# Energy Management of PV-based Parking Lots Considering Utility Satisfaction

Youmna Elsayed[1,a], Mohamed R. Hamouda[2,b], Maher Mohamed[1,c], Mohamed EL-Shimy[1,d]

[1]Electrical power and Machines Department, Ain Shams University, Cairo, Egypt
[2]Electrical and Electronics Engineering, Coventry University branch in Egypt, Cairo, Egypt

**Abstract**— The urgent need to reduce greenhouse gas emissions has prompted the exploration of cleaner energy options such as renewable energy resources (RES) and electric vehicles (EVs). With the increasing use of RES and EVs, there are new opportunities and challenges for the stakeholders involved, and traditional centralized power system management methods are insufficient to handle the complexity. The energy management of photovoltaic (PV)-based parking lots is one of the challenges tackled in recent research. The main obstacle in applying previous research is the elimination of the utility objectives from the energy management models. This paper proposes an energy management framework that enables the integration of PV-based parking lots in a smart grid environment, considering the satisfaction of the utilities as a key player. The proposed framework is modeled using an optimization software package (GAMS), and the results are compared with two different cases to ensure its feasibility and effectiveness. The proposed model succeeded in taking the utilities satisfaction into account by managing the charging and discharging of the EVs.

## 1. Introduction

During the last decades, environmental concerns about global warming have arisen. Transportation and burning fossil fuels for electricity are the largest sources of greenhouse gas emissions, and the electricity and transportation sector shares around 25% and 27% of 2020 greenhouse gas emissions, respectively [1]. Therefore, moving to cleaner energy, renewable energy, and electric vehicles (EV) can provide the optimal pathway to reduce $CO_2$ emissions and help mitigate the impacts of global warming. The future of energy production is looking increasingly bright, thanks to the growth of renewable energy sources. The International Renewable Energy Agency (IRENA) prepared a global roadmap showing that renewables will reach a share of the grid of around 60% in 2050. In China, the electric energy generated from renewable energy sources (RES) came to 7% in 2015 and is expected to grow to 67% in 2050. Meanwhile, in Europe, the share of renewable energy could grow from about 17% to over 70% by 2050 [2]. Among different types of distributed energy resources (DER) technologies, solar-photovoltaic (PV) energy generation is the most popular and widely used[3]. This is due to the low cost of PV raw materials and installation costs because of large-scale production [4].

On the other hand, EVs has been flourished in recent years and have a substantial global market. By 2050, studies show that there will be more than 1 billion EVs on the road, which is proof of the popularity and practicality of this exciting technology. China and the United States are the largest markets for EVs, with 2.6 million and 1.1 million, respectively, in 2019. Although EVs is a green transportation technology, they can also play a key role in supporting renewable energy sources and improving the overall reliability of our energy systems. In 2050, around 14 terawatt-hours (TWh) of EV batteries will be available to provide grid services, compared to 9 TWh of stationary batteries [5]. As the use of EVs increases, there is a growing demand for EV parking lots to be installed in various locations. Solar-based parking lots are proving to be a more advantageous option than grid-based charging stations due to their lower costs and higher environmental friendliness compared to the grid or fossil fuels [6]. Solar-powered charging stations are being established by private hospitals, offices, and industries to offer EV charging facilities to their employees in parking lots.

The massive and widespread integration of RES and EVs into power systems creates new opportunities and challenges for all stakeholders involved, but at the same time, the electric distribution system management has become more complex than before. Traditional centralized concepts of power system management methods are insufficient to handle this complexity and should be replaced by a smart grid. As Smart grid technology provides a decentralized approach to managing the distribution network, optimizing the integration of RES and EVs while maintaining grid viability.

One of the key features of the smart grid is the prosumer's participation in the electricity market. Prosumers are both energy producers and consumers in the electricity market. They can trade electricity with each

---

[a] 2102202@eng.asu.edu.eg, [b] Ad9748@coventry.ac.uk, [c] Maher_eldessoki@eng.asu.edu.eg, [d] shimymb@gmail.com

other directly to achieve a win-win situation for all players with reasonable tariffs, and the buyers can save on costs while sellers gain more profit [4]. The same is true for EV owners, who can sell or buy energy to and from the grid or other prosumers, creating a more dynamic and flexible as well as resilient energy market.

Numerous research have been conducted in recent years for the sake of building parking lots and handling EV demand and charging. In [7], the author only discusses charging stations powered with PV stations, which are undependable without a connection to the electrical grid. The author illustrates optimal EV scheduling for a solar-powered charging station. Authors in [8] propose a mixture between the grid, PV, and diesel generator for a charging station. Despite the system's dependability, the diesel generator still causes environmental problems. The author examines the optimum method for integrating PV with ESS [9]; however, the proposed approach is not grid-connected. Furthermore, the study in [10] describes a research study that aimed to optimize the sizing of PV and energy storage system (ESS) for EV charging. The study found that both the PV system and the ESS configuration is the most effective and economically feasible option. Other studies provide general overviews of EVs and charging station layouts [11]. Additionally,[12] proposes a charging station equipped with off-grid PV for EVs and hydrogen vehicles, but this work is only viable when used with hydrogen vehicles alongside EVs. A comprehensive scheme for properly deploying charging stations with PV systems that has an improved voltage profile, decreased power loss, and low costs within a distribution network [13]. A collaborative operating approach that combines a ESS, a charging station, and group of buildings is proposed in [14] to reduce operating expenses in a community microgrid.

This paper introduces an energy management framework that examines potential stakeholders' business models. The work presented in this paper has the following contributions:

1) Propose an energy management framework enabling energy transactions between EV-PV and the grid.

2) Develop a unique utility function for the grid to participate efficiently in the framework.

## 2. Architecture of Proposed System

The proposed architecture for the energy management framework represents an innovative energy marketplace to introduce a more flexible marketplace that benefits both prosumers and utilities. It mainly consists of prosumers (EVs), PV systems, and utilities. In contrast to the conventional scheme shown in Fig.1, where producers and consumers are forced to trade at a fixed price set by the utility, the proposed scheme introduces a more flexible and dynamic approach.

As illustrated in Fig.2, the proposed scheme allows prosumers to trade with each other or with the utility based on a mutual price agreement. This approach creates a more competitive and efficient market by enabling the participant to negotiate prices that benefit all players [12].

The system is designed for commercial buildings with parking lots where EVs are parked from 9 am to 5 pm. Therefore, an aggregator is proposed to manage the transitions between all players effectively. In addition, the aggregator will also handle EV charging and discharging decisions based on various factors such as the state of charge, parking duration, and cost. Table 1 presents the characteristics of the EV [15].

As the goal is to achieve satisfaction for all players involved through an optimization scheme, a new comprehensive approach is required. This approach enables all parties to achieve greater satisfaction.

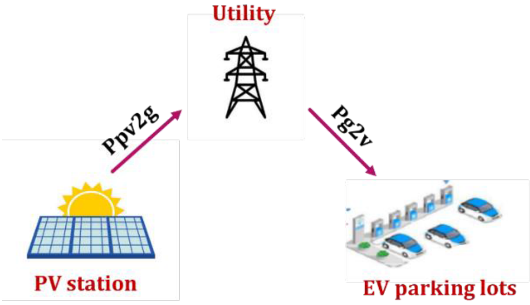

**Figure 1.** Conventional Regulation Scheme

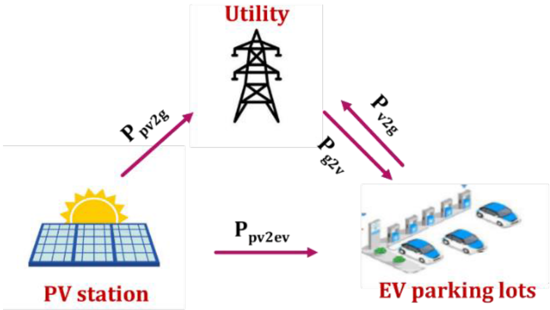

**Figure 2.** Proposed Scheme

**Table 1** EV Characteristic Parameters

| | **Battery capacity [kWh]** | **Max charging power [KW]** |
|---|---|---|
| Mitsubishi Outlander | 13.8 | 3.7 |
| Hyundai Ioniq | 38.3 | 7.2 |
| Tesla Model 3 | 55 | 7.4 |
| Toyota Prius | 8.8 | 3.3 |
| Nissan Leaf | 40 | 3.6 |

## 3. Proplem Formulation

The objective functions of the proposed scheme are defined as follows:

1. The main objective function:

Equation (1) is a multi-objective function that includes two sub-objectives. The first objective represents the parking lots' total running cost, including PV, and EV. The second objective represents utility satisfaction, which will be discussed in detail. That being said, the first term represents the cost of the proposed system, and the second term represents the grid satisfaction cost.

$$Min\ (C) = C_{tot} + C_g. \qquad (1)$$

2. The proposed system Cost of buying electricity:

The total parking lot cost is modeled using equation (2), which involves EVs and PV systems. The first term represents the price of purchasing electricity from the utility. The second term represents the cost of battery degradation. The third term in which describes the PV operation cost. The fourth term, the cost of power exported to the grid and the cost of power supplied to EV from a PV system, represents the profit for the system

$$\text{Min}(C_{tot}) = \sum_{p=1}^{P}\sum_{t=1}^{T}\sum_{i=1}^{N}[P_{i,t,p}^{g2v} \times C_{elec_t} + P_{i,t,p}^{v2g} \times C_{deg} + \left(P_{i,t,p}^{pv2ev} + P_{t,p}^{pv2g}\right) \times C_{pv} - \left(P_{t,p}^{pv2g} + P_{i,t,p}^{v2g} + P_{i,t,p}^{pv2ev}\right) \times C_{Fit}]. \quad (2)$$

3. The Grid satisfaction objective:

Equation (3) represents the objective function to minimize the utility cost, which is divided into two equations to model different objectives. Equation (4) aims to maximize the power during the on-peak hours in order to encourage the grid to buy more power during these peak hours and reduce the leakage of power during this period, and the utility has op. However, equation (5) aims to minimize grid cost, with the first term representing the power cost purchased by the grid, which is a cost incurred by the utility, and the second term representing the purchasing price of electricity from the utility, which is a profit earned by the utility

$$Min\left(C_g\right) = Cg1_{i,t,p} + Cg2_{i,t,p} \quad (3)$$

$$Cg1_{i,t,p} = -\sum_{p=1}^{P}\sum_{t=1}^{T}\sum_{i=1}^{N}[(P_{i,t,p}^{v2g} + P_{t,p}^{pv2g}) \times C_{Fit} \quad 7 \leq t < 11 \text{ and } 17 \leq t < 19 \quad (4)$$

$$Cg2_{i,t,p} = \sum_{p=1}^{P}\sum_{t=1}^{T}\sum_{i=1}^{N}[(P_{i,t,p}^{v2g} + P_{t,p}^{pv2g}) \times C_{Fit} - \left(P_{i,t,p}^{g2v} \times C_{elec_t}\right)]. \quad (5)$$

The constraints of the proposed scheme are defined as follows:

1) The following charging and discharging power limits for each EV are defined by specific boundaries that cannot be exceeded to prevent damage to the EV's battery and ensure optimal performance:

$$P_{i,t,p}^{g2v} + P_{i,t,p}^{pv2ev} \leq P_{i,t}^{Max\ ch} \quad (6)$$

$$P_{i,t,p}^{v2g} \leq P_{i,t}^{Max\ dsch}\ . \quad (7)$$

2) Equations (8) and (9) introduce additional constraints on the charging behavior of the EV. Equation (8) ensures that the EV can either charge or discharge at any specific time, but not both simultaneously, to prevent damage to EV's battery. Furthermore, equation (9) restricts the charging process of the EV to either the PV system or the grid, but not both sources at the same time as follow:

$$\left(P_{i,t,p}^{g2v} + P_{i,t,p}^{pv2ev}\right) * P_{i,t,p}^{v2g} = 0 \quad (8)$$

$$P_{i,t,p}^{g2v} * P_{i,t,p}^{pv2ev} = 0 \quad (9)$$

3) When EV is charged or discharged, some power is lost due to system inefficiencies. So, the charging and discharging process is not 100% efficient, with a charging/discharging efficiency of 90% [15]. The EV power equation is as follows:

$$P_{i,t,p}^{EV} = \eta_{ch} \times \left(P_{i,t,p}^{g2v} + P_{i,t,p}^{pv2ev}\right) - \left(P_{i,t,p}^{v2g}/\eta_{ch}\right) \quad (10)$$

4) The State of Charge (SoC) of EVs can be calculated using equation (11). The arrival SoC of EVs with varying levels, but they must determine their desired SoC at the time of departure based on their needs:

$$SOC_{i,t,p} = \begin{cases} 0 & t < T_{i,p}^{Arrv} \\ SOC_{i,p}^{Arrv} & t = T_{i,p}^{Arrv} \\ SOC_{i,t-1,p} + \frac{P_{i,t,p}^{Ev}}{BC_t} \times \Delta t & T_{i,p}^{Arrv} < t < T_{i,p}^{Dept} \\ SOC_{i,p}^{dept}. & t > T_{i,p}^{Dept} \end{cases} \quad (11)$$

5) Equation (12) defines a constraint that is essential for ensuring optimal performance and a longer lifespan of the battery by preventing deep discharges and overcharges:

$$SOC_{Min} \leq SOC_{i,t,p} \leq SOC_{Max}. \quad (12)$$

6) When EVs are not connected to the parking lot charging system:

$$\begin{cases} P_{i,t,p}^{v2g} = 0 \\ P_{i,t,p}^{g2v} = 0 \qquad t < T_{i,p}^{Arrv} \quad or \quad t > T_{i,p}^{Dept} \\ P_{i,t,p}^{pv2ev} = 0 \end{cases} \quad (13)$$

7) To prevent the PV system from generating excess power beyond its rated capacity with a converter and inverter efficiency of 98% [15]:

$$\frac{\sum_{i=1}^{N} P_{i,t,p}^{pv2ev}}{\eta_{dc-dc}} + \frac{P_{t,p}^{pv2g}}{\eta_{dc-dc} \times \eta_{inv}} < P_t^{pv} \leq P_{pv}^{Max} \quad (14)$$

## 4. Case Study

This section presents a numerical analysis of the feasibility and effectiveness of the proposed energy management framework for EV, PV, and utility over 24 hours. The optimization problem is solved using GAMS solver as a nonlinear problem. In order to evaluate the effectiveness of the proposed scheme in this study, three different case studies are performed. In the first case study, the objective will be to minimize the utility cost only. In the second case, the objective will be to mitigate the proposed system's total cost only. While in the third case, a multi-objective optimization problem is solved, which includes both the utility and the system.

This work investigates one EV parking lots with 25 EVs and a 40 kW PV system. The battery degradation cost is 0.056 C$/kWh. The LCOE for PV is 0.065 c$/kWh [16]. Time-of-use (TOU) pricing is categorized into off-peak, mid-peak, and on-peak hours, with corresponding prices of 0.074 c$/kWh, 0.102 c$/kWh, and 0.151 c$/kWh, respectively, as stated in reference [17]. The feed-in tariff (FIT) value chosen for the study is 0.0713 c$/kWh, as reported in reference [18].

### 4.1. Case study 1: The main objective is to minimize the total cost of the parking lots (Ctot) without considering the Grid satisfaction cost

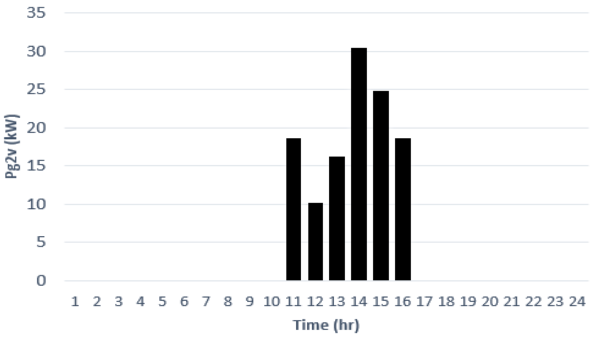

**Figure 1** G2V power in case 1.

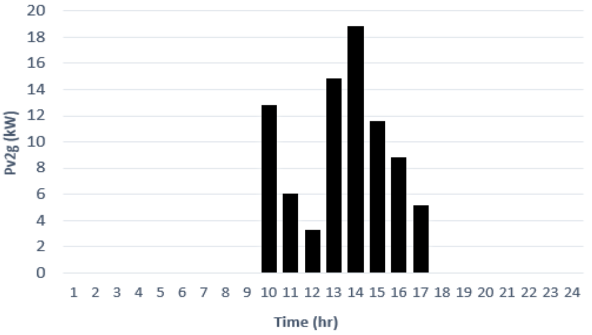

**Figure 2** V2G power in case 1.

The proposed case study aims to minimize the total cost of the system while ensuring optimal utilization of distributed energy sources. Fig. 3 shows the power purchased by the EVs from the grid (G2V power).

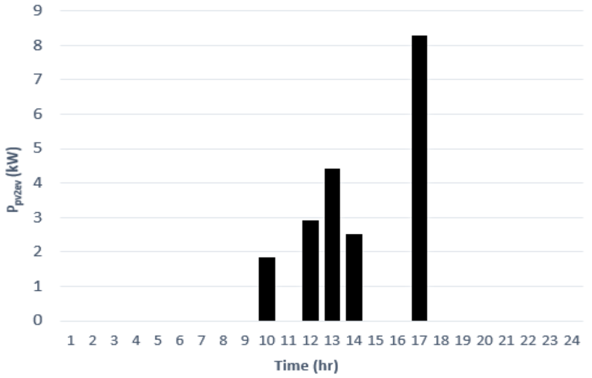

**Figure 3** PV2EV power in case 1.

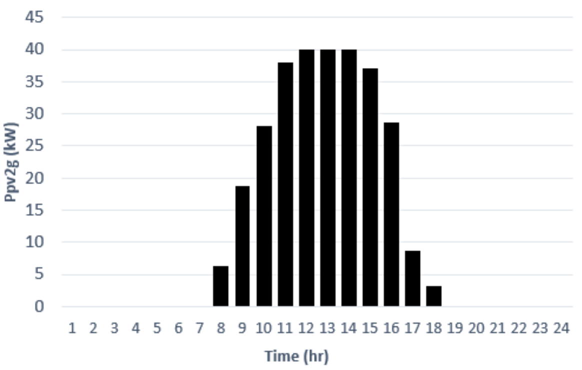

**Figure 4.** PV2G power in case 1.

It is observed from the results of Fig.4 and Fig.6 that the EVs and PV sell most of the power to the grid, which ensures a profit for both parties. However, the utility is forced to purchase most of the power generated by the EVs and PV, which results in financial losses to the utility. Fig.5 illustrates the quantity of power being drawn from the PV source and consumed by EVs.

### 4.2. Case study 2: The main objective is to minimize the grid satisfaction cost.

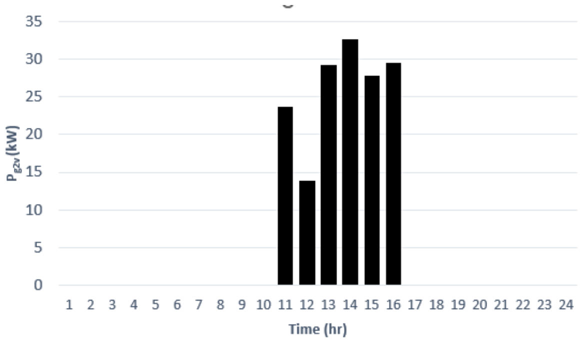

**Figure 5** G2V power in case 2

In this section, we present a case study of the proposed scheme with the objective of minimizing grid costs, maximizing power in on-peak hours, and maximizing profits. In Fig.7, demonstrates that a significant amount of power is drawn from the grid to charge EVs compared to other scenarios.

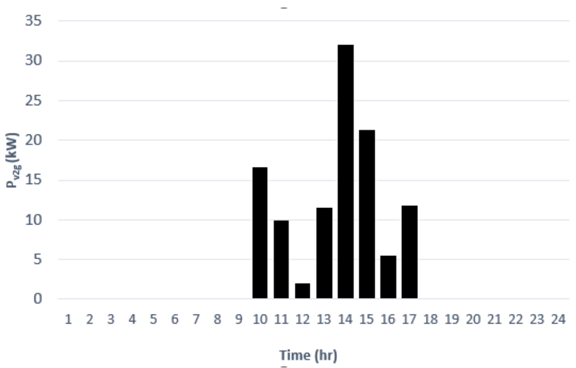

**Figure 6** V2G power in case 2.

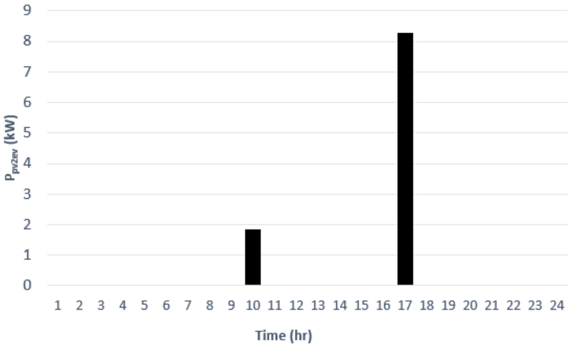

**Figure 7.** PV2EV power in case 2.

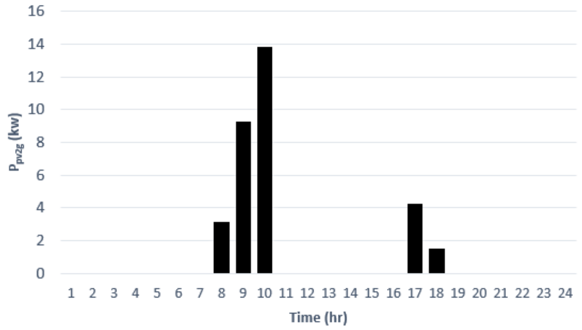

**Figure 8** PV2G power in case 2.

During on-peak hours, the grid does not inject power to EVs.

Fig. 8 shows that the EVs sold a significant amount of power to the grid, which contradicts the objective of minimizing grid cost. However, due to the State of Charge (SOC) restrictions, the EVs were compelled to sell their excess power, which included the purchased power to the grid. The results from Fig.7 and Fig.8 show that this approach resulted in financial losses for EVs. Fig 9. the PV system supplies power to the EVs during on-peak hours only, as the EVs are forced to buy most of their power from the grid in order to generate a profit for the grid. In Fig. 10, the PV system sells only a small amount of power to the grid. Fig.9 and Fig. 10 imply that renewable energy sources were not utilized to their full potential in this case.

### 4.3. Case study 3: The main objective is to minimize the main multiobjective function to account for the total parking cost and the grid satisfaction cost

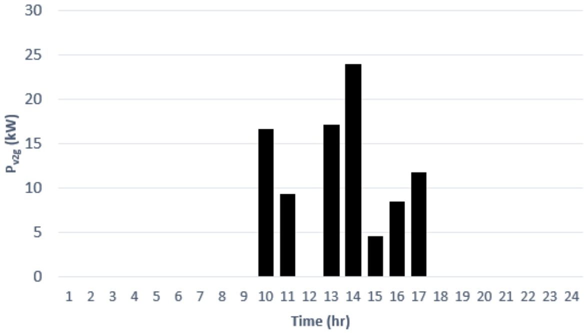

**Figure 9** V2G power in case 3.

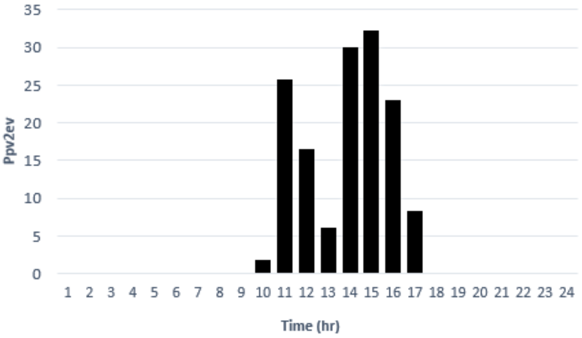

**Figure 10** PV2EV power in case 3.

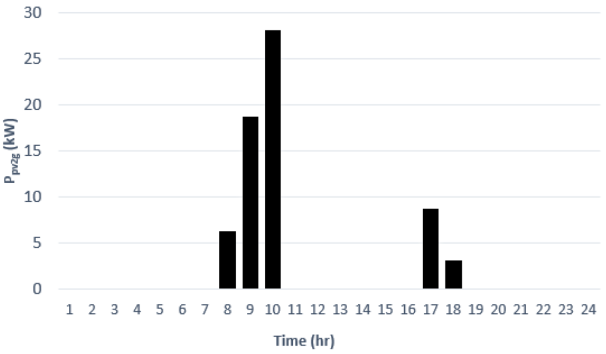

**Figure 11** PV2G power in case 3.

This case study presents a multi-objective optimization problem that aims to address the complex energy management challenges faced by EV, PV, and utility systems while ensuring profitable operations for all parties involved. It is essential to highlight that despite the utility not being able to achieve its objective of selling power to EVs, it was still able to fulfill one of its key goals, which was to maximize power in on-peak hours.

Also, the results demonstrate the effectiveness of this case in ensuring the optimal utilization of renewable energy sources, thus promoting sustainability while providing a significant economic advantage to both the EV and PV systems.

Fig.11 and Fig.13 depict the considerable contribution of EV and PV systems in selling power to the grid, especially during on-peak hours. Furthermore, as illustrated in Fig.12, the EV system effectively purchases all its power requirements from the PV system, taking advantage of the lower tariff prices.

Table 2 presents a comparison of the three cases, indicating that case 3 provides the optimal solution, resulting in a fair profit for both case 1 and case 2. This approach ensures that all parties involved are able to benefit economically.

**Table 2** Comparison of All Cases' Costs

| | **CASE 1** | **CASE 2** | **CASE 3** |
|---|---|---|---|
| Ct (C$) | -175.27 | -33.225 | -83.288 |
| Cg (C$) | 449.558 | -9.29 | -6.477 |
| C (C$) | 274.288 | -42.430 | -91.661 |

## 5. Conclusions

This article proposes an energy management framework for EV, PV, and utility systems that aims to ensure optimal utilization of distributed energy sources while maximizing profits and promoting sustainability. The proposed framework is evaluated through three case studies, which focus on minimizing the total cost of the proposed system, minimizing the utility cost, and addressing a multi-objective optimization problem that includes both the utility and the proposed framework. The results demonstrated that the multi-objective approach provided the optimal solution, ensuring a fair profit for all parties involved.

The findings of this study highlight the importance of considering multiple objectives when designing energy management frameworks for distributed energy systems.

This approach ensures the optimal utilization of renewable energy sources, promotes sustainability and provides a significant economic advantage to both the EV and PV systems. Overall, the proposed framework offers a promising solution for future energy management systems that prioritize sustainability and profitability for all stakeholders involved.

# NOMENCLATURE

| | |
|---|---|
| **Sets and Indices:** | |
| $t$ | Time period. |
| $i$ | Numbers of Electric vehicles. |
| $p$ | Number of parking lots. |
| **Parameters:** | |
| $C_{elec_t}$ | Utility selling price of electricity [C$/kWh]. |
| $C_{deg}$ | Cost of Battery degradation [C$/kWh]. |
| $C_{pv}$ | Levelized Cost of Energy (LCOE) [C$/kWh]. |
| $C_{Fit}$ | Cost of feed-in tariff [C$/kWh]. |
| $SOC_{i,p}^{arr}$ | EV's SoC Arrival [%]. |
| $SOC_{i,p}^{dept}$ | EV's SoC Departure [%]. |
| $T_{i,p}^{Arrv}$ | Arrival time of EV [hr]. |
| $T_{i,p}^{Dept}$ | Departure time of EV [hr]. |
| $SOC_{Min}$ | Minimum State of Charge of battery [%]. |
| $SOC_{Max}$ | Maximum State of Charge of battery [%]. |
| BC$i$ | Battery capacity of EV [kWh]. |
| $\eta_{dc-dc}$ | DC-DC converter efficiency [%]. |
| $\eta_{inv}$ | DC-AC inverter efficiency [%]. |
| $P_t^{pv}$ | PV output power [kW]. |
| $P_{pv}^{Max}$ | Maximum PV power [kW]. |
| $P_{i,t}^{Max\,ch}$ | EV's maximum charging power [kW]. |
| $P_{i,t}^{Max\,dsch}$ | EV's maximum discharging power [kW]. |
| $\eta_{ch}$ | EV charging efficiency [%]. |
| **Variables:** | |
| $C$ | Total cost which includes the proposed system and grid satisfaction [C$]. |
| $C_{tot}$ | Total cost for PV and parking lots [C$]. |
| $C_g$ | Grid satisfaction cost [C$/. |
| $P_{i,t,p}^{g2v}$ | Power transfer from grid to EV [kW]. |
| $P_{i,t,p}^{pv2ev}$ | Power transfer from PV to EV [kW]. |
| $P_{i,t,p}^{v2g}$ | Power transfer to grid from EV [kW]. |
| $P_{t,p}^{pv2g}$ | Power transfer from PV to grid [kW]. |
| $SOC_{i,t,p}$ | SoC of EV [%]. |
| $P_{i,t,p}^{EV}$ | EV 's total power transfer [kW]. |

# References

1. J. Soussan, The Mitigation of Climate Change. 2017. doi: 10.4324/9781351297967-12.
2. M. Larsson, Global energy transformation: Four necessary steps to make clean energy the next success story. 2009. doi: 10.1057/9780230244092.
3. A. ur Rehman, M. Ali, S. Iqbal, A. Shafiq, N. Ullah, and S. Al Otaibi, "Artificial Intelligence-Based Control and Coordination of Multiple PV Inverters for Reactive Power/Voltage Control of Power Distribution Networks," Energies, vol. 15, no. 17, 2022, doi: 10.3390/en15176297.
4. S. Aznavi, P. Fajri, M. B. Shadmand, and A. Khoshkbar-Sadigh, "Peer-to-Peer Operation Strategy of PV Equipped Office Buildings and Charging Stations Considering Electric Vehicle Energy Pricing," IEEE Trans. Ind. Appl., vol. 56, no. 5, pp. 5848–5857, 2020, doi: 10.1109/TIA.2020.2990585.
5. IRENA, "Electric-Vehicle Smart Charging: Innovation Landscape Brief," Innov. Landsc. Br. Electr. smart Charg. Int. Renew. Energy Agency, Abu Dhabi., pp. 1–24, 2019, [Online]. Available: www.irena.org
6. Q. Cheng et al., "A Smart Charging Algorithm Based on a Fast Charging Station Without Energy Storage System," vol. 7, no. 4, pp. 850–861, 2021, doi: 10.17775/CSEEJPES.2020.00350.
7. M. E. Kabir, S. Member, and C. Assi, "Optimal Scheduling of EV Charging at a Solar Power-Based Charging Station," pp. 1–11, 2020.
8. A. Verma and B. Singh, "Multimode Operation of Solar PV Array , Grid , Battery and Diesel Generator Set Based EV Charging Station," vol. 9994, no. c, 2020, doi: 10.1109/TIA.2020.3001268.
9. Y. Li and J. Wu, "Optimum Integration of Solar Energy With Battery Energy Storage Systems," pp. 1–11, 2020.
10. C. Leone, C. Peretti, A. Paris, and M. Longo, "Photovoltaic and battery systems sizing optimization for ultra-fast charging station integration," J. Energy Storage, vol. 52, no. PC, p. 104995, 2022, doi: 10.1016/j.est.2022.104995.
11. R. Patnaik and S. Mopidevi, "A technological overview & design considerations for developing electric vehicle charging stations," J. Energy Storage, vol. 43, no. September, p. 103225, 2021, doi: 10.1016/j.est.2021.103225.
12. Q. Guo, H. Zhou, W. Lin, and S. Nojavan, "Risk-based design of hydrogen storage-based charging station for hydrogen and electric vehicles using downside risk constraint approach," J. Energy Storage, vol. 48, no. August 2021, p. 103973, 2022, doi: 10.1016/j.est.2022.103973.
13. F. Ahmad, M. Khalid, and B. Ketan, "An enhanced approach to optimally place the solar powered electric vehicle charging station in distribution network," J. Energy Storage, vol. 42, no. August, p. 103090, 2021, doi: 10.1016/j.est.2021.103090.
14. X. Zhong, W. Zhong, Y. Liu, C. Yang, and S. Xie, "Cooperative operation of battery swapping stations and charging stations with electricity and carbon trading," energy, vol. 254, p. 124208, 2022, doi: 10.1016/j.energy.2022.124208.
15. A. Mohammad, R. Zamora, and T. T. Lie, "Transactive Energy Management of PV-Based EV Integrated Parking Lots," pp. 1–9, 2020, doi: 10.1109/JSYST.2020.3043327.

16. E. Summary, “RENEWABLE POWER GENERATION COSTS IN 2021,” pp. 1–4, 2021.
17. ONTARIO ENERGY BOARD, https://www.oeb.ca/consumer-information-and-protection/electricity-rates
18. solar electricity handbook, http://www.solarelectricityhandbook.com/canada-feed-in-tariff.html