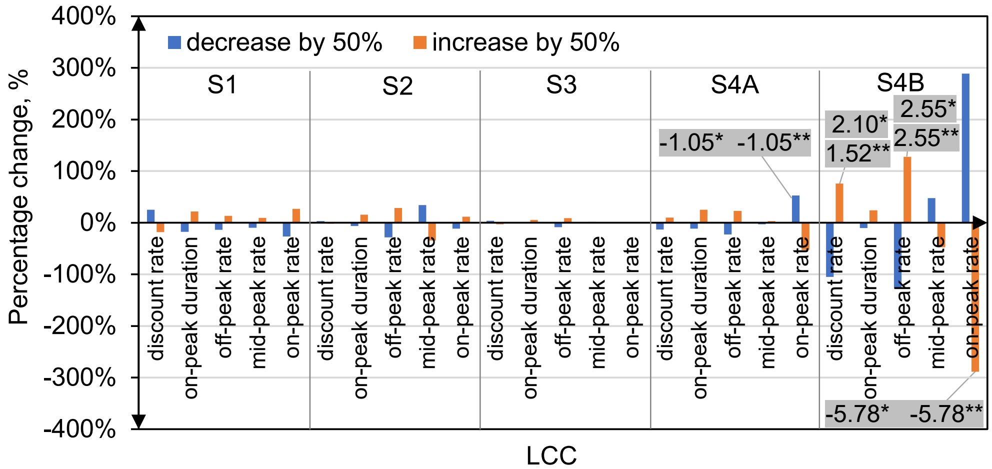

Figure 8. The percent change of LCC of the 50-panel 50-battery solar PV-battery system in response to decrease or increase of the selected variables by 50%. Shaded numbers indicate where the absolute values of the sensitivity index *D* are equal to or larger than 1. One asterisk and two asterisks represent the sensitivity index values that are associated with 50% decrease and increase of the tested variables, respectively.

Figure 9 presents the percent changes of life cycle climate change, water depletion, and fossil fuel depletion of the typical 50-panel 50-battery solar PV-battery system in response to changes in the on-peak grid fuel mix and the on-peak duration. Our results show all three environmental outcomes of Scenario S4B are highly sensitive to changes in the on-peak grid mix, as the battery system maximizes on-peak uses/sale of solar energy and shifts on-peak demand to the off-peak period. This highlights the importance of on-peak grid mix in influencing the environmental outcomes of battery management strategies that target solar energy sales during the on-peak hours. On the other hand, the on-peak duration can significantly influence the life cycle fossil fuel depletion of Scenarios S4B, as a result of changes in the amount of solar energy that will be available for sale or direct use during the on-peak hours. Scenario S3 was found to be the least sensitive to either tested variables, mainly due to a combined effect of its high baseline environmental impacts as well as the limited solar energy use or sale during the on-peak hours.

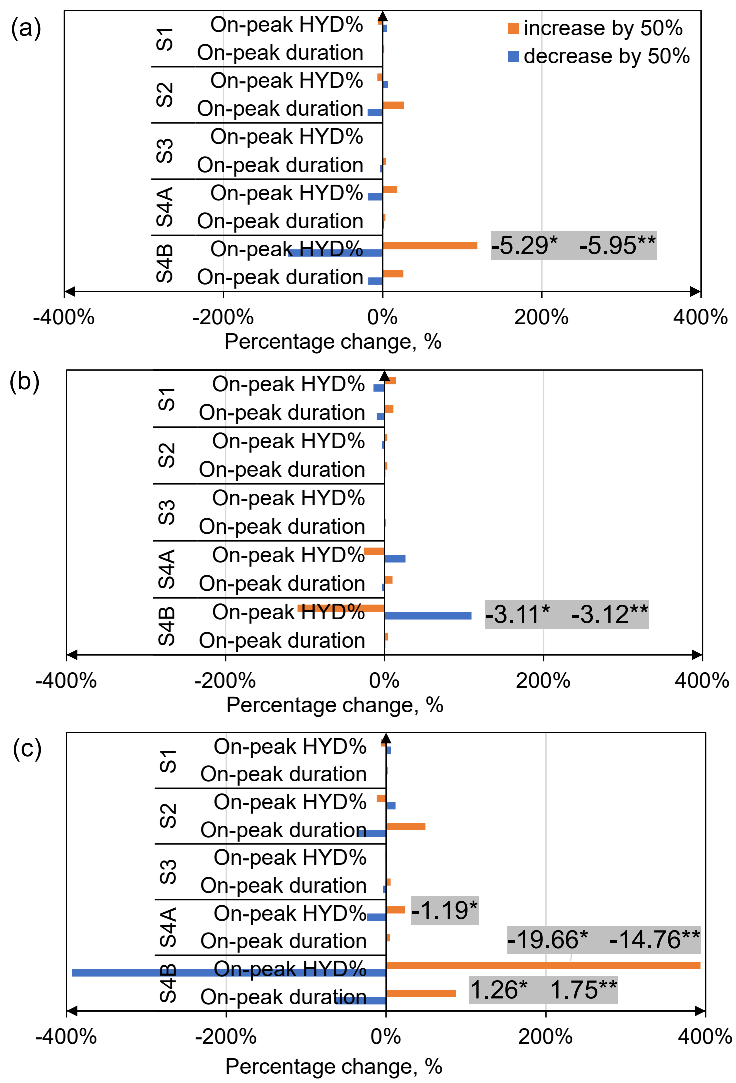

Figure 9. Life cycle (a) climate change, (b) water depletion, and (c) fossil fuel depletion of the PV-battery systems in response to decrease or increase of the selected variables by 50%. Shaded numbers indicate where the absolute values of the sensitivity index *D* are equal to or larger than 1. One asterisk and two asterisks represent the sensitivity index values that are associated with 50% decrease and increase of the tested variables, respectively.

4. Conclusion

SDM, LCCA, and LCA were integrated to investigate the design and operation of solar PV-battery systems that can achieve grid, environmental, and economic co-benefits under TOU rate design, using a 5-unit prototype house in the Boston-Logan, MA area as a case study. Five scenarios (S1-S4B) were investigated, each with different solar PV-battery system design and/or management strategy. We found scenarios that maximize the selling/use of solar energy during the on-peak hours through battery installation and control (Scenarios S4A and S4B) can achieve the highest on-peak load reductions and economic benefits under the TOU rate design. However, they do not necessary provide the highest environmental benefits, as on-peak hours in the New England grid have lower carbon emission and fossil fuel depletion factors as compared with the mid-peak hours. This indicates a potential tradeoff between the need of on-peak load reduction, economic saving, and environmental protection. From an environmental perspective, our finding demonstrates the necessity of better battery control or TOU designs that can effectively incentivize solar energy uses when the grid carbon intensity is the highest. While S4A is shown to be effective in reducing on-peak load in the grid, its overall load reduction from both mid- and on-peak hours is slightly less than Scenario S2 where PV panels are installed without battery. This is partly due to the energy loss resulted from battery charging and discharging. Overall, Scenario S4B presents relatively good performances from peak load reduction, economic, and environmental perspectives. However, its benefits might be limited by policies that cap grid charge and discharge from the battery systems. Out of the remaining scenarios, installing a PV system alone (Scenario S2) presents relatively strong economic and environmental performances, but its on-peak load reduction is limited. Installing a battery system without an effective control strategy (Scenario S3) results in relatively weak peak-load reduction, economic, and environmental outcomes. This highlights the importance of effective battery control in the implementation of solar PV-battery systems. Future studies may further include emerging technologies such as the vehicle-to-home systems as well as the interactions between distributed solar PV-battery systems and the centralized grid to allow for a more holistic and dynamic optimization of the solar PV-battery system design and operation.

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