A user-friendly smart charging algorithm based on energy-awareness for different PEV parking scenarios

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***Abstract* — Many studies show that collaborations between renewable energy sources especially PV arrays and plug-in electric vehicles can have a positive impact on the utilization of both emerging technologies. In fact, the intermittent nature of renewable sources and the high-demand for PEV charging will address by this partnership. This paper proposes a user-friendly algorithm for the control of PEV charging and discharging, aiming to satisfy all involved parties including user, parking owner and grid operator by considering the health of batteries and costs. First, the predicted input data are used to obtain the optimal position of PEVs through an extended linear optimization method in different scenarios. In this regard, three scenarios including uncontrolled, unidirectional and bidirectional are used and their impact on the battery health and charging cost is specified. Then, based on energy-awareness, the user selects one of those scenarios arbitrary by comparing their results. Finally, the real-time controller compensates the errors based on a traditional rule-based method. This procedure is repeated upon on arrival of each PEV, and the results are considered as input for the next step.**

Keywords—Plug-in Electric Vehicles, Energy management system, PV power production, Smart charging, User-friendly.

I. INTRODUCTION

Given the apparent challenges of conventional vehicles and their impact on the environment, the electric vehicle market has grown significantly in recent years in the presence of a rapid drop in battery prices [1]. In this regard, plug-in electric vehicles (PEV) is a power-dense, mobile and uncontrollable load, and the large demand for electricity to charge the PEVs is one of the important issues in this field. As an example, according to [2], the amount of load consumed by a house in the presence of a PEV increased by around 30%, especially in peak hours. Therefore, it is clear that the grid might not be able to support them, despite the beneficial effects of PEVs on the environmental concerns. However, it should be noted that electric vehicles are parked over 90% of their lifetime on average, and are utilized only minimum than 10% of the time for transportation [3]. So, long parking duration of PEVs offers the opportunity for improving the flexibility and charging price because they are available for a secondary function. On the other hand, the power generation of photovoltaic arrays depends on the weather condition like the amount of irradiation, which is also affected by factors such as temperature, orientation, time of day and local shade. Analysis of the production capacity of these resources shows that it is possible to produce power only during sunny days and the highest production is usually at noon which is less needed. Therefore, the need for an energy storage source along with PV panels is strongly felt.

In this special situation, recent researches emphasize the collaboration between batteries of electric vehicle and renewable energy sources like solar panels, which this cooperation is called smart charging [4]–[7]. In other words, smart charging is understanding of the synergies between PV power production, PEV charging and existing electricity consumption that can has several benefits like technical and economic advantages [8]. In this regards, the batteries used in electric vehicles could increase the flexibility of PV panels in different ways. For example, where PV is used as a local energy source, PEV batteries can be used as energy storage sources. Here we try to save the electricity when it has a low price and use it at higher prices for consumption [9], [10].

Generally, an energy management system (EMS) is used by operators in smart charging field to control and optimize the performance of the system. These energy scheduling approaches are classified into three main categories including rule-based method [11]–[14], optimization programming [15]–[18] and model predictive control (MPC) [19]–[21].

The rule-based or heuristic method is the fastest method but main disadvantage is simple rules that may not guarantee optimal solutions. The optimization strategies such as linear programming (LP) and mixed-integer linear programming (MILP) can be considered as the most well-known methods that solve a certain mathematical function to find the best solution in the presence of a set of constraints. However, MPC is widely used recently to control the nonlinear models and deal with uncertainties.

As mentioned earlier, there are some uncertainties in the controlled variables such as PV generation, mobility patterns of the PEVs (plug-in time and the state-of-charge (SOC)) and electrical load demand in the system that make considerable challenges in employing smart control. These variables should be predicted in advance. In this regards, it is shown in the literature that MPC method has better results [9]. However,

the forecasting errors will definitely remain in real-time implementation. Therefore, there will be a request for another simple and fast method in reality.

Also, energy scheduling approaches can be implemented based on different objective functions. It is clear in the literature review that all previous works rely only on the operator's interest such as load balancing, increasing PV utilization, reducing peak loads, increasing revenue for charging provider and so on [22]. However, in many applications such as workplaces, public parking lots or even buildings, the operator and the user are different persons, and user cooperation is more important than anything else. So far, the key role of the user in smart charging has been easily ignored and there is no attempt has been made to raise awareness and satisfaction of the user. Following these strategies can lead to failure in the real implementation of the algorithms. Indeed, the user should be aware of reasonable estimates about the cost of smart charging and state of health (SOH) of the battery.

In this paper, a new user-friendly algorithm for smart charging is proposed such that employs the MPC method in parallel with a fast rule-based method to satisfy all involved parties and compensate for errors caused by uncertainties. Based on this algorithm, the user can find out about the charging price and battery health for different scenarios. Three scenarios are used, including uncontrolled, unidirectional smart charging and bidirectional smart charging. After that, the user, with sufficient knowledge of the advantages and disadvantages, will make an aware decision. Finally, the overall goal of the algorithm is to minimize power consumption cost with the agreement of all actors under a time-varying electricity price in a real-time operating mode. It should be noted that different places have different load profiles, PV generation and PEV profiles. However, this algorithm is generic and can be suitable for all PEV parking scenarios including homes, residential buildings, workplaces, public buildings (hotels, hospitals, schools, supermarkets, and malls), parking fleets and etc.

II. System Description

The overall architecture of a PV-assisted PEV charging station is shown in Fig. 1. As stated in the previous section, the desired structure can be generalized to all PEV charging points. It usually includes solar energy, bidirectional PEV charger, local load demand and grid utility. It is obvious that the PV arrays are connected to the system by a power-electronic converter that controls the maximum power point tracking. Therefore in this structure, the maximum power is obtained from PV arrays, the local loads must be fed properly and completely, and the grid utility tries to balance the power of the whole system according to Equation (1). Therefore, the most accessible command for energy control is available in PEVs to meet the objective function.

$$P_{Grid} = P_{Load} - P_{PV} - P_{PEV} \tag{1}$$

The first step before implementing energy scheduling approach is identifying and collecting input data. In the proposed structure, there are three types of data with a 5-min temporal resolution. Some data such as weather conditions, electricity price and previous PEVs should be read only from the relevant parts. Some data require to be predicted by

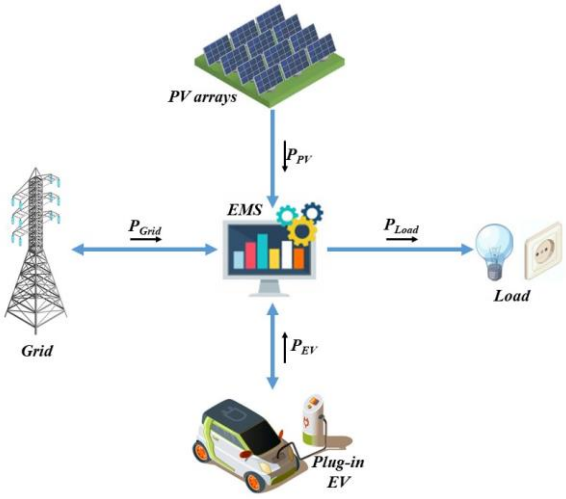

Fig. 1. Typical configuration of a PV-assisted PEV charging station.

suitable methods like PV power generation and load consumption profile. Here, it is assumed that predicted data were already available. The last type of data in the proposed algorithm must be received from the user or driver like the parking time, battery specification, initial and desired SOC.

In this regard, there are also some constraints related to input data that should be considered in the management problem. In this paper, minor constraints including PEV power constraint (Equation (2)), PEV energy constraint (Equation (3)) and desired SOC (Equation (4)), are employed.

$$P_{PEV}^{\min} \le P_{PEV} \le P_{PEV}^{\max} \tag{2}$$

$$E_{PEV}^{\min} \le E_{PEV} \le E_{PEV}^{\max} \tag{3}$$

$$SOC(t) = \begin{cases} SOC_{init}; & t = t_{arrival} \\ SOC(t-\Delta t) + \dfrac{P_{PEV}(t)}{E_{PEV}^{nom}}\Delta t; & t_{arrival} < t < t_{departure} \\ SOC_{final}; & t = t_{departure} \end{cases} \tag{4}$$

where E_{PEV}^{nom} is nominal capacity of battery and SOC_{init} and SOC_{final} are initial and desired SOC, respectively. Without any loss of generality, it should be mentioned that efficiency is ignored in this paper.

III. Proposed Smart Charging Algorithm

First, it is obvious that the grid operator, the owner of charging station and the PEV owner are usually different. Sometimes, it is possible that the interests of these roles for smart charging are in conflict. For example, reducing charging cost and battery health are important in the point of view of user, while for charging station owner, the revenue has the most priority. Typically, optimization is applied by the station owner, so it is better to consider the users' decisions in the algorithm as well.

The proposed smart charging algorithm aims to provide the desired level of charge for the PEV according to the user's command at parking time while minimizing the total cost, simultaneously. The whole flowchart of the proposed algorithm is shown in Fig. 2. Generally, this algorithm consists of seven steps.

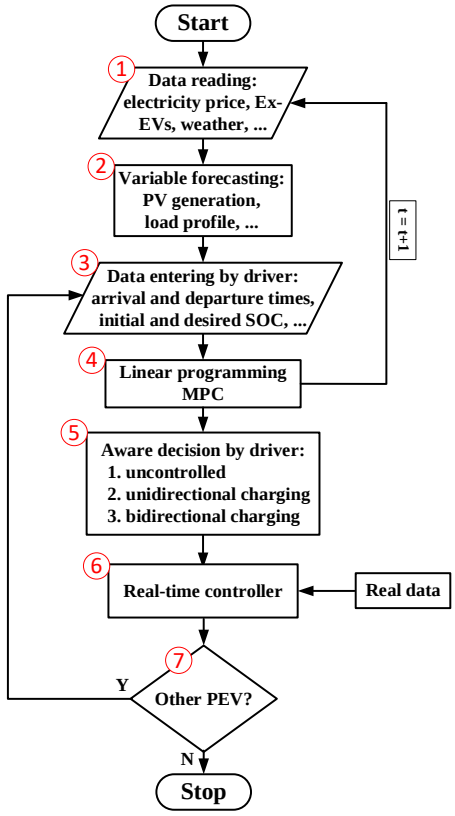

Fig. 2. Flowchart of the proposed smart charging algorithm.

As mentioned in the previous section, the first and second steps are related to data reading and variable forecasting, which are not the main topic of this paper and it is assumed that this information already exists.

In the third step, unlike the previous conventional methods, information about PEVs is received directly from the user upon entering the parking lot. This step greatly reduces errors in estimating vehicle-related variables in energy scheduling. Therefore, before the PEV enters the parking lot or the user announces in advance, the EMS is considered without the presence of the vehicle. In fact, the user gives the EMS a chance to update the optimization based on announcing the arrival time, the estimated parking time and the amount of desired SOC at the departure. Here, there is enough time between arrival time to the parking lot and complete stop to continue the next steps. Of course, the input information of this step can be announced before the arrival time by the applications available on smartphones to give the user more opportunity to make better decisions. It should be noted that there is still the possibility of minor changes in the announced information due to various reasons, including emergency requirements, which can be considered as a penalty parameter in these cases.

The MPC as a convenient option for optimizing the interpretation of constrained systems is used in the next step. This control method improves the systems' efficiency by handling constraints to work safely near constraint boundaries. Some steps have to be taken to implement the MPC [23]. The system state is taken as the starting point of the problem at the first step of time. Then, an optimum sequence is determined for the corresponding prediction period. After that, only the first control step is considered and applied. Finally, an upgrade is made with all details for the next time horizon when going to the next sampling period to re-apply the same steps. MPC is used in this work to solve the linear optimization problem for the next 20 hours according to Equations (1)-(4) due to its ability to update input data and to control multivariable constraints [20]. For a predicted 20-hour horizon, the number of time steps with a time interval of 5 minutes is obtained as

$$N = (20 \times 60) / 5 = 240 \tag{5}$$

In this regard, after solving the problem for the desired horizon, only the available solution for the present time, where here is the battery power output, is considered as output parameter. The objective function of this algorithm is formulated to minimize the cost of energy as a linear optimization problem as

$$\min(C_{grid,PEV}) = \min(C_{grid} \times \underbrace{P_{grid} \times \Delta t}_{E_{Grid}} - \lambda_{PEV} \times E_{PEV}) \tag{6}$$

where C_{grid} is the time-varying electricity price and λ_{PEV} is the weighting parameter. In other words, this objective function can be translated to reducing energy demand from the grid in high price. As it can be seen, in the next time step, the input data needs to be updated due to unavoidable forecasting error and the stated procedure is repeated based on the latest information in each time step.

In the fifth step, the optimal results for various technical and economic charging scenarios are presented to the user. In the simplest scenario, i.e. uncontrolled, the PEV will be charged traditionally as soon as it is parked. This scenario will usually have more cost and is chosen because the user does not know enough about smart charging.

In another scenario, as the simplest form of incentive, the user is encouraged to shift the charge from peak to off-peak time. This scenario is not interesting for the station owner because the PEVs connected to charging points cannot be used during peak time. Normally this case is managed by the user and therefore is not considered here.

In smart charging scenarios, the charging station owner tries to offer incentives to PEV users to use the car battery as a temporary load or source. In this regard, two scenarios of unidirectional charging and bidirectional charging are possible. In unidirectional smart charging, there is only control of the battery charging power, while in bidirectional smart charging, the battery can also be used as a temporary storage source. This scenario is usually the most attractive scenario for all involved parties, which can provide the profits of all of them. Therefore, the cost and health of the battery are given to the user for the mentioned scenarios so that the user can choose one of them with sufficient knowledge.

As seen in step four, MPC tries to implement the optimal charging based on some predictions on 5-min time-steps. Therefore, different errors may occur due to uncertainties in the real system. In fact, most of the challenges of EMS arise from uncertainties, which although this paper tries to almost eliminate car uncertainties, but there are still stochastic parameters in load profile and PV power generation. In this regard, in the sixth step of the algorithm, a rule-based real-time control scheme is employed according to Fig. 3 to compensate for the errors, which can act almost

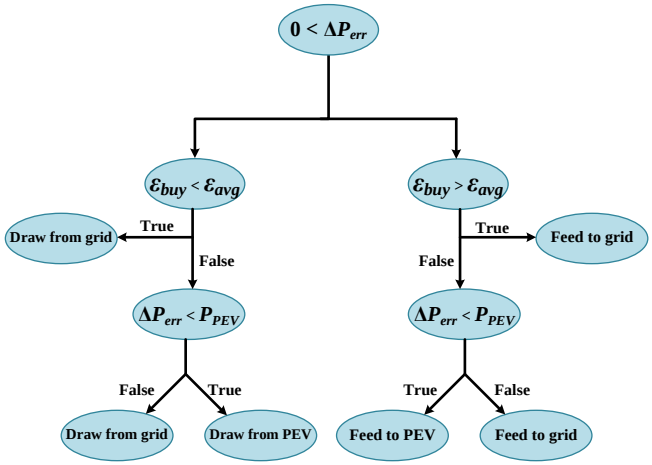

Fig. 3. Rule-based real-time control scheme [5].

instantaneously. ε_{buy} and ε_{avg} represent dynamic electricity price and its average one, respectively. The total error of the system ΔP_{err} is calculated using real data (P_{Load}^{act} and P_{PV}^{act}) and estimated ones (P_{Load}^{est} and P_{PV}^{est}) using Equation (7).

$$\Delta P_{err} = (P_{Load}^{est} - P_{Load}^{act}) - (P_{PV}^{est} - P_{PV}^{act}) \quad (7)$$

Finally, the mentioned PEV in this sequence is considered as fixed data in the system. Then, if another PEV arrives at the charging station and there is a free charging point, the proposed algorithm returns to the third step for a new car.

IV. Simulation Results

In this section, different scenarios are simulated in Matlab/Simulink software to examine the effectiveness of the proposed smart charging algorithm. PV and PEV specifications are given in Table I, which the PEV is a 2011 Nissan Leaf.

In this simulation, the electricity price during a whole day is shown in Fig. 4. In order to simplify the results and better understanding the scenarios, two price peaks are assumed in the morning (around 6) and at night (around 20), and at other times, the price is almost constant. It is also assumed that in a special case and again for simplicity and better understanding, the user arrives at the charging station at 3:00 o'clock with 40% of the initial SOC and announces that he/she intends to leave the station at 22:30 with 80% of the final SOC. Therefore, the PEV is almost available the whole day and operates like a stationary energy storage source.

A. Uncontrolled charging scenario

In the first scenario, the uncontrolled charge of PEV is investigated, which the results are shown in Fig. 5. In this figure, the output power of all parties, the PEV charge level and the cost of energy exchanged with the grid are presented during 24 hours. As expected, as soon as the PEV arrives, regardless of the electricity price, it starts battery charging to reach the desired charge level without interruption, which takes about 2.5 hours. Of course, here only a small part of charging is in the first low-amplitude peak and if the driver arrives later at the second peak, the charging cost will increase dramatically. Also, as it is observed, in this scenario, it is not possible to use solar power to charge the car, and the power

TABLE I
PV and PEV Parameters

Symbol	Description	Value
P_{PV}^{rated}	Installed capacity of PV arrays	7 kW
$P_{PEV}^{max/min}$	Maximum/minimum PEV power	3.5/-3.5 kW
E_{PEV}^{nom}	Nominal capacity of PEV battery	24 kWh
$SOC_{PEV}^{max/min}$	Maximum/minimum PEV SOC	90%/20%

Fig. 4. Electricity price (Cents/kW-h).

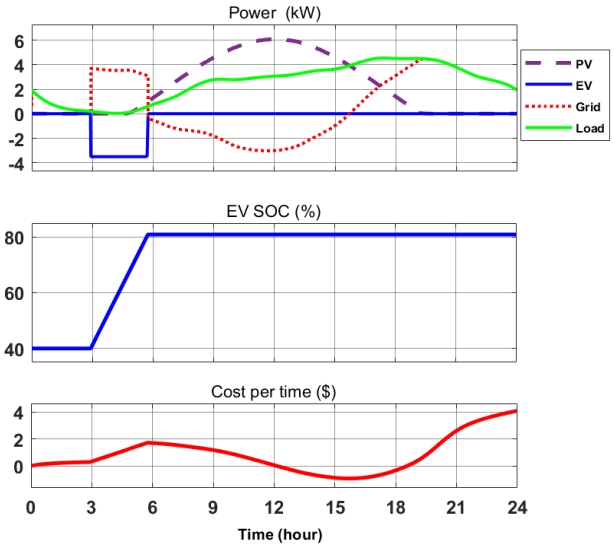

Fig. 5. Simulation results for uncontrolled charging scenario.

taken from the grid at peak prices is higher than other times. It is also obvious that the cost of energy exchanged with the grid goes through a similar curve to grid power.

B. Unidirectional smart charging scenario

In the second scenario, unidirectional smart charging is investigated and the results are presented in Fig. 6 to show how the power is distributed among different components. As mentioned before, it is not possible to discharge the battery in this scenario too and only battery charging power can be controlled. As expected, unidirectional smart charging tries to charge the PEV battery at the lowest possible cost, so charging process has stopped during the peak price. It should be noted that if the proposed algorithm takes into account the maximum use of solar power, the difference of electricity price between selling and buying, market dynamic price and efficiency, this scenario tends to use PV power generation to charge the car. Also, for the above reasons, the total cost of this scenario is not significantly different from the cost of the first scenario. It is possible that in other cases by considering the details, the

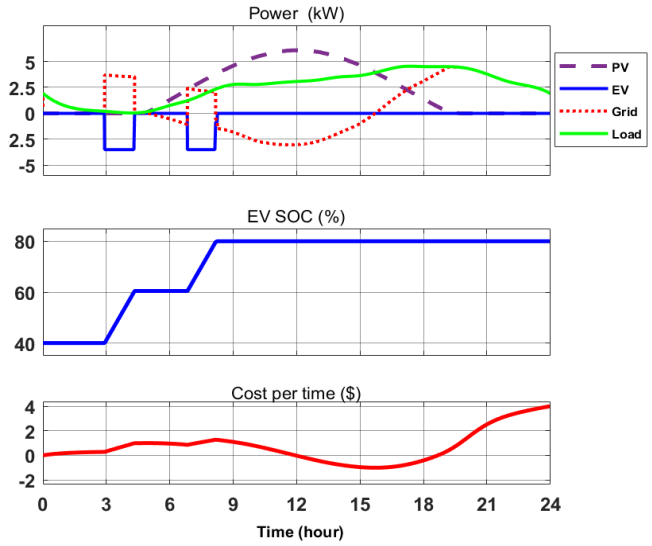

Fig. 6. Simulation results for unidirectional smart charging scenario.

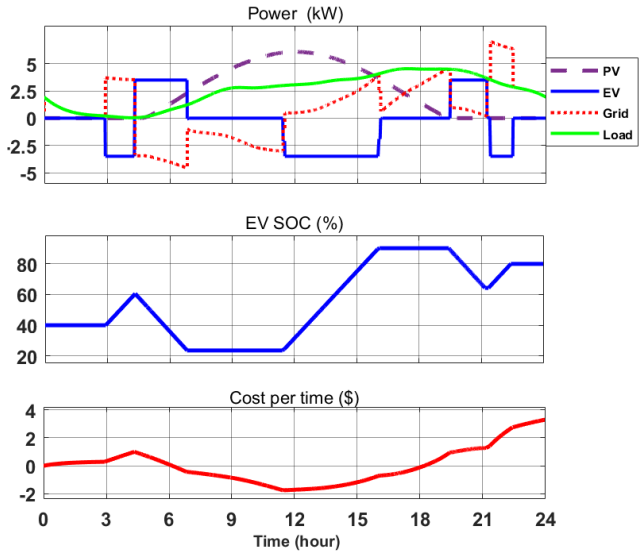

Fig. 7. Simulation results for bidirectional smart charging scenario.

difference between these two scenarios will increase, but it can be said that unidirectional smart charging will always bring more benefits than uncontrolled charging.

C. *Bidirectional smart charging scenario*

In the last scenario, called bidirectional smart charging, full control of charging and discharging is checked and the simulation results are shown in Fig. 7. As illustrated, the proposed algorithm employs battery power during price-peak periods for local load or injection into the grid and charges the PEV when the electricity price is low. In the specific case study, the PEV battery energy is fully utilized in the first price-peak, but in the second price-peak, due to the user's decision for leaving immediately after the price-peak period, battery usage will be less. In other words, the battery discharging is used at the highest prices in the second peak, but the desired SOC must also be provided and the battery should be recharged at lower prices during the second peak. As it can be seen, the energy received from the grid at high prices is significantly reduced in this scenario. Also, a large portion of the PEV battery charging is done at noon, when the PV array is the main power source.

TABLE II
COST COMPARISON IN DIFFERENT SCENARIOS

	Without PEV	**Uncontrolled charging**	**Unidirectional charging**	**Bidirectional charging**
Total cost (per day)	2.655$	4.087 $	4.013 $	3.29 $
Charging cost (day)	0	1.432 $	1.358 $	0.635 $
Charging cost(month)	0	42.96 $	40.74 $	19.05 $
Reduction percent	---	0	5.2%	55.7%

It should be noted that the goal of this paper was not to study different scenarios and choose the best one for charging by the algorithm. In fact, the proposed algorithm informs the user of the results of these scenarios, and he/she will select the appropriate charging scenario with sufficient knowledge, which will satisfy all parties. For example, Table II presents the simulation results of different scenarios. In the first column, the cost of energy exchanged with the grid without the presence of the PEV is calculated to obtain the PEV charging costs in other scenarios. In this special case and taking into account the relevant assumptions, bidirectional smart charging has a lower cost for the user than other scenarios. However, although the saved cost of a day may not be very attractive, on a one-month scale, assuming this procedure is repeated, the cost difference will signify. It is observed that bidirectional and unidirectional smart charging scenarios reduce the cost of PEV charging in this special case by 55.7% and 5.2%, respectively. Finally, it should be said that the battery health model and its associated constraints are not mentioned in the simulation results of this paper. Actually, they are the subject of the authors' future work. Considering the battery health parameter can affect the bidirectional smart charging scenario and may make other scenarios attractive as well.

V. CONCLUSION

Effective collaboration between the various components of a PEV charging station with smart charging algorithms greatly facilitates the operation of these systems. In this paper, a new user-friendly smart charging algorithm was proposed that intended to involve the PEV user as an important role in this process. The proposed algorithm was designed based on a linear optimization model predictive control along with a real-time rule-based controller. In this regard, based on the input and predicted data and data received from the user, different scenarios are examined. These scenarios included uncontrolled charging, unidirectional smart charging control, and bidirectional smart charging control. Next, the user is involved in choosing the final scenario with the help of sufficient information and an aware decision. In the case study of this paper, it was shown that the cost of PEV charging with bidirectional and unidirectional smart charging will be reduced by around 55% and 5%, respectively, compared to the uncontrolled charging scenario.

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