AUT Journal of Electrical Engineering

AUT J. Elec. Eng., 57(1) (2025) 131-146
DOI: 10.22060/eej.2024.23242.5595

Aggregator Design for Optimal Management of Charging and Discharging of Electric Vehicles in the Smart Grid Context

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ABSTRACT: The reduction of fossil fuel reserves, advancements in science and technology, increased network loading, the emergence of new energy sources and loads, etc., have contributed to the rise of smart grids. Within smart grids, distributed generation resources play a pivotal role in meeting the network's power requirements. Among these resources, renewable energies and electric vehicles are notable examples. In this context, the presence of electric vehicles on smart grids has led to numerous opportunities and challenges, underscoring the need for effective management of these vehicles. Among these concepts, a relatively new one known as the "Electric Vehicle Aggregator" is introduced. This aggregator provides the opportunity to participate in the demand-side management of energy networks by managing the scheduling of electric vehicle charging and discharging. In this paper, an attempt has been made to reduce the energy received from the grid by using the solar microgrid and considering the ability to connect to the upstream grid, and designing a new aggregator to maximize the profit of the owner of the aggregator. The proposed model has been designed, implemented, and tested over a 25-year time period using Homer software. The simulation results also show that using the proposed model despite considering the initial investment of the solar microgrid in the target functions, improvement and increase in the profit of the aggregator owner. The cost of the aggregator in the proposed method of this paper is 24.48$, while the same cost in the method used in the main reference is 29.62$.

Review History:

Received: May, 30, 2024
Revised: Jul. 23, 2024
Accepted: Aug. 13, 2024
Available Online: Aug. 13, 2024

Keywords:

Smart Grid
Electric Vehicles
EV Aggregator
Solar Microgrid
Vehicle-to-Grid

1- Introduction

Nowadays, fossil fuels are the dominant energy resources in the transportation and electricity generation sectors. Increasing global demand due to continuous population growth and human activities, coupled with the subsequent rise in air pollution, environmental issues, and the depletion of fossil fuel reserves, urges us to seek alternative energy sources for these sectors. In the realm of transportation, the emergence of electric vehicles presents a hopeful solution to tackle these challenges. Factors such as reducing fossil fuel consumption, curbing greenhouse gas emissions, and enhancing energy efficiency have positioned electric vehicles as significant players in electric energy systems. Considering the plans devised to further expand electric vehicle technology in various countries in the near future, exploring the diverse impacts of this technology on the power grid becomes essential. Consequently, scheduling for the charging and discharging of electric vehicles has garnered substantial attention as a new area of research.

According to the findings of studies conducted in [1], a solar-equipped electric vehicle parking lot has been proposed, along with an algorithm named "Parking Lot Management System" for optimal charging scheduling of vehicles. This system aims to reduce the energy obtained from the grid during high electricity price periods, thereby increasing the parking lot owner's profits. In [2], the feasibility and economic viability of a virtual power plant composed of commercial loads, electric vehicle parking lots, solar cells, and energy storage systems are discussed. The sequential energy management method is also utilized to optimally allocate the economic production and consumption schedule in the virtual power plant, aiming to mitigate electrical system constraints. Simulation results from various scenarios illustrate that deploying the virtual power plant and the proposed method would lead to cost reductions under different conditions. In reference [3], a real-time, sustainable, and flexible charging scheduling scheme is presented for electric vehicles in a commercial parking lot connected to solar panels. This scheme considers uncertainties like vehicle arrivals and departures, solar energy levels, etc., to enhance the profits of commercial parking lot owners. In reference [4], researchers propose a dynamic planning method to determine optimal attributes such as the number of electric vehicles, parking lot locations, capacities, and access times. This plan is aimed at constructing and expanding electric vehicle parking lot facilities within the distribution system. Estimating the power exchange between electric vehicles and parking lots

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is a fundamental requirement in parking lot scheduling. Thus, a creative approach is presented in this reference for the charging and discharging scheduling of electric vehicles as a subset of dynamic parking lot scheduling. This proposed method increases the parking lot operator's profits by minimizing additional costs, utilizing solar energy resources, and accounting for uncertainties related to investments and energy.

In [5], an optimal scheme for fast electric vehicle charging stations equipped with wind energy, solar energy, and energy storage systems (ESS) is suggested. Integrating renewable energy sources into electric vehicle charging stations poses challenges due to related uncertainties. Therefore, considering these uncertainties and network limitations, presenting this scheme is crucial. Different scenarios show that renewable energy resources, grid connection, and demand-side management can significantly enhance the performance of fast charging stations. Asynchronous and unplanned charging and discharging of grid-connected hybrid electric vehicles (HEV) can strain the power distribution network. To address this issue, reference [6] introduces a control management method called the "Charge and Discharge Control Algorithm". This algorithm considers the battery charge level of vehicles to determine the timing and mode of vehicle activation for consumption or injection of power to/from the grid. In reference [7], aiming to mitigate the impacts of a large number of electric vehicle charges on the grid, manage them effectively, and increase parking lot owner profits, the utilization of battery energy storage systems in parking lots is suggested. In [8], a coordinated charging scheduling method for electric vehicles is proposed, considering different charging scenarios, including both fast and slow charging, to adequately respond to various charging demands. Researchers in [9] delve into the cost-benefit analysis for participants in the Vehicle-to-Grid (V2G) service in Shanghai. Study outcomes indicate that engaging vehicles in V2G service during peak hours leads to positive profits for these vehicles. This not only generates income but also assists in relieving power grid peaks.

Reference [10] focuses on optimizing the charging of electric vehicles in a parking lot facility equipped with energy storage systems and solar panels. It proposes a joint power scheduling program between the grid, energy storage systems, and solar panels to efficiently charge vehicles. The charging optimization problem aims to minimize costs and is solved using a Grey Wolf optimization algorithm. In [11], researchers propose an intelligent charging scheduling algorithm to address the challenges posed by the random and asynchronous charging of numerous vehicles, aiming to alleviate network stresses. This algorithm aims to minimize the overall charging costs while incorporating bidirectional communication capabilities between the vehicles and the grid and utilizing real-time pricing in parking areas. Factors such as the feasibility of the chosen area in terms of renewable energy generation, investment costs, equipment maintenance, and payback period are considered in this article. The impact of various electric vehicle charging and discharging strategies and V2G technology on electric distribution networks is examined in [12]. This study explores active power regulation, reactive power support, load modulation, and harmonic current filtering as benefits and battery degradation due to frequent charging and discharging, the communication mechanisms between vehicles and the grid, and the necessity of implementing changes in the distribution network infrastructure as challenges arising from the interplay of V2G technology. The reference also delves into different charging and discharging strategies, including controlled and uncontrolled methods, delayed charging and discharging, bidirectional charging and discharging, and intelligent charging and discharging. Controlled charging and discharging are highlighted as an effective strategy for both electric vehicle owners and network operators.

Reference [13] introduces the concept of an aggregator as an independent entity to facilitate communication between participants in demand response programs and the electricity market. This aggregator can participate in short-term markets such as day-ahead markets and real-time markets by trading its acquired power. Within the proposed framework, an unknown electricity market price is considered, and researchers suggest an ESS to mitigate this uncertainty. Numerical results demonstrate that employing an electric ESS with appropriate capacity supports the aggregator against worst-case scenarios and negative effects arising from market uncertainty, leading to a significant increase in the aggregator's profit. In [14], electric vehicle aggregators are positioned as crucial intermediaries for coordinating the charging of numerous electric vehicles and establishing their connection to the grid and electricity market. The researchers propose an optimal two-stage exploitation strategy for an electric vehicle aggregator that operates in various markets under different uncertainties. In the day-ahead stage, a joint supply model is provided to assist the aggregator in participating in energy markets and simultaneously reserving under uncertain market prices. In the real-time stage, a multi-level planning model based on model predictive control is suggested to minimize energy deviation costs under uncertain reservation market prices. Numerical outcomes from this study indicate that the proposed exploitation strategy significantly enhances the profitability of the studied aggregator. Reference [15] presents an optimal exploitation model for electric vehicles in electric energy aggregators based on a Stackelberg game model. At the top level, the aggregator provides appropriate planning strategies and charge/discharge prices, while at the bottom level, electric vehicles respond accordingly to minimize costs. Simulation results indicate that the proposed model not only reduces costs for vehicles and the grid but also significantly assists in reducing power fluctuations and peak demand profiles. In contrast to conventional optimization models, reference [16] introduces a novel optimization approach for electric vehicle aggregators that collectively considers key profitability factors such as uncertainty, driving patterns, battery capacity constraints, charge levels, supply and demand regulations, and the grid. The aim is to maximize the aggregator's profit. The obtained results demonstrate that by adhering to the specified regulations and constraints, electric vehicles can have a substantial impact on increasing the aggregator's profitability.

The optimal planning in the operation of the power grid has been examined in several studies, but the investigation of the optimal planning of charging and discharging in the operation of the smart grid in the presence of aggregators of electric vehicles equipped with solar microgrids, taking into account the construction costs, the maintenance and repair of solar microgrid, the period of investment return, and also considering the environmental factors affecting the production power of solar microgrid, such as sunlight and ambient temperature in the place where the aggregator is located, have not been done. Since equipping the aggregator with a solar microgrid will involve costs for the owner of the aggregator, therefore, as mentioned, ensuring the profitability of this plan and its economic justification is necessary and unavoidable.

In fact, the innovation of this paper is the designing of an aggregator with the ability to establish two-way communication of the power of electric vehicles with the network, the solar microgrid with variable radiation levels in 12 months of a year in the electric market with variable buying and selling prices in 24 hours of a day. As a result of applying the proposed method, the power received from the upstream network decreases, the profit of the collector owner increases by considering the initial investment of the solar microgrid, and environmental pollutants are also reduced. In fact, the design of this structure and related economic studies are the main reasons for conducting this study.

Continuing with the paper, in the second section, the aggregator model for managing the smart grid and the relevant mathematical equations are presented. The third section introduces the proposed optimal charge and discharge scheduling algorithm. Moving on to the fourth section, simulation results are provided, analyzed, compared, and discussed. Finally, the fifth section concludes the article.

2- Aggregator Model for Smartgrid Management

2- 1- Electric vehicle modeling

With some contemplation regarding electric vehicles and their associated technologies, it becomes evident that as the number of electric vehicles increases, the opportunity arises to utilize their battery charging and discharging for both revenue generation and optimal management of the smart grid. This approach involves performing charging during low-demand hours and discharging during peak-load hours, leveraging vehicles as active grid components. The timing of electric vehicle arrival and departure to/from the aggregator and the initial state-of-charge (SOC) of vehicles upon arrival constitute crucial attributes, and these are provided to the aggregator system by the vehicle owners. Therefore, to model the uncertainty associated with the behavior of electric vehicle owners, the truncated normal distribution function (TG), as outlined in Eq. (1) to (3), is employed [17].

$$SOC_n = f_{TG}\left(SOC_n; \mu_{SOC_n}, \sigma^2_{SOC_n}, \left(SOC_n^{\min}, SOC_n^{\max}\right)\right) \quad \forall n \quad (1)$$

Where SOC_n represents the state-of-charge of the n-th electric vehicle upon arrival to the aggregator, and f_{TG} indicates a truncated normal distribution function. μ, σ^2 represent the mean and variance, and μ_{SOC_n}, $\sigma^2_{SOC_n}$ represent the mean and variance of the random variable SOC_n respectively. The subscripts min, max denote the range of the random variable SOC_n, and the values $SOC_n^{\min}$, $SOC_n^{\max}$ represent the minimum and maximum charge levels of the n-th vehicle respectively [17].

Similarly, Eq. (2) and (3) are utilized to generate scenarios related to the arrival and departure times of each vehicle [17].

$$t_{arv,n} = f_{TG}\left(t_{arv,n}; \mu_{t_{arv,n}}, \sigma^2_{t_{arv,n}}, \left(t_{arv,n}^{\min}, t_{arv,n}^{\max}\right)\right) \quad \forall n \quad (2)$$

$$t_{dep,n} = f_{TG}\left(t_{dep,n}; \mu_{t_{dep,n}}, \sigma^2_{t_{dep,n}}, \left(t_{dep,n}^{\min}, t_{dep,n}^{\max}\right)\right) \quad \forall n \quad (3)$$

Where the random variables $t_{arv,n}$, $t_{dep,n}$ respectively represent the arrival and departure times of the n-th vehicle to/from the aggregator. $\mu_{t_{arv,n}}$, $\mu_{t_{dep,n}}$ represent the mean value of the random variable $t_{arv,n}$, $t_{dep,n}$, and $\sigma^2_{t_{arv,n}}$, $\sigma^2_{t_{dep,n}}$ represent the variance of the random variable $t_{arv,n}$, $t_{dep,n}$. Additionally, the subscripts min and max in both equations indicate the range of the random variables $t_{arv,n}$, $t_{dep,n}$, and $t_{arv,n}^{\min}$, $t_{arv,n}^{\max}$ are associated with the minimum and maximum arrival times of the n-th vehicle to the aggregator, and $t_{dep,n}^{\min}$, $t_{arv,n}^{\max}$ represent the minimum and maximum departure times of the n-th vehicle from the aggregator.

The rate of battery charging and discharging of electric vehicles is another important characteristic, and in this article, similar to [18], it has been considered $10\ kWh$. Similarly, the maximum, minimum, and desired SOC values for electric vehicle owners have been considered as *100*, *10*, and *90* percent, respectively [1].

2- 2- Solar microgrid modeling

The generated power of a solar microgrid depends on various factors such as accessibility, solar radiation intensity, temperature, number of solar cells, etc. The stochastic nature of solar radiation intensity introduces uncertainty into solar microgrid systems. Therefore, to model this behavior, the probability density function (PDF) of a beta distribution, similar to Eq. (4) to (6), is employed as one of the most suitable probability distribution functions [19].

$$f(\theta)=\begin{cases}\dfrac{\theta^{\alpha-1}\times(1-\theta)^{\beta-1}}{B(\alpha,\beta)} & 0\le\theta\le1 \quad \alpha,\beta\ge0\\ 0 & otherwise\end{cases} \tag{4}$$

Where θ represents solar radiation intensity in kW/m^2, $f(\theta)$ is the probability density function of the beta distribution related to solar radiation intensity, and $B(\alpha,\beta)$ denotes the beta distribution function. α and β are parameters of the beta distribution function, which are calculated according to the following Eq. (5), (6).

$$\beta=(1-\mu_\theta)\times\left(\frac{\mu_\theta\times(1+\mu_\theta)}{\sigma_\theta^2}-1\right) \tag{5}$$

$$\alpha=\frac{\mu_\theta\times\beta}{1-\mu_\theta} \tag{6}$$

Where μ_θ and σ_θ^2 are the mean and variance values of solar radiation intensity, respectively.

The value of the generated power in the solar microgrid is also obtained from Eq. (7) to (11).

$$P_\theta=N\times FF\times V_\theta\times I_\theta \tag{7}$$

$$FF=\frac{V_{MPP}\times I_{MPP}}{V_{oc}\times I_{sc}} \tag{8}$$

$$V_\theta=V_{oc}-\left(K_V\times T_c\right) \tag{9}$$

$$I_\theta=\theta\times\left(I_{sc}+K_c\times\left(T_c-25\right)\right) \tag{10}$$

$$T_c=T_a+\left(\theta\times\frac{T_N-20}{0.8}\right) \tag{11}$$

Where P_θ represents the power generation of solar cells, N is the number of solar cells, and FF denotes the fill factor. V_θ, I_θ indicate voltage and current generated by solar cells, and V_{MPP}, I_{MPP} represent voltage and current at the maximum power point (MPP). V_{oc}, I_{sc} are open-circuit voltage and short-circuit current, and T_c, T_a, and T_N respectively related to the cell temperature, ambient temperature, and operating point temperature in $°C$, and K_v, K_c respectively indicating the temperature coefficient of voltage and current in $V/°C$ and $A/°C$. The values of V_{MPP}, I_{MPP}, V_{oc} and I_{sc} are obtained based on the information extracted from the current-voltage characteristic curve of solar cells.

2- 3- Optimal charge and discharge scheduling

The mathematical equations required for modeling the optimal charge and discharge scheduling of electric vehicles in an aggregator equipped with a solar microgrid are presented below. The mathematical modeling of vehicle information includes the required power level of the vehicle at the time of its departure from the aggregator. This information is communicated to the aggregator's management system by the vehicle owner and is calculated using Eq. (12) [1].

$$E_{car,n}=E_{\min}+d_n\times m_n \tag{12}$$

Where index car pertains to vehicles, $E_{car,n}$ represents the energy required by the n-th vehicle upon departure from the aggregator, $E_{\min}$ is the minimum energy required for the vehicle, d_n is the distance that the n-th vehicle is expected to travel after leaving the aggregator, and m_n is the electric power consumption rate of the n-th vehicle per kilometer (km), which varies based on the vehicle type.

The required charging duration for each vehicle is also different based on the charging rate and the energy demand of the vehicles. It is calculated using Eq. (13) [1].

$$T_{ch,n}=\frac{E_{car,n}}{Ch_{rate}} \tag{13}$$

Where the index ch corresponds to the battery charging of vehicles, $T_{ch,n}$ indicates the time required for charging n-th vehicle in hours (hr), and Ch_{rate} is related to the charging rate.

Therefore, by determining the required power for charging electric vehicles per hour and merging them according to Eq. (14), the aggregator's load curve in kWh is obtained [1].

$$P_{load,t}=\sum_{t_{dep}=1}^{T}E_{car,n,t_{dep}} \tag{14}$$

Where $P_{load,t}$ represents the total load required by the aggregator for charging vehicles at t-th time, and $E_{car,n,t_{dep}}$ denotes the energy required by n-th vehicle upon departure from the aggregator (t_{dep}) in terms of kWh.

As mentioned in Section 1, the objective function in this article, according to Eq. (15), aims to minimize the cost of purchasing power from the grid [1].

$$minimize \quad C_{pg,t} \tag{15}$$

Where the index pg represents the purchased power from the grid and $C_{pg,t}$ signifies the cost of the purchased power from the grid at t-th time in dollars ($).

The cost of purchased power from the grid is also calculated according to Eq. (16) [1].

$$C_{pg} = P_{grid,t} \times \rho_t \tag{16}$$

Where index $grid$ represents the grid, $P_{grid,t}$ denotes the power drawn from the grid at t-th time in kWh, and ρ_t signifies the real-time price.

According to Eq. (17), the difference between the total required charging load of electric vehicles by the aggregator and the amount of power generated by the solar microgrid calculates the purchased power from the grid in terms of kWh [1].

$$P_{grid,t} = P_{load,t} - P_{solar,t} \tag{17}$$

Where $P_{grid,t}$ represents the power drawn from the grid at t-th time, $P_{load,t}$ denotes the total required charging load of electric vehicles by the aggregator at t-th time in kWh , which can vary with the number of vehicles and time. The index $solar$ relates to the solar microgrid, and $P_{solar,t}$ signifies the power generated by the solar microgrid at t-th time in kWh

The constraints considered in the proposed optimal charge and discharge scheduling program are outlined as follows [1].

The charging and discharging of vehicle batteries should not exceed the maximum and minimum battery capacities as defined by Eq. (18).

$$E_{car,\min} \le E_{car,n,t} \le E_{car,\max} \tag{18}$$

Where E_{car} represents the battery energy of vehicles in terms of kWh, $E_{car,n,t}$ stands for the energy of the battery of the n-th vehicle at t-th time, and $E_{car,\min}$, $E_{car,\max}$ respectively denote the minimum and maximum battery energy capacities of the vehicles.

The solar microgrid's generated power, as described by Eq. (19), must not exceed the allowable maximum capacity.

$$P_{solar,t} \ge P_{solar,\max} \tag{19}$$

Where $P_{solar,t}$ represents the solar microgrid's generated power at t-th time, and $P_{solar,\max}$ pertains to the maximum capacity of the solar microgrid's generated power.

Vehicles must be charged prior to departure, as described by Eq. (20).

$$t_{arv,n} \le T_{ch,n} \le t_{dep,n} \tag{20}$$

Where $T_{ch,n}$ represents the time required for charging n-th vehicle, it must be constrained between two values, $t_{arv,n}$ and $t_{dep,n}$, corresponding to the arrival and departure times of n-th vehicle to/from the aggregator.

The power drawn from the grid and the power generated by the solar microgrid during off-peak hours are exclusively used for charging vehicles and should be constrained between the minimum and maximum values according to Eq. (21).

$$0 \le P^{ch-grid}_{t_{off-peak}} + P^{ch-solar}_{t_{off-peak}} \le P^{\max} \tag{21}$$

Where index $t_{off-peak}$ represents off-peak hours, superscripts $ch-grid$ and $ch-solar$ correspondingly denote power drawn from the grid and power generated by the solar microgrid, $P^{ch-grid}_{t_{off-peak}}$ signifies the power drawn from the grid during off-peak hours, $P^{ch-solar}_{t_{off-peak}}$ signifies the power generated by the solar microgrid during off-peak hours, and $P^{\max}$ stands for the maximum power required by the aggregator based on kWh.

In peak hours, according to Eq. (22), no vehicle should be charged through the grid.

$$P^{ch-grid}_{t_{on-peak}} = 0 \tag{22}$$

Where $t_{on-peak}$ is related to peak hours and $P^{ch-grid}_{t_{on-peak}}$ represents the charging power drawn from the grid during peak hours in kWh.

The solar microgrid's generated power for charging vehicles during peak hours should be zero as per Eq. (23).

$$P^{ch-solar}_{t_{on-peak}} = 0 \tag{23}$$

Where $P^{ch-solar}_{t_{on-peak}}$ represents the solar microgrid's generated charging power during peak hours in terms of kWh.

The amount of stored power in electric vehicle batteries for selling to the grid during peak hours, as described by Eq. (24), needs to be constrained within the maximum and minimum values.

$$0 \le P^{dch}_{t_{on-peak}} \le P^{\max} \tag{24}$$

Where the superscript dch refers to the discharge of vehicle batteries, $P^{dch}_{t_{on-peak}}$ represents the discharge power during peak hours, and $P^{\max}$ signifies the maximum required aggregator power in kWh.

According to Eq. (25), the stored power in vehicles for selling back to the grid during off-peak hours should be zero.

$$P^{dch}_{t_{off-peak}} = 0 \tag{25}$$

Where $P^{dch}_{t_{off-peak}}$ represents the discharge power during off-peak hours in terms of kWh.

As a result, considering the aforementioned constraints, the vehicle is allowed to perform charging and discharging operations.

3- The proposed optimal charging and discharging scheduling algorithm

In Section 3, an algorithm is presented for optimal electric vehicle charging and discharging scheduling in the aggregator. This algorithm is employed in the aggregator management system to achieve this goal. The subsequent steps are elaborated upon.

a.The inputs considered for this algorithm include data related to vehicles, solar microgrid power generation, and real-time electricity prices.

The vehicle-related information consists of:

- The vehicle type, determined based on the mileage and the battery capacity of the vehicle
- Arrival time to the aggregator
- Departure time from the aggregator
- The distance intended to travel
- SOC level of the vehicle upon arrival time

b. The required charge for each vehicle is calculated based on the vehicle type and the distance intended to travel.

c. Upon calculating the required power, the time needed for charging the vehicle is determined.

d. In cases where the power price is low, the strategy is to have all the vehicles charged during that time period.

e.Otherwise, during periods of abundant solar energy, identify and consider both the departure time and the total required charging time, and vehicles in time slots with high power prices are moved to these abundant solar energy periods.

f. On the other hand, during peak load hours, if vehicle owners are willing, it is possible to contribute to the aggregator's revenue by discharging the vehicle batteries using V2G technology while considering the aforementioned constraints.

g. In conclusion, following the outlined steps, vehicles are scheduled for charging and discharging. Subsequently, the aggregator's owner benefits from the optimization process by using this scheduling to initiate the charging and discharging of vehicles.

Fig. 1 illustrates the proposed framework for optimal charging and discharging scheduling, and Fig. 2 depicts the process of deploying the presented algorithm in the aggregator management system.

4- Simulation

Based on the provided equations and models in Section 2, a simulation is conducted by considering electric vehicle aggregators equipped with solar microgrids, taking into account the V2G capability of electric vehicles, and aiming to reduce the costs of the aggregator's owner.

4- 1- The Studied System

For simulation purposes, an intelligent electric vehicle aggregator with *20* charging stations is selected, and the arrival and departure times of the electric vehicles, along with the distance they intend to travel, are considered inputs to the aggregator management system. In this simulation, two types of electric vehicles with battery capacities of *24* and *30* kWh and mileages of *0.3* and *0.4* kilowatt-hours per kilometers (kWh/km) with a minimum battery SOC of *10%* are taken into account.

The simulation is conducted considering a *15%* interest rate and a *6%* inflation rate over a *25*-year time span, taking place in Hyderabad, one of the major cities in India. Additionally, the number of vehicles available to the aggregator during peak hours is set to *50* with *100* kwh capacity.

4- 2- Simulation parameters

4- 2- 1- Arrival and departure rates of vehicles to/from the aggregator

These data are generated by a random function between numbers 1 to 24. Based on this, Fig. 3 and 4 illustrate the arrival and departure rates of vehicles to/from the aggregator per hour, which are crucial data for calculating the required electrical power of the aggregator and scheduling the charging and discharging of vehicles. It's important to note that the departure time of vehicles should not be earlier than their arrival time at the aggregator.

4- 2- 2- The electrical power required for each vehicle at the time of departure

The electrical power required for each vehicle is calculated based on the distance intended to travel, the mileage, and the battery capacity of each vehicle. Fig. 5 illustrates the required charging power for each vehicle at the time of departure based on the assigned identifier, which is then utilized to calculate the grid load profile.

4- 2- 3- Aggregator's load profile

The aggregator's load profile is equal to the total required charge within a specific time interval and is used in the aggregator management system. Fig. 6 illustrates the daily load profile of the aggregator based on its hourly load requirements, and it's another important dataset used in the charging and discharging scheduling of vehicles.

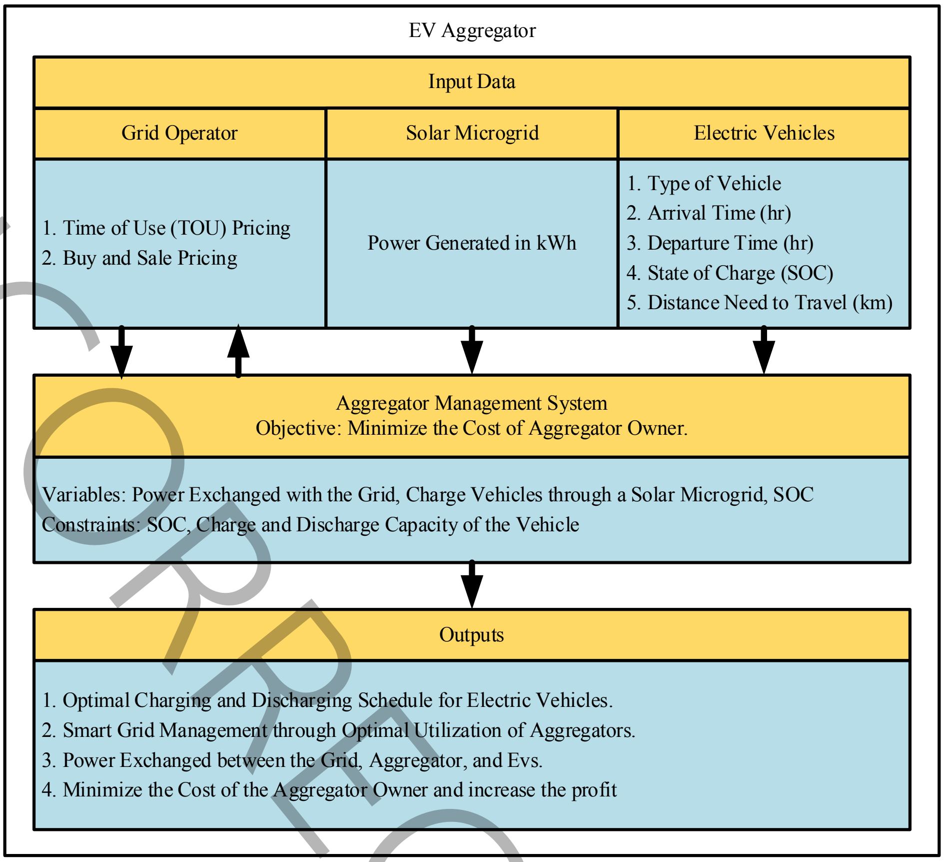

Fig. 1. The proposed framework for optimal charging and discharging scheduling

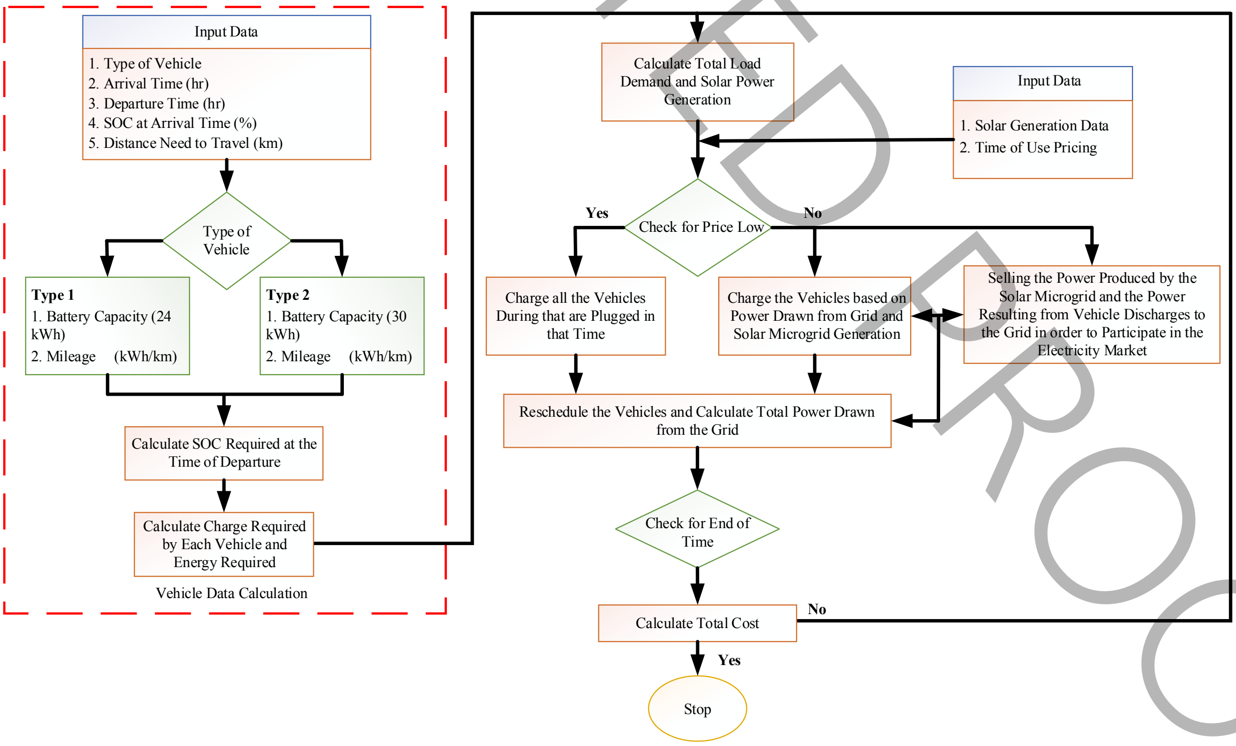

Fig. 2. Flowchart of the deployment process of the proposed algorithm

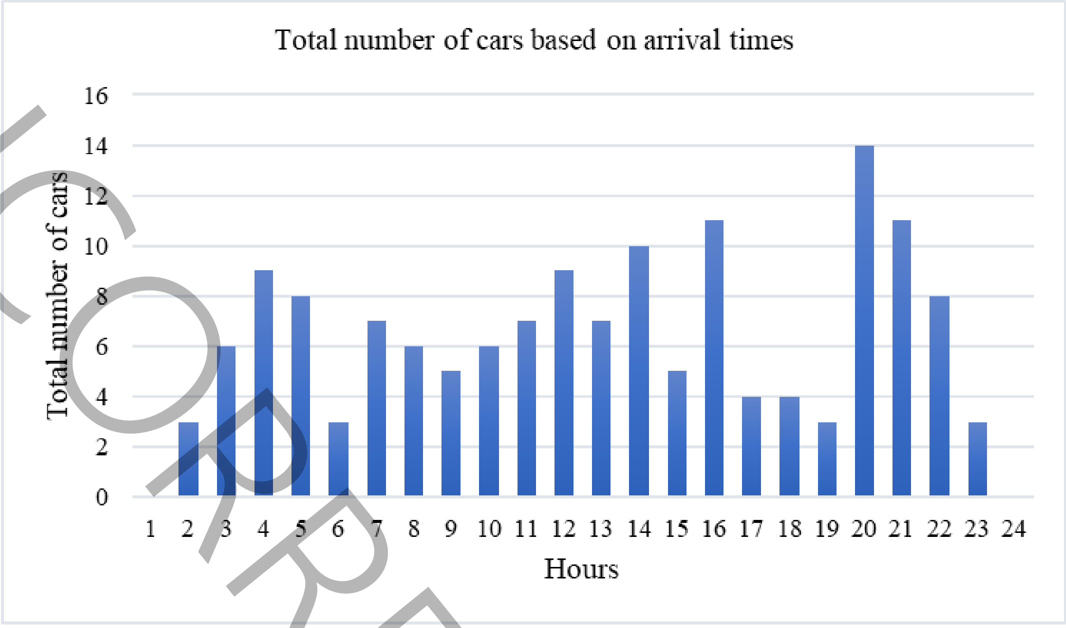

Fig. 3. Arrival rate of vehicles

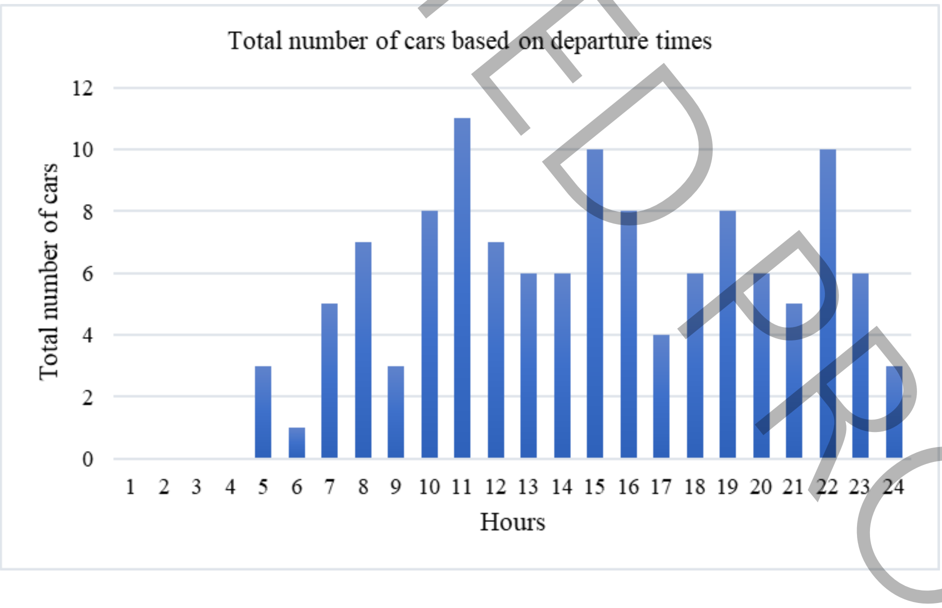

Fig. 4. Departure rate of vehicles

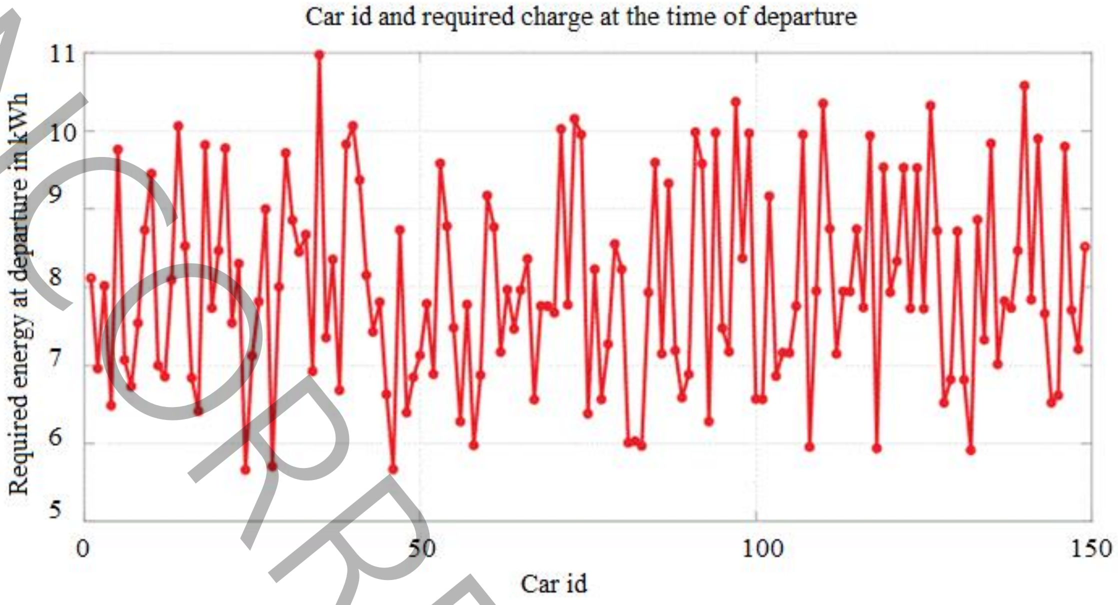

Fig. 5. Vehicles and their required charging power at the time of departure

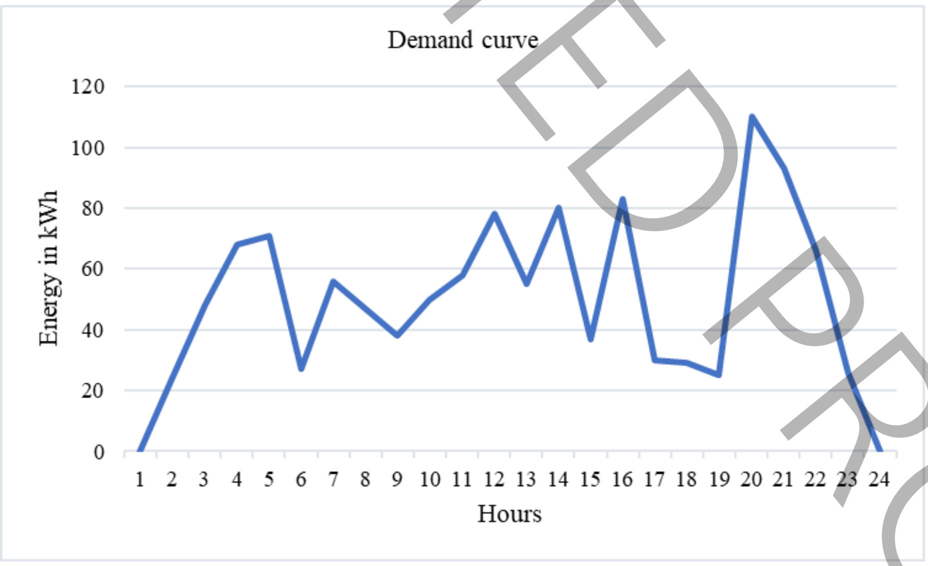

Fig. 6. Aggregator’s load profile related to electric vehicle charging

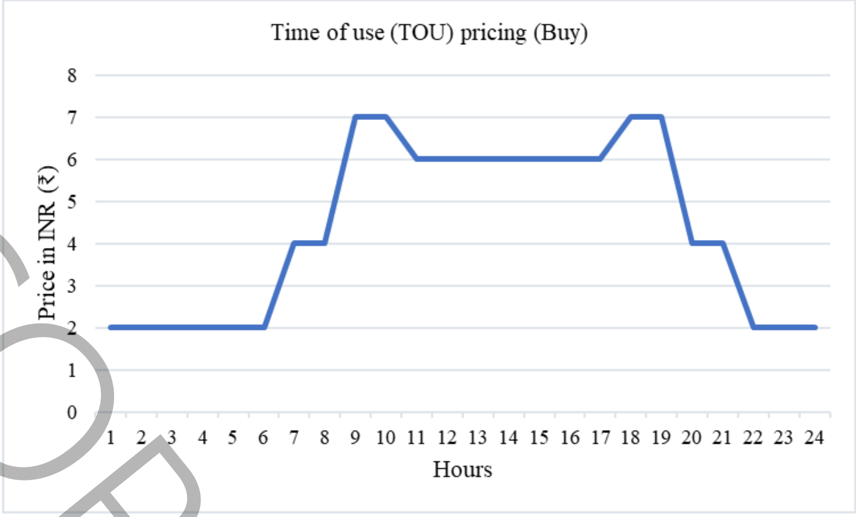

Fig. 7. Real-time electricity purchase price from the grid

4- 2- 4- Real-time electricity purchase and sale prices

Real-time electricity purchase and sale prices from/to the grid and vehicles are also used as data inputs in the aggregator management system. Fig. 7 to 9 respectively depict the real-time electricity purchase price from the grid, the real-time electricity purchase price from vehicles, and the real-time electricity sale price to the grid. The data extracted from these figures is utilized in the demand response programs employed in the proposed algorithm and holds significant importance in influencing the willingness of both aggregators and vehicle owners to participate in the proposed charging and discharging schedule outlined in this article.

4- 2- 5- Solar microgrid

The information related to the capacity of the solar microgrid, equipment lifetime, and associated investment costs is as follows.

The solar power plant capacity considered in this simulation is $25\ kW$.

Based on the conducted investigations, the useful lifespan of solar panels and inverters is determined to be *25* years.

The costs related to the purchase and replacement of solar panels per kW are 0.*45* $ and *0.36* $, respectively, and the costs related to the purchase and replacement of inverter per kW are *0.12$* and *0.09$*, respectively.

The intensity of sunlight and temperature are two influential factors in the generation of solar microgrid power. Fig. 10 and 11 represent the monthly average intensity of sunlight and temperature, respectively. These figures are derived from meteorological and solar energy data from NASA and are relevant to the city of Hyderabad, India. They provide valuable data for calculating the generated solar microgrid power.

4- 3- Simulation results

All the simulations were done in the Homer software environment. Homer software is known as a simulator of hybrid systems and renewable energies and is responsible for designing and simplifying the technical and economic evaluation of microgrids in two modes, islanded and connected to the network. This software is designed to save energy consumption, transferring equipment to the use of renewable energy, and reducing greenhouse gas emissions, and it consists of three main parts: Simulation, Optimization, and Sensitivity analysis.

4- 3- 1- Aggregator model

The proposed aggregator structure presented in Fig. 12 consists of a power grid, a solar microgrid, an inverter, electric vehicles, and the load related to the vehicle charging which has been examined in 3 scenarios introduced in Table 1. As it is clear from Table 1, the most complete scenario is scenario 3, in which the power received from the upstream network, the solar microgrid, and the power received from the electric vehicles as well as the investment cost are considered. So the simulation results related to scenario 3 are given in detail below, and in some cases, they will be compared with the results of other scenarios.

4- 3- 2- The electrical power

The data related to the amount of network and solar microgrid electrical power generation, as well as the power consumption for charging electric vehicles, is presented in Tables 2 and 3.

As observed, a portion of the solar microgrid's generated power is used to meet the load demand, while another part is sold back to the grid. Therefore, the power received from the grid has decreased accordingly.

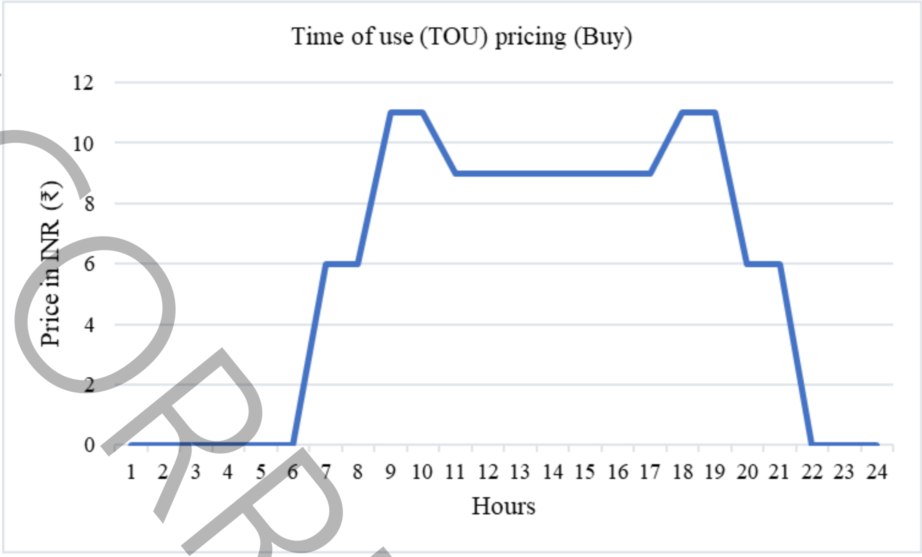

Fig. 8.Real-time electricity purchase price from the vehicles

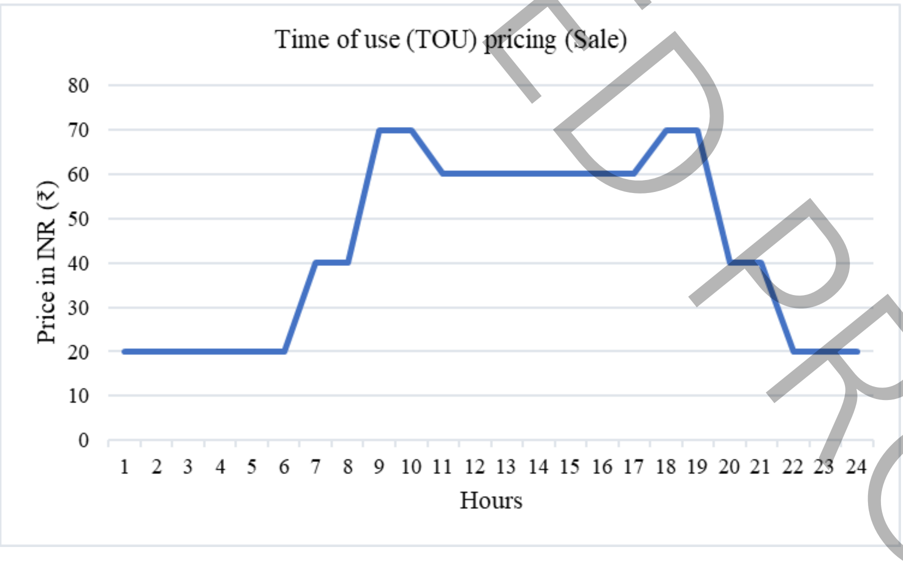

Fig. 9. Real-time electricity selling price to the grid

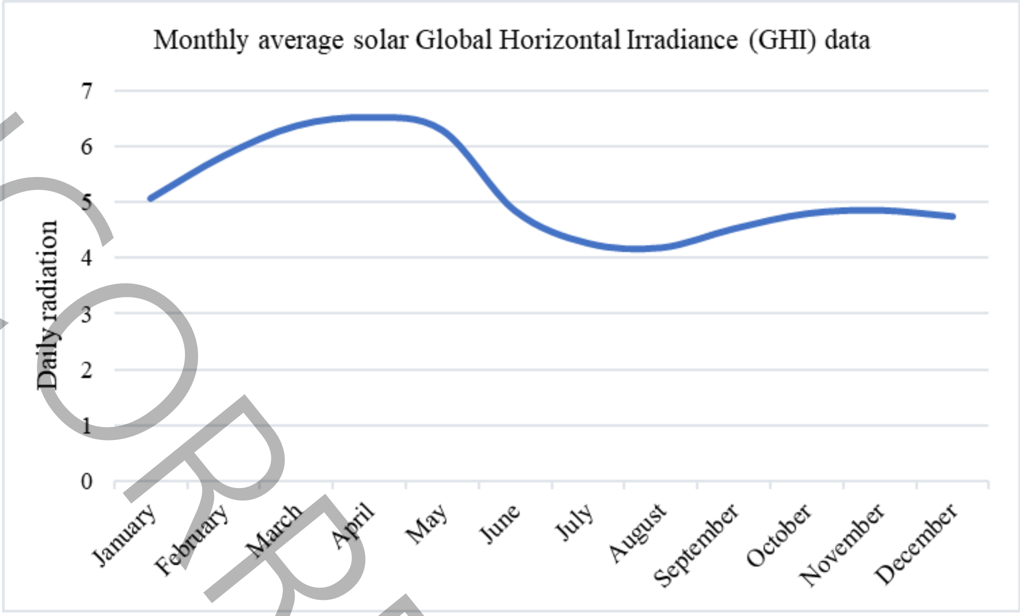

Fig. 10. Monthly average sunlight intensity

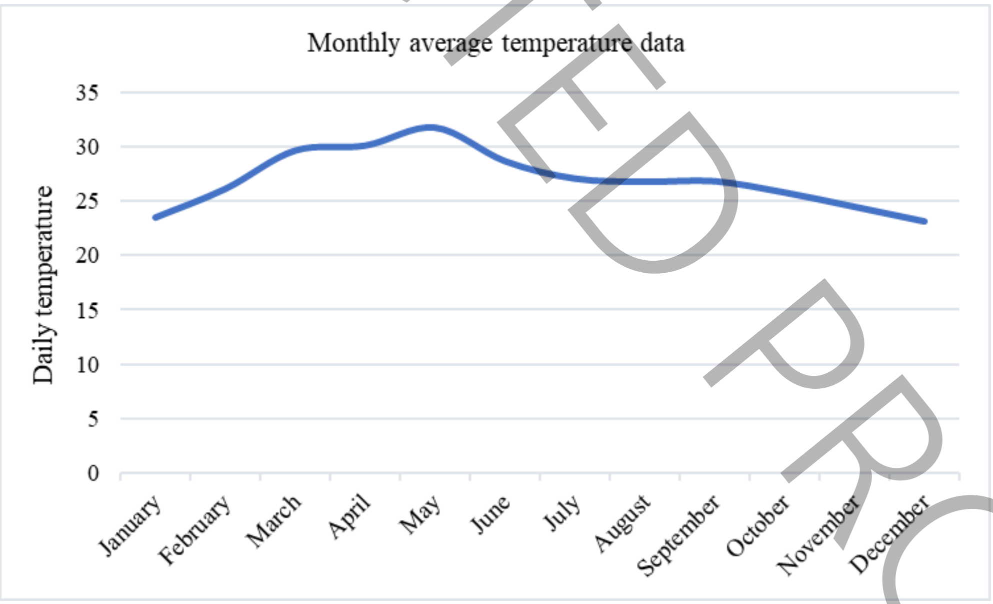

Fig. 11. Monthly average temperature

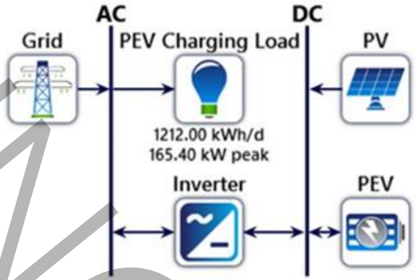

Fig. 12. The aggregator schematic

Table 1. Introducing different scenarios

scenario	Aggregator model			
	Grid	PV	Investment cost	PEV
1	✓		-	-
2	✓	✓	✓	-
3	✓	✓	✓	✓

Table 2. he amount of network and solar microgrid electrical power generation

Component	Production (kWh / yr)
Solar Microgrid	39,771
Grid Purchases	401,351
Total	441,123

Table 3. he amount of power consumption for electric vehicle charging

Component	Consumption (kWh / yr)
PEV Charging Load	442,380
Grid Sales	313
Total	442,693

Table 4. Net Present Cost (NPC)

Name	Capital	Operating	Total
PEV	0.00	0.00	0.00
PV	11.22	0.00	11.22
Grid	0.00	0.21M	0.21M
Inverter	2.52	0.00	2.52
Aggregator	0.014M	0.21M	0.22M

Table 5. Total Annual Cost (TAC)

Name	Capital	Operating	Total
PEV	0.00	0.00	0.00
PV	1.1	0.00	1.1
Grid	0.00	0.02M	0.02M
Inverter	0.25	0.00	0.25
Aggregator	1.34	0.02M	0.022M

4- 3- 3- Costs

The costs that are imposed on the aggregator owner for responding to the electric vehicle charging demand are presented in Table 4 and Table 5. Table 3 represents the Net Present Costs (NPC) incurred by the aggregator over the project's duration and Table 5 represents the total annual costs.

Based on Table 4 and Table 5 and the calculation of the NPC for one day and comparing it with the reference data [1], taking into account the interest rate, inflation rate, and capital investment costs in the simulation, we observe a significant reduction in the aggregator's costs. Table 6 presents the results of this comparison. As it is clear in the results of Table 6, the application of scenario 3 in the aggregator model has the best results.

4- 3- 4- Greenhouse gases

The emissions of greenhouse gases for the proposed system are presented in Table 7 in kilograms per year (kg / yr). Due to the use of solar microgrids and V2G technology, we have observed a reduction in the emissions of these pollutants. Considering this reduction in emissions, we can also explore the cost effects. In this case, the reduction in emissions can lead to cost savings and further improvement in results compared to previous conditions.

4- 3- 5- Payback

In Table 8, the payback period is presented with and without considering the interest and inflation rate. The payback period is one of the important factors for investors to consider to ensure the profitability of the project.

Table 6. Comparison of the simulation results of 3 scenario with the reference [1]

Scenario	NPC/day Reference [1]	NPC/day Simulation	Compare
1	64.31$	64.31$	same
2	32.45$	26.85$	Decrease
3	29.62$	24.48$	Decrease

Table 7. Emissions of greenhouse gases

Quantity	Value	Units
Carbon Dioxide	253,654	kg / yr
Sulfur Dioxide	1,100	kg / yr
Nitrogen Oxide	538	kg / yr

Table 8. Payback period

Metric	Value
Simple Payback (yr)	1.97
Discounted Payback (yr)	2.26

5- Conclusion

With the increasing adoption of electric vehicles (EVs) and their ever-growing integration into the grid, addressing the various impactful dimensions of this technology is crucial. In this paper, the issue of optimal scheduling in the operation of a smart grid in the presence of EV aggregators equipped with solar microgrids and V2G technology, taking into account demand response programs, is studied, analyzed, and examined. Considering private ownership for the aggregator, the goal of the scheduling is cost reduction from the aggregator's perspective. To achieve this goal, an algorithm for optimal charging and discharging scheduling is designed and presented for use in the aggregator's management system. The aim is to maximize profits by reducing costs. Optimization techniques are utilized for modeling this system, and simulations considering investment costs are conducted using the provided equations and models to assess the impact of the proposed algorithm on the aggregator's performance. In the end, the results obtained from various simulations are analyzed and discussed in detail. It is evident that by employing the proposed algorithm and method, the aggregator's costs can be significantly reduced.

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HOW TO CITE THIS ARTICLE

R. Eslami. Aggregator Design for Optimal Management of Charging and Discharging of Electric Vehicles in the Smart Grid Context . AUT J. Elec. Eng., 57(1) (2025) 131-146.

DOI: 10.22060/eej.2024.23242.5595