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Şebeke Entegreli Elektrikli Araç ve Hidrojenli Araçları İçeren Otoparklar İçin Karbon Vergisi Odaklı Optimal Enerji Yönetimi

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Öz

Bu çalışma, fotovoltaik (PV) üretimi, elektrikli araçlar (EV) ve yakıt hücreli elektrikli araçlar (FCEV) içeren şebeke bağlantılı bir otoparkın optimal enerji yönetimini ele almaktadır. Otopark, EV'lerin şarj taleplerine cevap verecek şekilde donatılmış olup park alanındaki elektrolizör aracılığıyla FCEV'ler için hidrojen üretimi sağlanmaktadır. Hem EV şarj gücü hem de elektrolizör talebi, PV sisteminden, enerji depolama sisteminden (ESS) veya elektrik şebekesinden esnek bir şekilde karşılanabilmektedir. Çalışmanın temel amacı, karbon vergisinin etkisini de dikkate alarak toplam işletme maliyetlerini en aza indirmektir. Karbon vergisinin dahil edilmesiyle birlikte, önerilen optimizasyon çerçevesi araç şarjı ve hidrojen üretimi süreçlerinde emisyonların azaltılmasını doğal olarak hedeflemektedir. Optimizasyon problemi, Karmaşık Tamsayılı Doğrusal Programlama (MILP) modeli olarak formüle edilmiş ve GAMS programı kullanılarak uygulanmıştır. Çözüm, CPLEX çözücüsü ile elde edilmiştir. Elde edilen sonuçlar, PV enerji üretimi, şebeke elektriği kullanımı, EV şarj zamanlamaları ve hidrojen üretiminin optimal şekilde eşgüdümüyle önerilen yöntemin maliyetleri düşürmede ve emisyonları azaltmada etkili olduğunu doğrulamaktadır. Sonuçlara göre karbon emisyonundan ve karbon vergisinden %21.63 kar edilmiştir.

Anahtar kelimeler: Karbon vergisi, Şarj istasyonları, Enerji yönetimi, Hidrojenli araçlar, Optimizasyon.

*Yazışılan Yazar

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Carbon Tax-Aware Optimal Energy Management for Grid-Integrated Parking Facilities with Electric and Fuel Cell Vehicles Supported by PV Generation

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Abstract

This study addresses the optimal energy management of a grid-connected parking lot integrating photovoltaic (PV) generation, fuel cell electric vehicles (FCEVs) and EVs. The parking area is equipped to meet the charging demands of EVs, and hydrogen is produced for FCEVs via an electrolyzer located within the parking area. Both EV charging power and electrolyzer demand can be met flexibly from the PV system, energy storage system (ESS) or the electrical grid. The objective is to minimize total operational costs while incorporating the impact of carbon taxation. Due to the inclusion of carbon taxes, the proposed optimization framework inherently aims to reduce emissions during vehicle charging and hydrogen production processes. To address the problem, a mixed-integer linear programming-based optimization model is constructed and executed within the GAMS platform. The solution is obtained with the CPLEX solver. Results confirm that the proposed methodology effectively achieves cost reduction and emission mitigation by optimally coordinating PV energy generation, grid electricity usage, EV charging schedules, and hydrogen production. According to the results, a 21.63% saving was achieved in carbon emissions and carbon tax.

Keywords: Carbon tax, Charging stations, Energy management, Hydrogen vehicles, Optimization

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Nomenclature

Sets

t	Time horizon set
m	Electric vehicle fleet set
e	Fuel-cell vehicle set
d	Set of hydrogen requirements for hydrogen vehicles

Parameters

t^{tot}	Total time [h]
CE^{ESS}	Energy conversion efficiency of ESS during charging
DE^{ESS}	Discharge conversion efficiency
CR^{ESS}	Charge power limit of ESS
DR^{ESS}	Discharge power limit of ESS
$SoE^{ESS,init}$	Initial energy level stored in the ESS [kWh]
$SoE^{ESS,max}$	Upper limit of energy capacity for the ESS [kWh]
$SoE^{ESS,min}$	Minimum state of energy for ESS [kWh]
$\beta_t^{sell,gr}$	Electricity selling price to the grid during period t[₺]
F^{tax}	Carbon emission tax rate [₺/kg]
$n^{H_2,st/P_{init}}$	Initial hydrogen quantity in the tank [kg]
$n^{H_2,cap/P}$	Maximum hydrogen tank capacity [kg]
$n^{H_2,st/P_{min}}$	Minimum hydrogen storage level [kg]
P_t^{PV}	PV power output during period t [kW]
$\beta_t^{buy,gr}$	Electricity purchase price from the grid during period t [₺]
$SoE_m^{EV,max}$	Maximum state of energy for EVs [kWh]
CR_m^{EV}	Charging rate of EVs [kW]
CE_m^{EV}	Charging efficiency of EVs
$SoE_m^{EV,init}$	Initial state of energy for EVs [kWh]
$SoE_m^{EV,dem}$	Minimum required energy level for EVs [kWh]
$T_m^{d,EV}$	Departure time of EVs from the parking area
C_t^{gr}	Carbon emissions coefficiency of the grid during period t [kg/kWh]
$D_{t,d}^{H_2}$	Hydrogen demand of hydrogen vehicles over time period t [kg]
$T_m^{a,EV}$	Arrival time of EVs from the parking area.

Variables

P_t^{gr}	Net power exchange with the grid during period period t [kW]
$P_t^{gr,buy,ESS}$	Power ımported from the grid for ess charging at time t [kW]
$P_t^{gr,sell,ESS}$	Power exported to the grid from ESS at time t [kW]
$P_t^{PV,use,gr}$	Amount of power produced in PV and sold to the grid during period t [kW]
$P_t^{PV,use,ESS}$	Amount of power produced in the PV and given to the ESS [kW]
$P_t^{ESS,chg}$	Power supplied to the ESS for charging at time t [kW]
$P_t^{ESS,disch}$	Power extracted from the ESS through discharging at time t [kW]
SoE_t^{ESS}	State of energy for ESS in period t [kWh]
$P_{m,t}^{EV,fr,gr}$	Power drawn from the grid for EVs during time interval t [kW]
$P_{m,t}^{EV,fr,PV}$	Power drawn from PV for EVs during time interval t [kW]
$P_{m,t}^{EV,fr,ESS}$	Power drawn from ESS for EVs during time interval t [kW]
$SoE_{m,t}^{EV}$	State of energy for EVs in period t [kWh]
$P_{m,t}^{EV,chg}$	Power required to charge EVs during time interval t [kW]

u_t^{ESS}	Binary variables for ESS
$cost^{min}$	Minimum total cost [₺]
P_t^{elk}	Electrical power consumed by the electrolyzer during period t[kW]
N_t^{elk,H_2}	The amount of pressure caused by hydrogen gas in the hydrogen tank in period t [kg]
$P_t^{H_2}$	Hydrogen tank pressure in time *t* [bar]
$cost_t^{crb}$	Total cost of carbon emissions [₺]
C_t^{tax}	Carbon emission coefficient of the grid at time *t* [kWh/kg]
$P_t^{gr,sell}$	Electrical power sold by the grid during the time period *t* [kW]
$P_t^{ESS,elk}$	Power supplied by the ESS to the electrolyzer over the time interval *t* [kW]
$P_t^{PV,elk}$	Electricity generated by the PV system and directed to the electrolyzer at time *t* [kW]
$P_t^{gr,elk}$	Grid-supplied electricity used by the electrolyzer during time interva *t* [kW]
$P_t^{elk,\boldsymbol{capacity}}$	Maximum capacity of electrolyzer [kW]

1. Introduction

1.1. Research motivation and related works

The transportation sector plays a major role in global greenhouse gas emissions, contributing approximately one-third of energy-related CO_2 emissions in nations like the United States [1]. The health risks and climate threats associated with CO_2 emissions have led policymakers to implement various strategies that promote the adoption of environmentally friendly vehicles and discourage the use of conventional fossil-fuel cars through financial mechanisms such as carbon taxation [2]. The urgency to reduce carbon emissions in transportation has been widely recognized in global frameworks such as the Paris Agreement and COP26, both of which promote electric vehicles (EVs) as a central solution for achieving carbon neutrality by 2040 [3]. However, according to estimates by the International Energy Agency, transportation-related emissions could increase by 50% globally by 2050 if no effective mitigation measures are implemented [4]. In parallel, the deployment of distributed energy resources—such as photovoltaic (PV) systems and battery energy storage systems (ESSs)—has gained significant momentum, driven by rapid technological advancements and growing environmental awareness [5].

Recent solar energy and electromobility advancements have opened up new opportunities, particularly for integrated solutions and applications. When energy storage systems are incorporated into PV-based charging infrastructures, they enable effective and efficient management of supply-demand balance while stabilizing the system by absorbing excess solar production [6-7]. These systems contribute to a higher share of renewables in the energy sector while allowing EVs to be charged during peak times with solar energy that was stored earlier. This helps to reduce the strain on the grid and provides an effective way to minimize grid dependency. Thanks to this mutually beneficial relationship between the PV sector and electromobility, sudden fluctuations in electricity prices can be mitigated, helping to avoid scenarios of negative pricing [8-10].

In recent years, the alignment of carbon pricing and energy market mechanisms with carbon markets has become a frequently discussed topic in power system planning, leading to active policies in many countries. For instance, China officially launched its national carbon trading market in 2021 [11] to regulate emissions and establish emission limits. In Türkiye, efforts toward carbon pricing have been ongoing since 2013 and are in line with the 2053 Net Zero Emissions and Green Development targets. By 2020, the Emissions Trading System was identified as the most appropriate pricing mechanism [12]. Academic research, a key driver in shaping these policies, has shown that integrating energy and carbon markets leads to more sustainable and economically efficient operations.

This has led to a growing body of literature focusing on the optimal management of charging and refueling operations at stations serving electric and hydrogen vehicles in a way that reduces carbon emissions, further enriching our understanding of these complex systems. For example, the study in [13] investigated how EV owners could benefit from bidirectional charging, with a particular focus on how these advantages change depending on electricity prices, grid tariffs, and support mechanisms for energy pricing. A cost minimization problem was formulated to analyze the benefits of discharging EV batteries to the grid. However, there is no evaluation based on carbon taxation, and hydrogen-powered vehicles have not been considered in that analysis.

A multi-period distribution system expansion model was proposed in [14], where uncertainties in demand growth, renewable generation, EV load, and energy prices were addressed using a CVaR-based approach to minimize investment, operational, and carbon-related risks. The model enabled optimal planning of DERs, EV charging stations, and storage systems under carbon tax and budget constraints. Gong et al. proposed [15] a coordinated planning approach for low-carbon distributed energy stations by modeling the spatial-temporal charging behaviors of four EV types using Monte Carlo simulations and integrating PV and power-to-gas systems under a stepped carbon trading mechanism. In [16], the problem of selecting the optimal power level for a single EV charging station, considering carbon tax and computational energy constraints, was formulated as a cost and delay minimization task. A Multi-Agent Deep Deterministic Policy Gradient algorithm was employed to address dynamic user behaviors, resulting in reduced charging costs, CO_2 emissions, and load imbalance across stations. In [17], a mixed-integer linear programming model (MILP) was proposed for a charging network operator managing geographically distributed EV charging stations, where electricity market costs, carbon taxes, and reserve market incentives are jointly considered to maximize operational profit. However, the studies did not consider fuel cell electric vehicles (FCEVs) [14-17], or the integration of DERs [16-17] which limits its applicability in comprehensive low-carbon transportation and energy management systems.

The study in [18] introduced a carbon footprint evaluation method that accounts for spatial and temporal variations in electricity generation. By incorporating a carbon integration mechanism aligned with green electricity trading, the Authors enabled the identification of low-carbon charging routes, encouraging environmentally sustainable EV usage and supporting the transition to carbon-neutral mobility. In [19], Zhang et al. developed an optimization framework for managing the operation of integrated photovoltaic–storage–charging stations by simultaneously considering electricity and carbon market dynamics. The study utilized game-theoretic modeling to represent the strategic interaction between charging station operators and EV users, with the objective of maximizing overall revenue, reducing load variability, and improving user satisfaction. A ladder-based carbon trading scheme was incorporated into the model, and a genetic algorithm was applied to derive optimal solutions. In [20], the authors explored the integration of decentralized EVs into the carbon trading framework, with the goal of mitigating peak-valley load disparities and promoting coordinated charging behavior. To this end, a two-level Stackelberg game model was formulated: the upper-level problem sought to optimize the revenue of a centralized EV aggregator, while the lower-level model aimed to minimize the charging expenses of individual EV users. Li et al. [21] proposed an optimal scheduling strategy for a coupled electric-hydrogen energy system involving both EVs and hydrogen-powered vehicles. Their model incorporated Vehicle-to-Grid (V2G) operations along with carbon market participation, enabling dynamic coordination between energy exchange and environmental policy constraints. The model addressed renewable energy uncertainties using Latin hypercube sampling and scenario reduction. While the scenario-based modeling approach enhances theoretical robustness, its computational intensity might hinder real-time or large-scale practical deployment.

Another study by the author, presented in [22], proposed a real-time optimization model for managing a multi-energy system integrating combined heat and power units, heat pumps, renewable sources, and hydrogen-based technologies to meet the electricity, heating, cooling, and transportation demands. While it successfully reduced grid dependency through local renewable use and optimized hydrogen logistics, it did not consider participation in carbon markets, which limits its applicability in carbon-constrained policy environments.

In their study, Yadav et al. employed nonlinear cointegration analyses to examine how carbon taxation and electricity price fluctuations affect the demand for gasoline, diesel, and EVs in India's road transport sector [23]. Using an agent-based evolutionary game model, Huang et al. explored how policies such as carbon taxes influence investment decisions in electric vehicle charging stations [24]. Focusing on the growing integration of electric vehicles with traffic and power distribution networks, Qiao et al. developed a bi-level game-theoretic model combined with a decentralized algorithm to minimize charging costs through carbon-tax-based pricing [25].

1.2. Contributions and organization of the study

This study provides key contributions to advancing a sustainable energy and transportation system.

- First, it introduces a MILP-based optimization model that jointly manages EV charging operations and hydrogen refueling processes for FCEVs at a grid-connected station. Unlike many previous studies, this study brings together two different vehicle types under a single framework, contributing to cleaner mobility and zero-emission goals through coordinated energy management.
- Second, carbon taxation is directly included in the cost function, allowing for a more realistic evaluation of policies and their economic impact. This makes the study stand out from many previous works that typically focus only on traditional energy markets, overlooking the cost of carbon emissions. In addition, using PV systems and ESSs together as distributed sources allows for a more flexible and efficient operation. By supporting charging and hydrogen production with green technologies, the model promotes a cleaner and more resilient operation overall.

The structure of the remaining sections is as follows. Section 2 introduces the mathematical background of the proposed energy management model—developed with consideration for carbon taxation—is introduced. Section 3 provides a detailed discussion of the simulation results and evaluates the model's effectiveness through numerical analysis. Finally, Section 4 concludes the study by summarizing the main outcomes.

2. Methodology

In this study, an optimization model has been developed aiming to minimize costs at a station used by EVs and hydrogen FCEVs. The model considers the electrolyzer process for hydrogen production, PV generation at the station, the ESS, and the carbon taxation system.

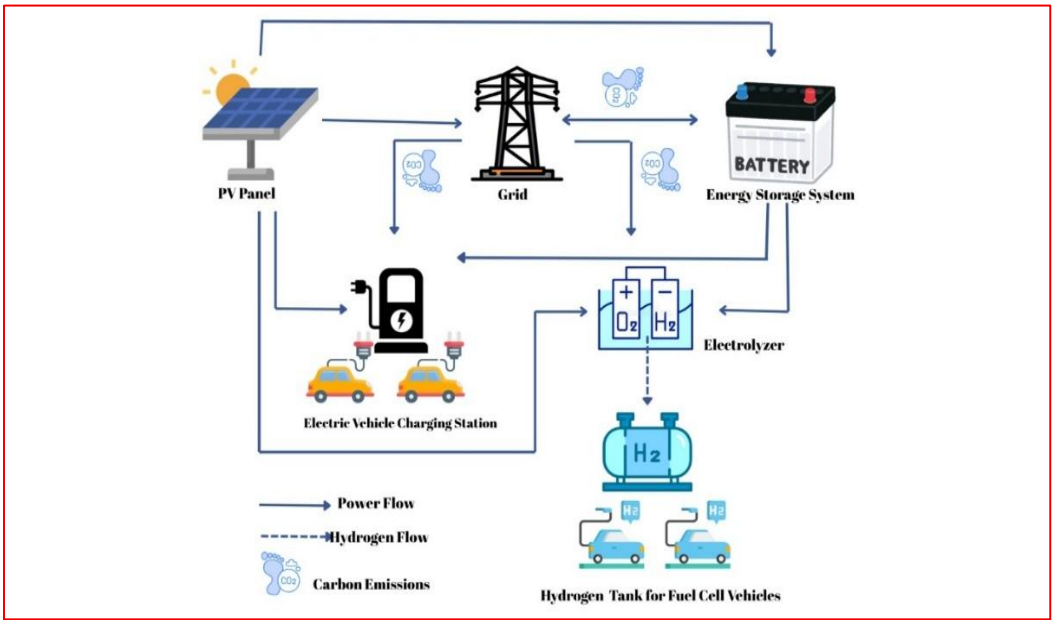

Figure 1. The schematic of carbon tax-aware optimal energy management system

As illustrated in Figure 1, the electricity required for both vehicle charging and hydrogen production is supplied from three sources: the grid, PV generation, and the ESS. A time-based constraint ensures that EVs are charged within their designated arrival and departure time slots.

For hydrogen FCEVs, the electrolyzer produces hydrogen using electricity drawn from the available sources. The model also accounts for the time-varying carbon emission factor of the grid and evaluates the financial impact of carbon taxation. The overall objective is to minimize the total electricity-related costs.

2.1. Input

In the proposed model, the vehicle parking area has a capacity of 50 EVs. A total of 25 AC charging ports are available. The parameters related to EVs are provided in Table 1.

Table 1. Specifications of EV

Charging Efficiency	Battery Capacity [kWh]	AC Charging Rate [kW]
0.96	50	7.2

The capacity of the PV system installed at the parking facility was selected considering both the expected daily energy demand of the EVs and the hydrogen production requirements of the electrolyzer. The power generation of the PV system located in the parking area is presented in Figure 2.

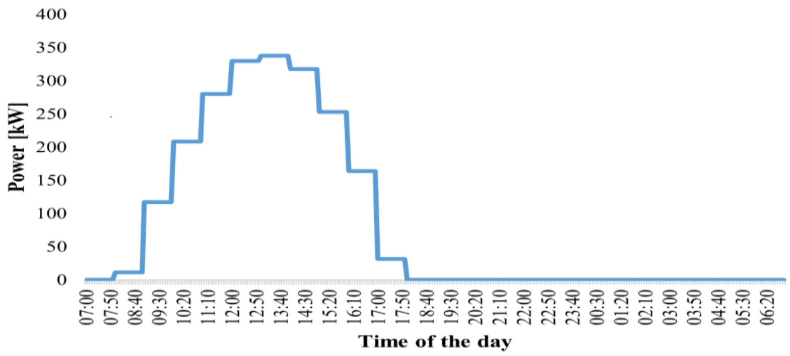

Figure 2. Power generation of PV

The parking area is also equipped with an ESS, and its parameters are given in Table 2.

Table 2. Specifications of ESS

Charging/Discharging Efficiency	Charging/Discharging Rate [kW]	Battery Capacity [kWh]
0.95	25	100

An electrolyzer and a hydrogen tank are installed to support the charging operations of FCEVs. The capacity of the electrolyzer was set at 510 kW to meet the hydrogen demand of the FCEVs.

Moreover, the grid electricity selling price is illustrated in Figure 3. The price of electricity sold to the grid is 0.32 TL.

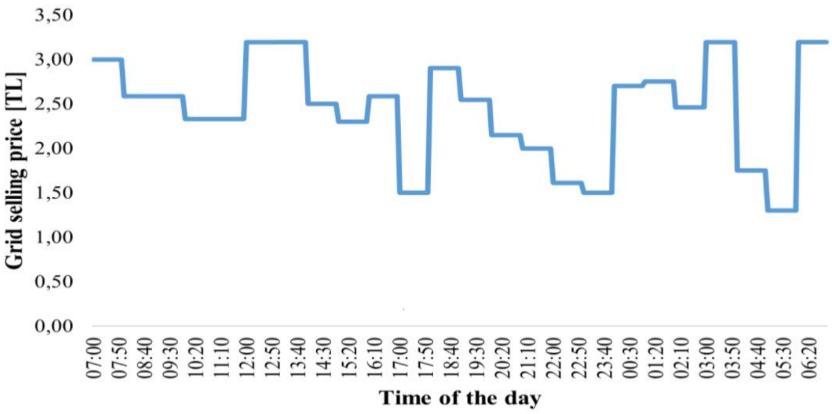

Figure 3. Energy selling price of grid

The carbon tax corresponding to the energy production in 5-minute intervals over a day is presented in Figure 4 according to open access data.

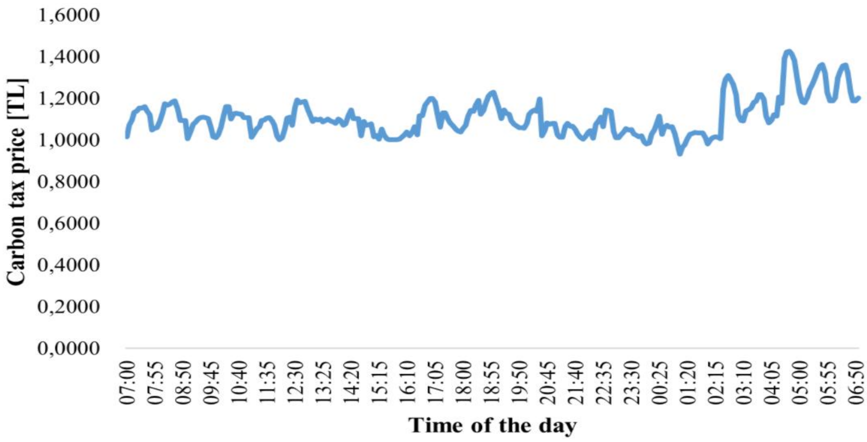

Figure 4. Time-dependent carbon tax pricing profile applied to grid electricity during the simulation period

2.2. Mathematical model of proposed scheme

$$cost^{min} = \sum_t \left(\sum_m \left(P_{m,t}^{EV,fr,gr} + P_t^{gr,buy,ESS} + P_t^{gr,elk} \right) \cdot DT \cdot \beta_t^{buy,gr} \right) + \sum_t cost_t^{crb} - \sum_t \left(P_t^{PV,use,gr} + P_t^{gr,sell,ESS} \right) \cdot DT \cdot \beta_t^{sell,gr} \quad (1)$$

The primary objective is to minimize the overall electricity expenditure, accounting for both the carbon tax imposed on grid-supplied electricity and the revenue generated from feeding electricity back into the grid. This objective is mathematically expressed in Equation (1).

$$P_t^{gr,sell} = P_t^{gr,sell,ESS} + P_t^{PV,use,gr} \quad (2)$$

$$P_t^{PV} = P_t^{PV,use,gr} + P_t^{PV,use,ESS} + \sum_m \left(P_{m,t}^{EV,fr,PV} \right) + P_t^{PV,elk} \quad (3)$$

$$P_t^{gr} = P_t^{gr,buy,ESS} + \sum_m \left(P_{m,t}^{EV,fr,gr} \right) + P_t^{gr,elk} \quad (4)$$

$$cost_t^{crb} = P_t^{gr} . C_t^{gr} . F^{tax} \quad (5)$$

As expressed in Equation (2), the total electricity fed into the grid at time t is determined by the combined contribution of energy discharged from the ESS and that generated by the PV system during the same interval. Equations (3) and (4) describe how the available electricity at time t is allocated, with respect to its origin—either from the PV system or the grid. In turn, Equation (5) quantifies the carbon tax by considering the amount of grid-supplied electricity consumed at time t, along with the associated emission factor for that period.

$$P_{m,t}^{EV,fr,gr} + P_{m,t}^{EV,fr,PV} + P_{m,t}^{EV,fr,ESS} = P_{m,t}^{EV,chg} \tag{6}$$
$$P_{m,t}^{EV,chg} \leq CR_m^{EV}, \forall t, T_m^{a,EV} < t \leq T_m^{d,EV} \tag{7}$$
$$P_{m,t}^{EV,chg} = 0, t < T_m^{a,EV}, t > T_m^{d,EV} \tag{8}$$
$$SoE_{m,t}^{EV} = 0, t < T_m^{a,EV}, t > T_m^{d,EV} \tag{9}$$
$$SoE_{m,t}^{EV} = SoE_m^{EV,init}, \text{if } t = T_m^{a,EV} \tag{10}$$
$$SoE_{m,t}^{EV} = SoE_{m,(t-1)}^{EV} + CE_m^{EV} \cdot P_{m,t}^{EV,chg} \cdot DT, \forall t, T_m^{a,EV} < t \leq T_m^{d,EV} \tag{11}$$
$$SoE_{m,t}^{EV} = SoE_m^{EV,dem}, \text{if } t = T_m^{d,EV} \tag{12}$$
$$SoE_{m,t}^{EV} \leq SoE_m^{EV,max} \tag{13}$$

Equation (6) represents the total power used to charge the EVs at time t, injected from the grid, ESS, and PV system. Equations (7) and (8) ensure that the EV is only charged during its stay at the station, while Equations (9) to (13) calculate the battery's State of Energy (SoE), enforce the required SoE at the time of departure, and set the upper bounds.

$$P_t^{PV,use,ESS} + P_t^{gr,buy,ESS} = P_t^{ESS,chg} \tag{14}$$
$$\sum_m \left(P_{m,t}^{EV,fr,ESS}\right) + P_t^{gr,sell,ESS} + P_t^{ESS,elk} = P_t^{ESS,disch} \tag{15}$$
$$P_t^{ESS,chg} \leq CR^{ESS} \cdot u_t^{ESS} \tag{16}$$
$$P_t^{ESS,disch} \leq DR^{ESS} \cdot (1 - u_t^{ESS}) \tag{17}$$
$$SoE_t^{ESS} = SoE^{ESS,init}, \text{if } t = 1 \tag{18}$$
$$SoE_t^{ESS} = SoE_{t-1}^{ESS} + CE^{ESS} \cdot P_t^{ESS,chg} \cdot DT - \frac{P_t^{ESS,disch} \cdot DT}{DE^{ESS}}, \text{if } t > 1 \tag{19}$$
$$SoE_t^{ESS} \leq SoE^{ESS,max} \tag{20}$$
$$SoE_t^{ESS} \geq SoE^{ESS,min} \tag{21}$$

Equations (14) and (15) define the sources of ESS charging and the distribution of discharged power for each station. Equations (16) and (17) together ensure that the station's ESS cannot charge and discharge simultaneously at time t. Equations (18) and (19) calculate the ESS's SoE, while Equations (20) and (21) ensure that the SoE stays within capacity limits.

$$P_t^{elk} = P_t^{gr,elk} + P_t^{PV,elk} + P_t^{ESS,elk} \tag{22}$$
$$P_t^{elk} \leq P_t^{elk,capacity} \tag{23}$$
$$P_t^{elk} \geq 0 \tag{24}$$
$$N_t^{elk,H_2} = \frac{0.9 \times P_t^{elk}}{240} \times 3.6 \times DT \tag{25}$$
$$P_t^{H_2} = P_{t-1}^{H_2} + K \times \frac{N_t^{elk,H_2} - D_{t,d}^{H_2}}{2}, if\ t > 1 \tag{26}$$

Equations (22) and (23) constrain the power consumed for electrolysis within the electrolyzer's capacity limits. Equation (24) determines the total power input to the electrolyzer at time t. Equation (25) calculates the total molar amount produced by the electrolyzer. Equation (26) calculates the hydrogen tank pressure at time t based on the amount of hydrogen produced at time t and the tank pressure at time $(t-1)$.

3. Test and Results

In the proposed model, PV and ESS are integrated into EV parking lot operating under a carbon taxation scheme, with the aim of minimizing its operational costs. The system also includes hydrogen-powered vehicles, for which an electrolyzer is incorporated to supply the necessary hydrogen fuel. A detailed cost analysis is conducted for the entire system, explicitly incorporating the effects of carbon taxation. The formulated optimization problem is solved using the MILP method within the GAMS environment. All time references in this paper are provided using the 24-hour clock format for consistency and clarity.

As a result of the simulations, the graph illustrating the power balance in the ESS is presented in Fig. 5. As shown in Figure 5, the ESS is charged from the grid during the hours of 17:00–18:00 and later at night, when the grid selling prices are low. The energy drawn from the grid during these low-price periods is then utilized for operating the electrolyzer and charging EVs. As also observed from the graph, the ESS is predominantly charged from the grid, as the PV generation is mainly reserved for operating the electrolyzer and charging the EVs.

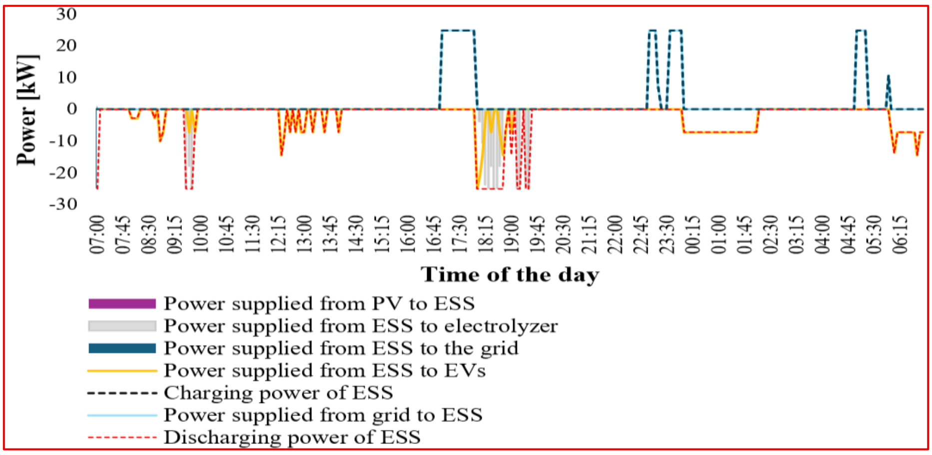

Figure 5. General power balance of the system over time

As shown in Figure 6, the charging profile of EVs indicates that during periods of PV generation, the vehicles are primarily charged using PV power. Furthermore, during certain hours when PV generation is insufficient due to increased demand from the electrolyzer, the ESS also contributes to vehicle charging. In hours without PV generation, the EVs are supplied by both the grid and the ESS. Notably, during periods of high grid prices—such as between 00:00 and 02:05—the ESS supplies the vehicles, whereas before 00:00, when the grid price is lower, the vehicles are charged directly from the grid.

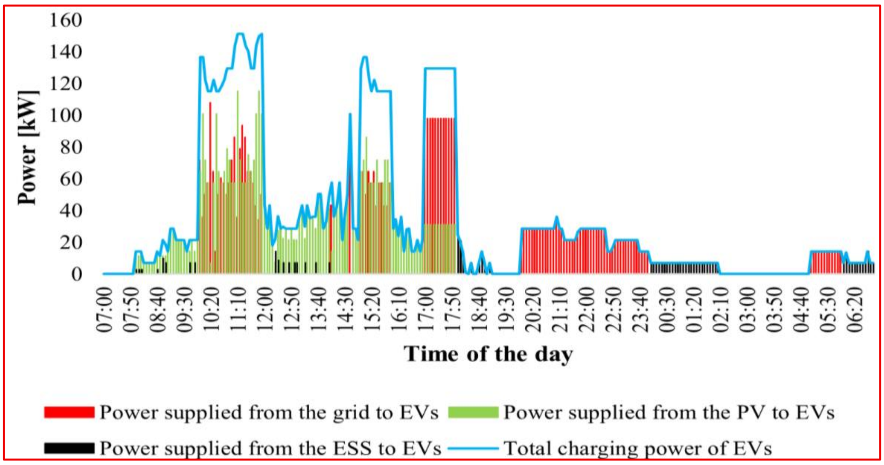

Figure 6. Battery charging and discharging status over time

As illustrated in Figure 7, the power profile of the electrolyzer shows that the majority of its energy demand is met by PV and the grid. Due to the limited capacity of the battery, the contribution from the ESS remains relatively low. During the peak hydrogen demand period between 09:35 and 09:45, when PV generation is insufficient, the remaining energy required by the electrolyzer is supplemented by both the battery and the grid.

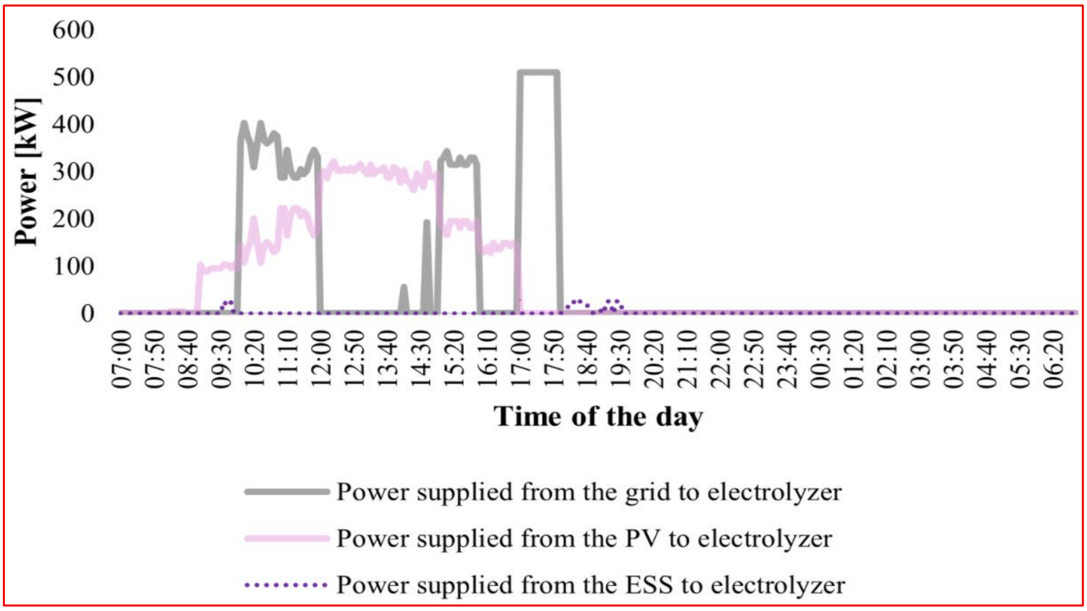

Figure 7. Electrolyzer power balance over time

The load profile of the PV system is shown in Figure 8. The graph indicates that the PV generation is used entirely for powering the electrolyzer and charging EVs. There is no energy sold to the battery or the grid. This is mainly because there is a constant energy demand, and selling electricity to the grid offers low returns. As a result, feeding energy into the grid and then meeting the loads later from the grid would be more costly.

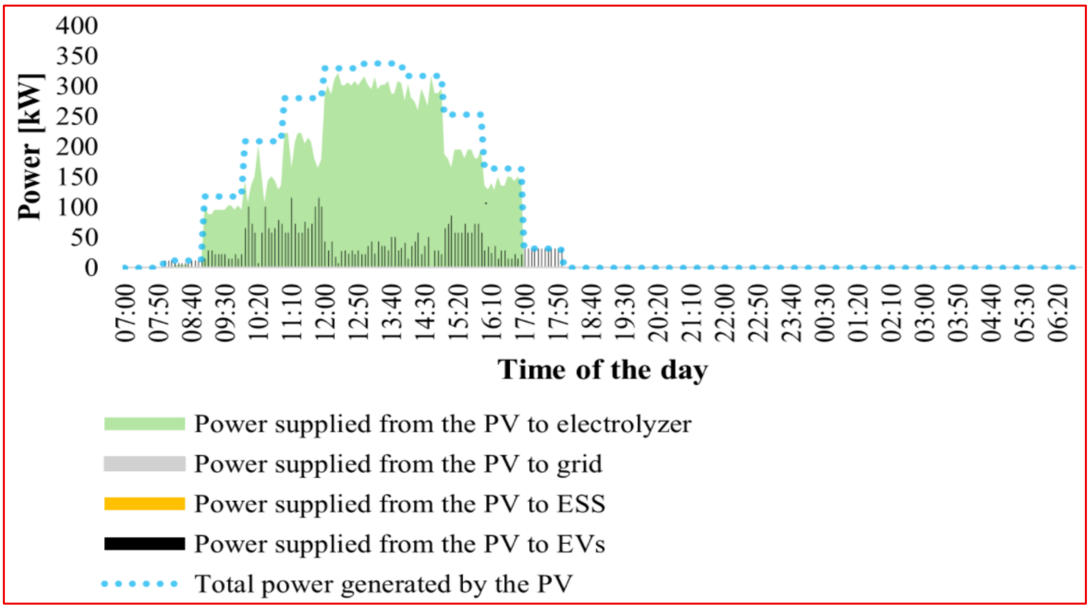

Figure 8. PV system power balance over time

The graph showing the power imported from and exported to the grid is presented in Figure 9. As seen, the only instance of energy being sold to the grid occurs at 07:00, when there is no power demand from the electrolyzer or EVs, and the ESS discharges to the grid. No further grid export is observed after this point. During other time intervals, particularly when PV generation is available, less energy is drawn from the grid. Additionally, the ESS is charged from the grid between 22:45 and 23:45, when carbon emissions—and therefore the carbon tax—are relatively low. Grid electricity prices also influence this behavior. In hours with no demand from hydrogen FCEVs or EVs, no grid transactions (neither purchase nor sale) are carried out due to the combined effects of high electricity prices and carbon taxation.

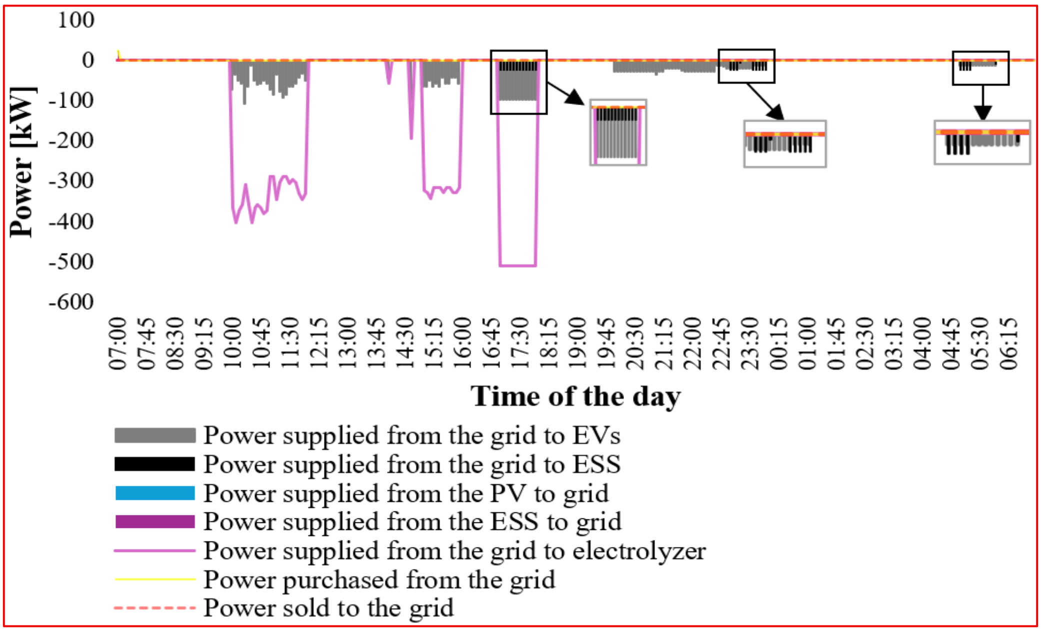

Figure 9. Power balance of the grid over time

4. Conclusion

In this study, a comprehensive cost-minimization model for a grid-connected parking facility serving both EVs and FCEVs was proposed and analyzed. The system integrates PV generation, an ESS, and an electrolyzer for on-site hydrogen production, all under a carbon taxation framework. The model was formulated as a MILP problem, ensuring accurate representation of operational constraints, energy flows, and carbon tax considerations.

The optimization model was implemented using the GAMS platform and solved via the CPLEX solver. The solution process for the defined scenario, which included a one-day horizon with 5-minute intervals (resulting in 288 time steps), was completed within approximately 22 seconds on a standard workstation (Intel i7 processor, 16 GB RAM). This confirms the computational efficiency of the proposed framework, making it suitable for practical planning purposes.
Simulation results demonstrated the tangible economic and environmental benefits of the proposed model:

- 21.63% reduction in carbon tax costs was achieved compared to a non-optimized baseline scenario, emphasizing the model's effectiveness in lowering emissions through coordinated energy management.
- The PV system supplied 51.58% of the electrolyzer's total energy demand, minimizing grid dependency during high-carbon periods.
- The ESS played a critical role by charging predominantly during low-price, low-emission periods (e.g., between 17:00–18:00) and discharging during high-price periods, supporting both cost savings and carbon reduction.

- The system avoided unnecessary electricity export to the grid, as internal consumption of PV energy was prioritized, which prevented additional costs associated with repurchasing electricity at higher rates.

Furthermore, the model enabled dynamic allocation of power between EV charging and hydrogen production, adapting to time-varying PV output, grid prices, and carbon emission factors. This flexibility allowed the system to maintain continuous energy supply for critical services while reducing operational costs.

In summary, the proposed model not only provided significant cost savings and emission reductions but also demonstrated operational strategies that can contribute to net-zero carbon targets in multi-energy parking facilities. Future studies may enhance the model by incorporating dynamic electricity markets, carbon trading mechanisms, and other regulatory frameworks to further explore its economic and environmental benefits.

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6. Author Contribution Statement

In the conducted work, Author 1 contributed to the formation of the idea, the design, and the analyses; Author 2 contributed to the evaluation of the obtained results and the development of the concept; Author 3 contributed to the interpretation of the results and the writing process; and Author 4 contributed to the literature review, the writing, the development of the modeling, and the interpretation of the results.

7. Ethics Committee Approval and Conflict of Interest

"There is no need for an ethics committee approval for the prepared manuscript."
"There is no conflict of interest with any individual or institution in the prepared manuscript."

8. Ethical Statement Regarding the Use of Artificial Intelligence

No artificial intelligence-based tools or applications were used in the preparation of this study. The entire content of the study was produced by the authors in accordance with scientific research methods and academic ethical principles.

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