Optimal Collaborative Energy Model among Vehicle-to-Home (V2H) and Solar Systems

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Abstract
Replacing traditional car engines with electric vehicles (EVs) has been suggested as an effective strategy to address climate change. The EV boom will also increase electricity demand especially if EV charging times coincide with peak-electricity demand. Most EV drivers are charging their vehicles at home, and some are doing it using solar-generated power. At the same time, the number of smart homes that can potentially coordinate the generation, consumption, and storage of energy across the available resources is steadily increasing. Because EVs spend more than 90 percent of their use time off the road and parked, their batteries could be used to store and distribute solar-generated electricity. With the aid of vehicle-to-home (V2H) systems, we can communicate with the smart home to store and discharge electricity generated from renewable energy sources. The use of EVs as electricity storage needs to be properly managed to not only avoid the negative impacts of EV charging on the power distribution network but also to help strengthen the grid and reduce operating costs. Among available renewable energy systems, rooftop solar represents a significant source of power generation in smart homes. This study investigates energy models to optimize energy flow among smart homes equipped with rooftop solar and EVs.

Keywords
Vehicle-to-Home, Solar Systems, Electric Vehicle, Smart Buildings

1 Introduction

Saving energy is neither simple nor easy. It requires innovation, planning and last but not least, changing deep-rooted behavior. Most world energy supplies come from high-carbon sources such as fossil fuels that cause climate change. Only 11.4% of global primary energy came from renewable energy sources such as hydropower, wind, solar, bioenergy, geothermal, and wave and tidal in 2014 (Schlömer *et al*. 2014). Renewable energy sources share in the world energy production raised to about 26% in 2018 (IEA 2020a) and continues to increase.

One effective and feasible strategy to counter global climate change is replacing traditional cars with electric vehicles (EVs). The boom in EVs has its challenges as it increases electricity demand and makes the case less environmental-friendly when the EV charging times coincide with peak-electricity demand and or when the electricity is provided by fossil-fueled power plants. It is important to note that many drivers are charging their EVs at night or using solar-generated power to reduce demand from the grid at peak hours. In addition, the number of smart homes that can potentially coordinate the generation, consumption, and storage of energy across the available resources is steadily increasing. As all vehicles are parked 95% of the time, the batteries in electric vehicles could be used to dispatch electricity to the grid (Yura 2020).

Returning electricity to the grid is called vehicle-to-grid (V2G) which was introduced by Kempton and Letendre (1997). The EV batteries could be used to store and distribute solar-generated electricity. With the aid of vehicle-to-home (V2H) systems, EVs can communicate with the smart homes to store and discharge electricity generated from renewable energy sources. Penetrating renewable energy sources into power systems will require energy storage systems to smoothly support electric grids so that the electrical power demand and provided power are met at all times (Mwasilu *et al.* 2014). Therefore, EVs are suitable to be used as dynamic energy storage systems in both V2G and V2H systems. As a result, the network of EVs can perform as the virtual power plant (VPP) concept model (Vasirani *et al.* 2013).

The connection of EVs to the power grid can increase the short-circuit currents, bring the voltage level out of standard limits, increase the power demand, and impact the lifespan of the pieces of equipment (Dulău and Bică 2020). The use of EVs as electricity storage needs to be properly managed to not only avoid the negative impacts of EVs charging load on the power distribution network but also to help strengthen the grid and reduce operating costs. At the time of this study, Nissan (Leaf & e-NV200), Mitsubishi (Outlander) and Renault (Zoe) are the only EVS that support bidirectional Charging technology.

The scope of this study does not include the economic viability of V2H and the battery degradation. Economists and researchers have debated these issues for years, and consensus does not appear likely mainly because there are multiple factors impact the degradation of the battery (e.g. state of charge (SoC) of the battery and depth of discharge (DoD), how often and how much you discharge (discharging current), at what temperature, etc). This study seeks to explore the optimal collaborative energy model among V2H and solar systems. The next section discusses the background to the study, thereby highlighting its importance. This is followed by a discussion of an optimal energy model and a case study. A presentation of the key findings from the study and their wider implications, and trajectories conclude the paper.

2 Vehicle to Home (V2H)

V2H is a concept that enables EV batteries to associate with homes. Any vehicle that can be connected to an electric plug can be used for V2H technology (Morris & Cleveland 2006). The purpose of the V2H is to optimize transportation and usage of EVs as electrical energy distribution and using them as VPPs. V2H helps keep renewable energy in the energy system and it causes moderation in climate change (Musio *et al.* 2010). In this concept, electric car batteries would store electrical energy from the power distribution system and dispatch it back based on the electricity demand. All these batteries would join a network and be used for 'peak shaving' (sending power back to the grid at high demand) and 'valley filling' (charging when demand is at its lowest point which is at night) to balance the distributed load (Wagner 2014). In many power generation systems, gas or combined power plants are used as peaking units. These systems are fast to run but not climate-friendly (Nag 2014). However, renewable energy sources are not as fast to run depends on the time of the day and environmental situations. This is why excessive renewable energy goes to waste due to being more than power demand at night if it is not stored or used (Nag 2014). This is where V2H functions to save more renewable energy. The batteries are being charged by electricity produced by renewable sources at night when the demand is at its lowest point. Then, a few hours later, when load demand tends to reach its peak load, the power stored in batteries can be released to take some percentage of the load from the grid and stabilize renewable energy in the system. This will cause the load curve to level and also is much cheaper than building new utilities (Lund & Kempton 2008). "Carbitrage" is a combination of the words "Car" and "Arbitrage". Arbitrage is benefiting from simultaneously purchasing and selling the same asset in different markets with different prices to profit from this difference. The carbitrage presents the economic benefit of the V2H concept (Kim et al. 2012).

It is anticipated that there will be 116 million EVs by 2030 which indicates many new demands on electric utilities (Statista 2021a). An average residential house consumes less than 24 kWh in a day (EIA 2020). Average electric car batteries have capacities of 45 kWh (Statista 2021b). Therefore, they can supply more than enough electricity for an average residential building. This is another reason for coining the portmanteau carbitrage; the battery can be charged at night at the base load curve and support the home at the peak to form an electricity cost reduction by reducing the energy demand at peaking periods (Naghibi 2018).

Household building and transportation energy consumption play an important role in global energy consumption with 24% of energy usage which is 6.4 PWh of energy (IEA 2020b). Therefore, considering enhancing energy efficiency in the building and transportation sectors is a great potential for saving energy and provide a healthier living environment for people around the globe.

3 Optimal Energy Model

We limit the scope of the study by focusing on small-scale cases where a household member or members live in a house suitable for solar power. We use a case study with real energy data in the next section to further demonstrate the application of the proposed model. The objective is to determine the optimal use of solar energy (production, storage, and distribution) to achieve maximum profit per unit of inputs used (e.g. \$/kWh). Figure 1 shows the architecture of the model beginning at t_i, i=1 with the time interval of t_{i+1}- t_i.

The U.S. Department of Energy compared energy costs per mile for electrical and gasoline-fuelled vehicles and concluded that the energy cost of EVs with electricity cost of about 30 cents per kWh is equal to that of gasoline vehicles with gasoline cost per gallon of \$3.50 (DOE 2019). Since the average cost of solar energy per kWh is between 6-12 cents, charging EVs using a solar system is undoubtedly the optimum solution. As shown in Figure 1, the energy model recommends charging the EV when this option is available.

When solar is used as the primary energy source, the expected supply, S_{solar}, can be calculated as follows:

$$S_{solar} = E_{cell} \times G \times A_{cell} \times (1 + (TkP \times (AT - 25)) \quad (1)$$

where S_{solar} is measured in watts, E_{cell} is the solar cell efficiency (%) under standard test conditions (temperature of 25°C, irradiance of 1000 W/m^2, air mass 1.5 spectrum), G is the irradiance of input light (measured in W/m^2), A_{cell} is the surface area of the solar panels (measured in m^2), TkP is the temperature coefficient of the solar panel (%/°C), and AT is the ambient temperature (°C).

The charging time, t_C depends on the state of charge (SoC) of battery (%), vehicle acceptance rate (VAR), and the charging station delivery rate (DR) (both in kW). For example, if the VAR of an EV is 4 kW and the station's maximum output capacity is 5 kW, then it takes 5 hours to fully charge an empty 20 kWh battery. The following equation is used to calculate the charging time:

$$t_C = (1 - SoC) \times C / \min(VAR, DR) \quad (2)$$

where C is the battery capacity (kWh) and t_C is the charging time (hr).

If charging the EV is not possible (whether the EV is not at the charging station or it is fully charged), the solar power should be used to power the house. When the solar system is producing more than the house need ($S_{solar} > D_{home}$), any excess electricity (i.e. S_{solar} - D_{home}) is fed into the electric utility's grid. S_{home} is the electricity consumption for the house.

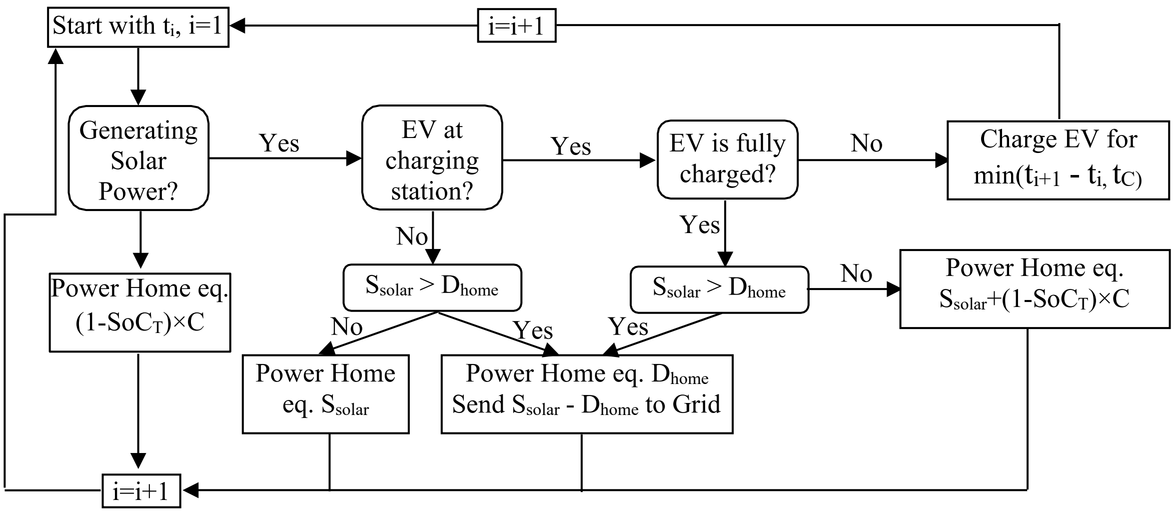


Figure 1. V2H with solar system energy model architecture

In this study, the energy model is developed based on a standard electricity plan, in which the same rate is paid for electricity regardless of the time of day. The EV can supply homes with power generated from its battery when the solar system does not produce sufficient electricity to power the house. It is important to determine the threshold SoC (or SoC_T) below which the EV stops discharging the stored electricity. A fully charged EV with 100 kWh battery capacity and SoC_T of 20% can discharge up to 80 kWh. The threshold SoC can be calculated using the following equation:

$$\text{SoC}_T = 1 - \frac{P(S_{solar} \rightarrow EV)}{P(\sum_{j=1}^{N} D_{trans.})} \quad (3)$$

Where $P(S_{solar} \rightarrow EV)$ is the probability that the EV is charged with solar power and is calculated using equation 4, and $D_{Trans.}$ is the probability of EV electricity consumption during a given period of time (from j =1 to N). For instance, we can calculate the EV electricity consumption per day for a 7-day (one week) period. In this case, j represents a daily time interval and N=7. Since the SoC_T is about the likelihood of certain events occurring in the future, we are using probabilities to quantify the energy supply and demand to deal with uncertainty.

$$P(S_{solar} \rightarrow EV) = \sum_{i=} \begin{cases} 0 & if\ EV\ is\ not\ at\ the\ charging\ station \\ S_{solar} \times i & if\ EV\ is\ at\ the\ charging\ station \end{cases} \quad (4)$$

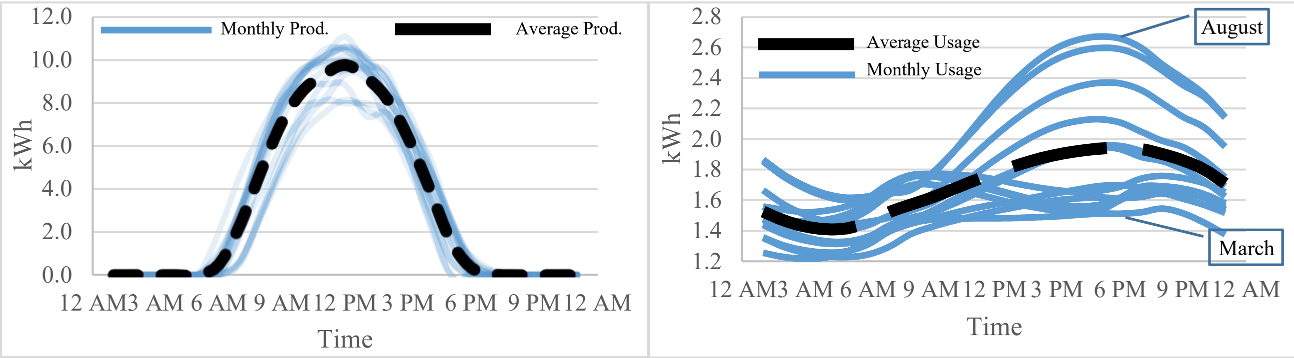
In order to calculate the SoC_T, we also need to decide about the associated confidence level. With a 95 percent confidence level, we would expect the SoC_T to be a given percentage 95% of the time.

4 Case Study

The described energy model is employed for finding the optimal solution for managing the energy supply and demand of a single-family house in Houston, Texas. Since the average size of homes in the US is around 226 m^2 (2430 SF), a 223 m^2 house (2400 SF) is selected for the case study. Figure 2 shows a conceptual model of the house with the available rooftop area of 200 m^2 (around 2150 SF) for installing solar panels (around 70% of the roof area).

Figure 2. Architectural model of the case study project (an average size house in the US)

We use equation 1 to estimate solar power production for the case study. The hourly temperature and irradiance of the house location along with an efficiency of 15% and temperature coefficient of -0.44%/ ^{o}C for a typical solar panel is used for the calculation. Figure 3-a shows the S_{solar} for the case study. It is expected that the solar system will generate 875 kWh per month (daily average ≈ 72 kWh). For estimating the D_{home}, we use the average hourly electricity use for a Texan household in 2020. The data is adopted from the US Energy Information Administration (EIA) and shown in Figure 3-b (daily average ≈ 40 kWh).



(a) (b)

Figure 3. (a) Hourly electricity production (S_{solar}) for the case study (b) Hourly electricity consumption (D_{home}) in a Texan home

The average commute distance and time of travel for a Texan is used to calculate the transportation energy consumption ($D_{trans.}$). The average weekday commute distance and time for someone living in the project area is 45.5 miles and 32.7 minutes (or 91 miles and 65.4 minutes per day if we assume a round trip), respectively. The weekend commutes are 25.8% of the weekdays. The information is based on data collected in the American Community Survey (ACS) conducted annually by the U.S. Census Bureau. We used the traffic data for interstate highways to estimate the travel time. Figure 4 shows the travel time distribution per weekdays and weekends.

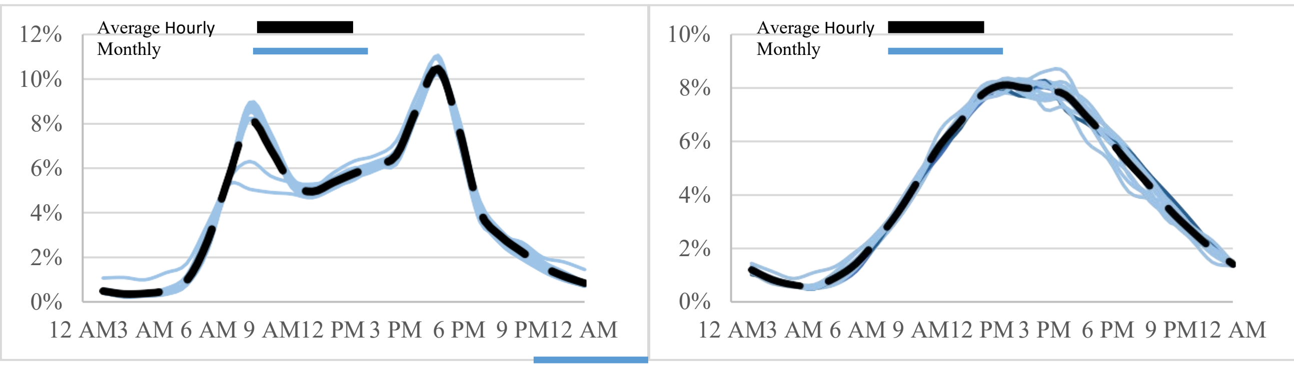


Figure 4. Hourly traffic time (a) weekdays (b) weekends

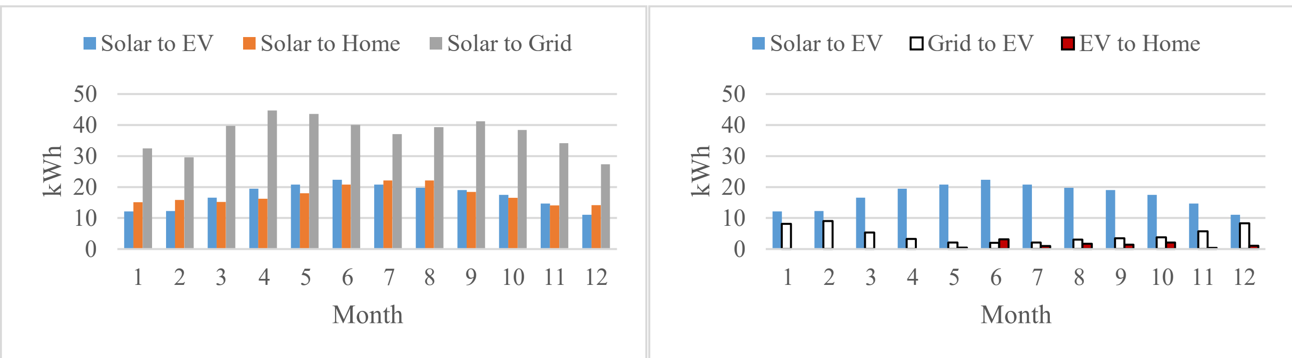
We collected energy consumption data for thirteen EVs available in the market. On average, EVs can travel 100 miles by using an average of 29.85 kWh energy (or around 48 kWh/100 km). The average estimated battery capacity is 43 kWh and 4 kWh/hr charging time rate is used in the study. The proposed model is used to show the optimal scenario for producing, storing, and distributing energy. We begin the analysis at t = January 1st, 12:00 am with a fully charged EV. We also assume that January 1st is Monday, a working day.

Table 1 shows the results of the energy production and distribution for the case study project. Please note that the amount of electricity stored in the EV and returns to the home is calculated based on SoC_T of 60%. This amount varies depending on the solar power generation, energy consumption, and the number of holidays and weekends per month. For example, when the solar power is less than 2,000 kWh per month, there is not much opportunity for the EV to return the power back to the home. December is an exception because of the reduced number of working days in this month. Our analysis shows that only weekends or holidays allow for powering home with the electricity stored in the EV's battery. Also, the SoC_T plays a major role in the amount of EV to Home power. The SoC_T is found to be 100% for a 7-day (one week) period. That means if we want to have enough electricity to commute for a week, there may not be any electricity that returns to the home. The model is analyzed for a 2-day period with an approximate SoC_T of 60% (refer to equations 3 and 4).

Table 1. The Results of the Energy Analysis for the Case Study

Month	No. of Days	No. of Weekdays	S_{solar} (kWh)	Solar to EV (kWh)	Solar to Home (kWh)	Solar to Grid (kWh)	Grid to EV (kWh)	EV to Home (kWh)
1	31	22	1,851	375	468	1,008	252	0
2	28	20	1,614	342	445	828	252	0
3	31	23	2,217	514	472	1,230	164	0
4	30	22	2,409	583	486	1,340	96	0
5	31	22	2,553	643	559	1,351	64	12
6	30	22	2,494	669	622	1,202	60	93
7	31	23	2,478	644	686	1,148	64	29
8	31	23	2,518	614	686	1,218	92	52
9	30	21	2,360	572	553	1,235	104	40
10	31	20	2,247	542	514	1,191	116	64
11	30	20	1,887	440	422	1,025	172	11
12	31	17	1,630	345	440	845	256	34

To better understand the energy production and distribution per month, the amounts listed in Table 1 are normalized based on the energy per day and shown in Figure 5. Although the proposed energy model gives the highest priority to the Solar to EV option, the availability of the EV at the charging station requires the EV to rely on the grid particularly during weekdays and after 6-7 pm when there is no sunlight. Another contributing factor is the transportation energy consumption ($D_{trans.}$) for the case study. To commute around 91 miles per day, a commercially available EV with an average efficiency of 29.85 kWh per 100 miles needs around 27 kWh per day. Not only this amount account for around 40% of the total solar power, but also the solar system barely produces this amount when the EV is available at the charging station (in the morning or evening).

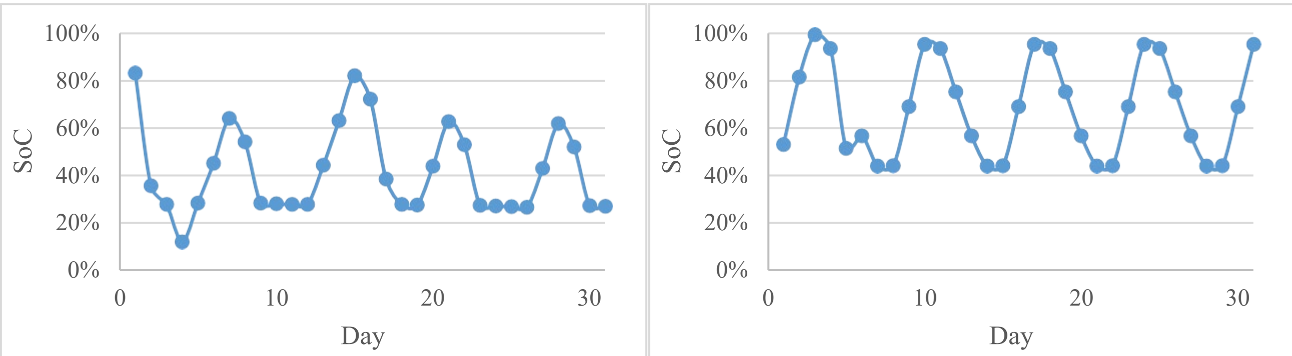


(a) (b)

Figure 5. Energy communications between the Home, Grid, and the (a) solar system (b) EV

Because the EV is not at the charging station during the peak solar energy production, and the home demand D_{home} is lower than the S_{solar} during these times, most of the energy produced by the solar system will be sent to the grid (see Figure 5-a). When the solar system produces less energy during November through February, the EV relies more on the grid to meet its energy need. On average, the EV has to use the grid power 16 days a month from November through February. In contrast, only 10 days in a month the grid power is needed to meet the D_{trans}. during May through August. The EV does not communicate with the home during the first four months of the year (as shown in Figure 5-b). The electricity consumption in the house and the available solar power are two contributing factors. On one side, these months are typically characterized by relatively mild temperatures in the case study location and thus the energy demand for air conditioning is significantly reduced. On the other side, the solar system does not produce sufficient energy to meet the D_{trans}. and the D_{home}.

The energy production during the summer outweighs the rise in cooling demand. Therefore, the EV needs less energy from the grid and can return more energy to the home. Figure 6 shows the SoC of the battery in two different months to see the impact of the weather (temperature and sunlight) on the energy system. Please note that the average SoC per day is shown in Figure 6. The average SoC in January for the weekdays is 33% and for the weekends is 62%. The average SoC in July for the weekdays is 58% and for the weekends is 95%. Although the D_{trans}. remains the same in both January and July, but the 34% more solar energy production during July supplies enough energy for the EV to keep the SoC above 50% even during weekdays.



(a) (b)

Figure 6. SoC for the case study EV during (a) January (b) July

5 Conclusions and Further Research

The large-scale use of EVs has been recognized as a practical solution for reducing greenhouse gas emissions and mitigating the threat of global climate change. However, the rapid growth of EV use and their electricity demand can negatively impact the power distribution network since the majority of EVs are being charged at home. In this study, we explore the optimal collaborative energy model among smart homes equipped with rooftop solar and EVs. We apply the model to a single-family house in Houston, Texas as our case study and determine the optimal use of solar energy (production, storage, and distribution) to maximize profit. Our analysis shows that the amount of electricity stored in the EV depends on factors including solar power generation, energy consumption, and the number of holidays, and weekends per month and that only weekends and holidays allow for powering home with the electricity stored in the EV's battery. Future studies can test the robustness of the proposed energy model by performing a sensitivity analysis on the key parameters. They also can apply the proposed energy model to other case studies and also can consider other factors in their analysis.

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