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Integration of Electric Vehicle Power Supply Systems—Case Study Analysis of the Impact on a Selected Urban Network in Türkiye

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Abstract: Undoubtedly, the transition to electromobility with several million new, efficient charging points will have consequences for the energy industry, and in particular for network operators of the distribution infrastructure. At the same time, in the coming years the energy landscape will change into a system in which an increase in decentralized systems based on renewable energy sources will take over the leading function. This transformation process will further increase the complexity and overall pressure for change in energy systems over the next decade. In order to be able to ensure the energy supply and the reliable system operation of the grids in the future as well, communicative networking of generators, storage systems, electrical consumers and grid equipment is indispensable. This study aims to investigate the consequences of including electric vehicles in Istanbul's power system using a unit commitment simulation model. The presented considerations analyze how uncertain and managed charging strategies affect the power system in terms of operating costs and renewable resources. The presented simulations indicate that, in economic terms, the use of a managed charging strategy saves 2.3%, reducing the total cost from USD 66.71 million to USD 65.18 million. The recipients of the presented research are both the demand and supply sides of the future energy transformation based on the idea of synergy of electromobility and renewable energy sources within the framework of the smart city idea.

Keywords: electromobility; optimized charging of electric vehicles; power systems; system integration; smart city

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1. Introduction

No researcher doubts that greenhouse gas emissions contribute to climate change, which can have serious consequences for humans and Earth's ecosystems through increased sea and air temperatures and more frequent extreme droughts and floods [1,2]. One way to counteract this change was the Paris Agreement was signed through a UN conference in 2015. The purpose of the Paris Agreement is to work to keep the global temperature increase below 2 °C [3]. One of the countries where this goal has become an important element of energy policy is Türkiye. The country has introduced a series of climate packages, directives and binding targets that aim to minimize greenhouse gas emissions by the end of 2030 and 2050 [4]. It is worth emphasizing the fact that Turkey decided in 2021 that its national net greenhouse gas emissions by 2050 should be zero (Turkey's ambition is to have 100% renewable energy production by 2050, but also to reduce the country's emissions) [5]. As indicated in the literature on the subject, the road transport sector accounts for approximately one-fifth (81 Mt of CO_2e) of Turkey's total national greenhouse gas emissions, calculated as carbon dioxide equivalent [6]. To ensure Turkey's future

sustainable development, the road transport sector must be transformed into climate-neutral transport. To make mobility climate neutral, an energy transformation is necessary. The strategic plan to make the transport sector fossil-free is important to achieve climate goals. Especially since the Turkish government is one of the few in this geographical region that invests in the production of its own electric vehicles.

At this stage of considerations, it is important to emphasize that the development of renewable energy sources is another promising way to achieve decarbonization of the fossil fuel-dominated energy system and several approaches for the optimization of renewable energy system deployment exist in the literature [7]. However, the intermittent nature and volatility of renewable electricity generation present significant challenges to the economic functioning and security of the power system [8]. A decrease in renewable resources is inevitable. Therefore, the process of increasing the share of natural renewable energy and the development of energy-sharing paradigms [9] is of utmost importance.

In 2030, it is expected that there will be 2.5 million electric vehicles and 1 million charging stations will be established in Turkey [10]. In other words, 10% of Turkey's passenger car stock will be electric vehicles in 2030, and one of every two vehicles sold will be electric vehicles. Therefore, electrification of the transport sector is a promising way to address climate goals by accelerating toward sustainable energy sources and increasing energy supply security, especially in urban areas.

In the available literature on the subject [11–17], several researchers have pointed out a key aspect regarding the role of integrating energy networks by connecting electromobility with energy management scenarios. The EV charging demand often has to cope with peak demand and operating costs because it operates expensive power plants capable of handling sudden loads. Some studies [18–20] indicate that if EV charging demand is optimally managed, vehicle grid integration can significantly reduce peak demand, provide power system flexibility, and enable frequency regulation [21]. Based on these, the large-scale use of EVs can facilitate the achievement of the country's renewable energy use target and the integration of electricity generation with mutual benefits locally. Entities with energy storage that supply energy to hybrid or fully electric vehicles can offer competitive prices where the energy comes from renewable sources. This mentioned problem seems to be particularly important in urban areas [22] where integration processes in the area of electromobility take place particularly quickly.

As electric vehicles take increasingly larger market shares, more people are connecting to the electricity grid for charging [15]. In the first stage, however, it is necessary to answer the question: what does the charging infrastructure in Turkey look like today, especially in cities, what types of chargers are used, and does electricity come from renewable sources? The Turkish electricity grid is already burdened in parts of Turkey today, especially in larger cities. In response to this situation, Türkiye is expanding renewable energy sources that are highly dependent on the weather, which can result in periods of higher or lower power load on the electricity grid. How does the electricity grid stand against an electric vehicle fleet, will it need to be strengthened in parts of the country or is it possible to route the power loads in a more efficient and smarter way during less active hours to decrease the load? Hence, there are many questions related to the planned energy transformation and the challenges posed by the new technology, but with it there are also proposals for new model solutions in the network–vehicle–energy relationship.

Currently, no one has any doubts that with the rapid growth of the EV population in the next 6–8 years, EVs could be one of the major load demands for the power system. Connectivity options need to be explored today to meet the required energy demands of a fleet of hundreds of vehicles charging simultaneously. However, there are few studies [23–25] which include analyzes of the energy demand for electric vehicles and energy from regional power plants in relation to large metropolises. Consider that the benefits of managed EV charging can help plan large-scale EV adoption and renewable energy generation [23–25].

The aim of this study is to explore and evaluate the impacts on the city of Istanbul's 2030 electricity system, including power plant operating costs, as part of various electric

vehicle grid integration strategies. The implementation costs of different electric vehicle grid integration strategies has been investigated and the power system costs resulting from the integration of EVs have been calculated. Hourly simulations for regional electricity generation for the Istanbul power system are used in the electric vehicle charging behavior model. The implementation of the presented tasks will allow the development of a model for implementing the integration of electric vehicle energy systems and assessing the impact on selected energy networks in large metropolises as part of the smart city idea.

Analysis of the literature on the subject showed that this is the first approach to this topic involving a description of a given metropolis of Istanbul and referring to real data. Therefore, the presented research has both theoretical and practical dimensions. In short, the presented article brings a new look at the existing literature in the following areas: (I) integration of power grids with electric vehicles, (II) vehicle charging optimization process, (III) flexible load, (IV) use of renewable energy sources in the process of charging electric vehicles in cites, and (V) smart city concept.

The article is organized as follows. Section 1 provides an introduction to the topic. Section 2 contains a detailed description of the materials and methods—a description of the model. Section 3 describes the EV load estimation and charging strategies. Section 4 presents the experimental results and their interpretations—scenario description. Section 5 contains the final conclusions of the research, indicating its limitations, practical application, and future directions of research in this area.

2. Materials and Methods—Research Model

A unit commitment and economic dispatch simulation model is applied to represent the operating rule of the power system whose purpose is to minimize the overall operating costs of power plants to meet the electrical load. Equation (1) is the cost function of the optimization problem including capital costs of power facilities, fixed annual operation and maintenance costs of all power stations, start-up/down costs, fuel (natural gas, coal) costs, and connecting costs for integrating power plants into transmission lines. Figure 1 depicts the schematic representation of the proposed integrated system with the parameters, uncertainties, and optimal decisions. The main objective is to minimize the overall costs of all unit generators to meet the electricity load with the optimal power generation, and integration of battery electric vehicles. In this study, the unit commitment problem, which is a traditional power system economics problem, also has to deal with the scheduling generation which will be examined. It is important to understand the difference between economic dispatch for units and unit commitment. In the economic dispatch problem, a load and a set of generating units producing synchronously online are given to the system. The question sought to be answered is how much each of these production units must produce to meet this load at minimum cost. However, in power systems, the load does not remain constant. It does not need the same number of generating units when the load is small, and this leads to the unit commitment problem. The unit commitment problem is given a set load profile which is the value of a load for each hour of the day. The model tries to answer the question of when each of these power generators should be started, when should it be stopped, and how much should it generate to meet the load at minimum cost.

The model developed in this study serves as a planning tool for the capacity expansion of the power system, integrating the introduction of EVs. It optimizes the augmentation of capacity for electricity generation facilities, taking into account hourly load demand and renewable energy output profiles while satisfying the projected electricity demand for 2030. The temporal analysis for optimization encompasses both weekdays and weekends. Geographically, the model encompasses the entire power system derived from renewable sources. This model simultaneously optimizes investment decisions and operational allocation to minimize the total costs of electricity generation, adhering to multiple constraints such as power balancing and renewable resource limitations, as illustrated in Figure 1. The model presented in this study is a linear programming framework designed to minimize the aggregate of all investment and operational costs. These costs encompass capital expen-

ditures for generators, fixed Operation and Maintenance (O&M) costs for all generators, transmission line expenses, and fuel costs. The model is governed by two principal sets of constraints: system constraints and unit constraints. Additionally, the model integrates carbon emission constraints and the natural resource limitations of renewable energy sources, while also optimizing for EV charging. The inputs for the model data include detailed information about power plants, fuel costs, capital costs associated with production technologies, and assumptions regarding the O&M costs of these technologies. These inputs are based on renewable electricity production profiles. Through this comprehensive approach, the model aims to provide an optimized strategy for capacity expansion and operational efficiency in the power system.

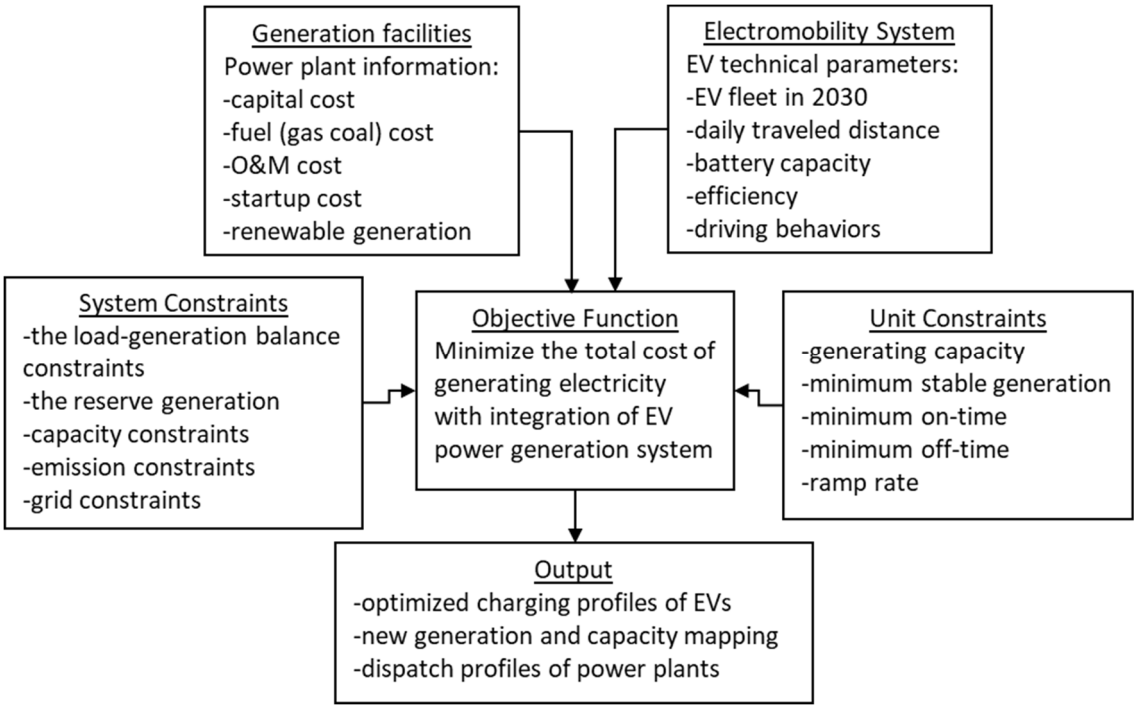


Figure 1. Schematic representations of the proposed system inputs, decisions and uncertainties.

Numerous studies have examined methods to decarbonize the energy sector. For instance, a study [26] proposed the electric road model to decarbonize Turkey's transportation sector, determining that the country could meet its 2045 greenhouse gas emission targets by optimizing its electricity generation mix. They concluded that fostering the development of renewable energy power could significantly reduce national CO_2 emissions. This study proposes a comprehensive evaluation pathway utilizing large-scale electric vehicles to cost effectively support the decarbonization of Turkey's transportation sector. Based on the development trajectory of electric vehicles, this study initially simulates the daily charging profile of EVs and the temporal availability of EVs connected to the grid using the Monte Carlo method. Subsequently, the integration of long-term electric vehicle supply scenarios into the power system under various conditions is examined. Finally, the study assesses the mix of renewable generation capacity, annual costs of the power system, emissions, and the driving distance per EV.

It can make some observations on the basis of power plants. If enough units are not committed to a synchronized system that is ready to generate the power, it will not be able to meet the demand. If there are not enough production units, its demand still can be met, but some of these units may be operating above optimum efficiency points and more money will have to be spent than necessary. On the other hand, if there are too many units committed, some of these units may be operating below optimal economic dispatch. Finally, if there are too many units committed, there will be a problem with minimum

generation because it will exceed the demand, and an impossible combination will occur. Another observation has to do with the no-load costs of the generating units. In economic dispatch, the no-load cost does not affect the optimal dispatch, but it affects the choice of optimal combination.

The approach used must have taken all constraints into account in order to fully resolve the unit commit problem. There are two types of restrictions to consider: unit restrictions, and system restrictions. Unit restrictions affect each unit taken individually, while system restrictions affect units taken as a whole. The problem with constraints is that some of these constraints create a link between different periods. That is to say, solving problems separately in each period is not a good solution.

Another thing to consider is startup costs. The startup cost is a cost incurred when we start a production unit, and different production units will have different startup costs [27,28]. Large units will tend to have a high startup cost but will be efficient later on while small power plants will tend to have a lower startup cost but will be less efficient in this case. Therefore, there will be a trade-off to be made between starting and generating power plants or running other higher-output power plants.

$$\min\left[\sum_{u} C_u^{cap} + \sum_{u} C_u^{OM}\right] \tag{1}$$

where

C_u^{cap}—the initial capital expenditure,
C_u^{OM}—the operational and management costs.

2.1. Initial Capital Expenditure

This sub-section will detail the initial costs associated with the acquisition and installation of generation technologies, including both traditional and renewable sources. It (Equation (2)) provides a breakdown of costs for equipment, infrastructure, and other capital investments.

$$\sum_{u} C_u^{cap} = \sum_{u}(Cap_u^{w} + Cap_u^{pv} + Cap_u^{gas} + Cap_u^{coal}) + \sum_{u} C_u^{tr} \tag{2}$$

where

Cap_u^{w}—the procurement and installation costs of the wind turbine unit,
Cap_u^{pv}—the procurement and installation costs of the PV units,
Cap_u^{gas}—the capital cost of the gas-fired unit,
Cap_u^{coal}—the capital cost of the coal-fired unit,
C_u^{tr}—the capital cost of the transmission system.

2.2. Operational Startup Costs

This sub-section will focus on the costs incurred during the startup phase of operations. It will cover expenses such as workforce training, initial fuel costs, maintenance, and any other operational expenditures necessary to bring the power generation units online. The annual fixed operation and management cost is calculated as in Equation (3):

$$\sum_{u} C_u^{OM} = \sum_{u}(C_u^{w} + C_u^{pv} + C_{u,t}^{gas} + C_{u,t}^{coal}) \tag{3}$$

where

C_u^{w}—the fixed operational cost of the wind turbine unit,
C_u^{pv}—the fixed operational cost of the PV unit,
$C_{u,t}^{gas}$—the startup cost of the gas-fired unit at time t,
$C_{u,t}^{coal}$—the startup cost of the coal-fired unit at time t.

2.3. Unit Constraints

The unit constraints that affect each unit are taken individually. Constraints that affect each power plant individually are maximum generating capacity, minimum stable generation, minimum on time, minimum off time, and ramp rate [29].

- Minimum on and off time

Operators impose some restrictions so that the plant continues to operate for a long time and does not affect the life of the plant. One of these restrictions is what is called the minimum uptime of the plant. The idea is that once a generating unit starts up, it will not be shut down immediately because doing this more or less often will shorten the life of the plant; so mathematically we can formulate it as follows:

1. If $u(i,t) = 1$ and $t_i^{on} < t_i^{on,min}$; $u(i,t+1) = 1$ (then the plant should remain on at the next time period)
   where
   $u(i,t)$—the status of power generator i at the period t;
   $u(i,t) = 1$—the power generator i is on at the period t;

This restriction with minimum downtime has an inverse and essentially, if the generation unit is shut down, it is not allowed to restart it immediately and is expressed mathematically as follows:

2. If $u(i,t) = 0$ and $t_i^{off} < t_i^{off,min}$; $u(i,t+1) = 0$ (then the plant should remain on at the next time period)
   where
   $u(i,t) = 0$—the power generator i is off at the period t;

If the plant is off (must be off for at least the minimum amount of time that must be off), then this plant must remain off for the next time period.

- Ramp rate

Another constraint to consider is the ramp rate which is the rate at which the plant can increase or decrease its generation. This constraint is also imposed to protect the life of the power plant (to avoid damaging the turbine, etc.), and can be expressed mathematically as follows:

$$\Delta P_i^{up,max} \geq x(i,t+1) - x(i,t) \tag{4}$$

Similarly, a maximum ramp-down constraint specifies that which is needed to reduce the output.

$$\Delta P_i^{down,max} \geq x(i,t) - x(i,t+1) \tag{5}$$

where

$x(i,t)$—the generated power by i during the period t.

2.4. System Constraints

The system constraints affect more than one unit. These are mainly the load-generation balance constraints, the reserve generation capacity constraints, emission constraints, and grid constraints.

- The load generation balance constraint: the produced power by the generators must be equal to the load at all times.

$$\sum_{n=1}^{N} u(i,t) \cdot x(i,t) = L(t) \tag{6}$$

where
n, N—a set of available power generators;
u, x—the produced power;
L—a load at times t.

- The reserve generation capacity constraints: It is a restriction imposed to maintain the operational reliability of the system. Every once in a while, the power plant can suddenly go out due to a problem or due to restrictions. This power generation will cause an acceptable frequency drop if not fixed quickly. Therefore, there must be the ability to increase the generation of other units to prevent the frequency from falling beyond acceptable limits. It can be expressed mathematically as follows:

$$\sum_{n=1}^{N} u(i,t) P_i^{max} \geq L(t) + R(t) \quad (7)$$

where
$R(t)$—a set of available power generators.

- Emission Constraints: It defines the CO_2 emission constraints for the power system responsible for generating and transmitting energy to meet the electricity demand over time. CO_2 emissions are produced by coal-fired and gas-fired power plants during power generation and the annual CO_2 emission constraints are formulated as follows:

$$\sum_{t} fuel_{n,\,t} \leq crbn_{lim} \quad (8)$$

$fuel_{n,t}$—the rate of use of fuel (coal, gas) by generator n, during timepoint t,
$crbn_{lim}$—annual CO_2 emissions limits for the power system.

It is the sum of cases where the maximum capacity of all available power generators must be greater than or equal to the load and some reserve requirement. The rapid increase in the generation is only possible if committed power plants are not all operating at their maximum capacity.

Besides all these constraints, the scheduling of production units can be affected by environmental constraints. Environmental constraints were not examined in detail in this study. Also, generation scheduling can be affected by transmission networks. Some switchboards that will not be needed for economic reasons may need to be operated to provide voltage support. On the other hand, the output may be limited as some units that can be very efficient may exceed the transmission capacity of the network. In this study, the grid constraints are neglected.

This unit commitment model enables the investigation of the comprehensive impact of electric vehicle charging modes on the Istanbul electricity system with high penetration levels of renewable resources in 2030.

Electricity consumption, peak demand, and generation capacity are estimated based on historical data [30]. The estimated installed power capacity of the Istanbul power system in 2030 is shown in Table 1. Figure 2 shows the capacity factors of selected power generators.

Table 1. Power capacity of the Istanbul power system.

Power Plant	Hydro	Solar	Wind	Natural Gas	Coal
Capacity	17 GW	1.5 GW	12 GW	25.8 GW	1.5 GW

The hourly variations of hydropower, solar power, electricity demand, and charging demand of EVs are considered. Solar power and hydropower are regarded as zero-cost generation and zero-emission resources. Therefore, operators prefer to use renewable energy sources to reduce operating and management costs and CO_2 emissions. However, the intermittent nature of renewables requires significant reserves for conventional fuel units. The hydroelectric power plant has a ramp facility as it has a dam/reservoir.

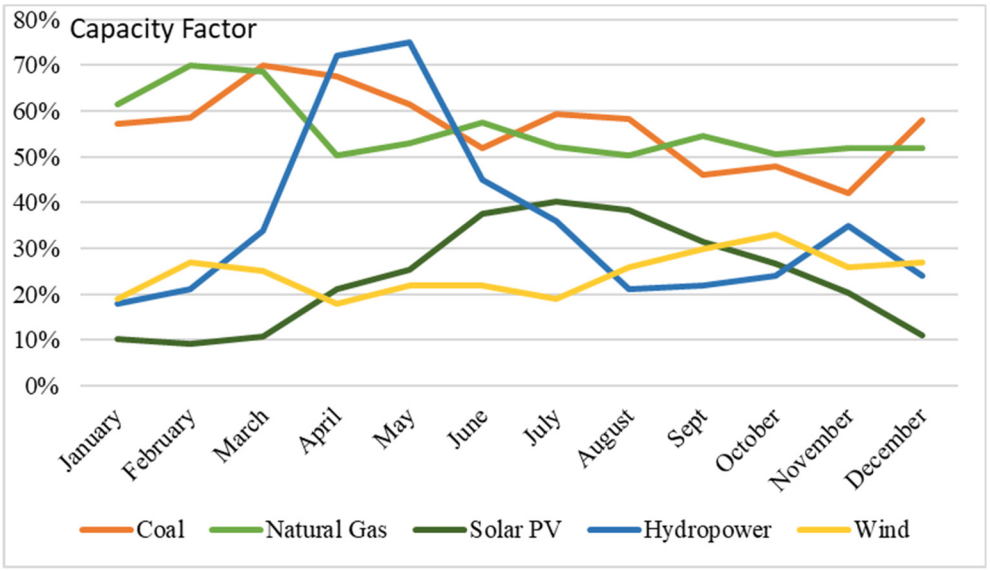


Figure 2. Monthly capacity factors of selected power generators.

3. EV Load Estimation and Charging Strategies

At the beginning of the considerations, a question should be answered. What are the conditions for controlling electric car charging and how is the electricity grid affected by electric car charging in the current situation and by a future growing electric car fleet? This question is crucial from the perspective of an electricity distribution company in Istanbul.

The electricity demand from EVs depends on the size of the car fleet, driving behaviors, wear and tear of the EV, battery health, driving distance, and traffic conditions [31,32]. According to the BloombergNEF Electric Vehicles Outlook 2021 report, there will be more than 169 million EVs on the road by 2030. It is predicted that the number of electric vehicles in Turkey will reach 2.5 million and the number of charging stations will reach 1 million by 2030 [10,33]. The parameters related to the electric vehicles used in this study are summarized in Table 2. Energy consumption for driving purposes only for an EV ranges from 0.16 kWh/km to 0.35 kWh/km [34]. In this study, energy consumption is assumed to be 0.30 kWh/km, since the traffic density in the city of Istanbul is high and the topology of the city is hilly. The annual energy consumption of electric vehicles will be 23.8 TWh, corresponding to 7.2% of electricity consumption. This study focuses on only passenger electric cars rather than electric buses and heavy vehicles.

Table 2. Parameters related to electric cars.

Number of EVs	2.5 million
Mileage per day	Weekday: 25 km Weekend: 35 km
Battery capacity	40 kWh
Energy consumption and emission factor	EVs 0.30 kWh/km Gasoline-driven vehicles 7 L/100 km, (2.3 $kgCO_2/L$)
Charging rate	Fast charging: 7.2 kW Slow charging: 2.5 kW

Electric cars in Istanbul are mostly used for commuting between workplaces and homes. In this study, it is assumed that electric vehicles are generally used between 7:00 and 9:00 in the morning and between 17:00 and 19:00 in the evening. On weekdays, the charging times for electric vehicles are between arriving home in the evening and leaving home in the morning. On weekends, it is assumed that electric cars are used for non-work

purposes such as shopping, entertainment, and sightseeing. It is assumed that the daily driving distance of electric cars is 25 km on weekdays and 35 km on weekends.

The charging behavior of electric vehicles has been produced by the Monte Carlo method based on the probability distributions of departure and arrival times and daily driving distance. The daily driving distance is created depending on whether the day is a weekday or weekend, and the probability is determined according to the charging location.

In this study, two charging strategies are defined, namely the managed charging strategy and the uncertain charging strategy. Uncoordinated charging assumes each EV charges as soon as it is plugged in without any consideration of the electricity supply and it stops charging when the electric car's energy requirement is met. Most research postulates an uncertain charging scenario in which the grid is pressured via many EV drivers coming home from work and plugging in a type at the same time, which occurs to be coincident with the day-by-day peak load. With managed charging which most often occurs unidirectionally, electric car charging is controlled by considering the electricity supply, within the constraints of the user's mobility needs. Charging power limits and cumulative charging energy constraints are applied to represent the energy and power limits of electric cars. This often includes shifting the electric car charging times based on electricity pricing or other incentive signals.

In this section, it will be explained how to solve the unit commitment problem. Decision variables come in two types. The status of each generating unit at each period has to be found.

$$u(i,t) \in [0,\ 1]\ \forall\ i,t \tag{9}$$

In addition, the output of each unit needs to find out what it generates at each period.

$$x(i,t) \in \left[0, P_i^{min}, P_i^{max}\right]\ \forall\ i,t \tag{10}$$

The mathematical formulation of the entire fleet of the electric vehicle's flexibility is shown as follows:

$$E_t^{lower} \leq \sum_{t=1}^{T} \Delta T \cdot x(i,t) \leq E_t^{upper} \tag{11}$$

where

E_t^{lower}—the lower boundaries for the aggregated energy demand by time t;
E_t^{upper}—the upper boundaries for the aggregated energy demand by time t.

The charging demand (EV_{dem}) of EVs is calculated annually by aggregating different vehicle types, accounting for their numbers, average travel distances, and energy consumption rates. This provides a comprehensive view of the overall energy requirements for electric vehicles each year.

$$EV_{dem} = \sum_{p} \frac{NrEV_p \cdot DisEV_p \cdot EffEV_p}{ChEV_p} \tag{12}$$

where,

EV_{dem}—the energy demand of EVs in period p (kWh),
$NrEV$—number of EVs in year p,
$DisEV_p$—the annual travel distance of EVs in period p,
$EffEV_p$—fuel consumption of EVs in period p (km/kWh),
$ChEV_p$—charging efficiency of EVs in period p (%).

At this stage of research, it is important to emphasize that over the years, attempts have been made to develop many techniques to solve the problem of individual involvement. This drive for new techniques has arisen from the need to find solutions that are closer to the optimum, find solutions faster, and improve the way in which the constraint is modeled.

4. Results Analysis—Scenario Description

To solve a research problem, three different scenarios have been created for the unit commitment optimization of the power system with and without electric cars scenario.

1. Managed charging strategy (MCS): In this strategy, where the charging time is not fixed, the electricity supply is taken into account within the constraints of the electric vehicle user's mobility requirements. This type of charging of electric cars can be differentiated by the direction of electricity flow and how charging is controlled.
2. Uncertain charging strategy (UCS): EVs are charged depending on user preferences, vehicle characteristics, and trip requirements; with a fixed charging time, which starts as soon as the EV arrives at home or the workplace.
3. Without electric cars (WEC): No electric cars are connected to the power grid.

The generation profiles of renewables and hourly load profiles are shown in Figure 3.

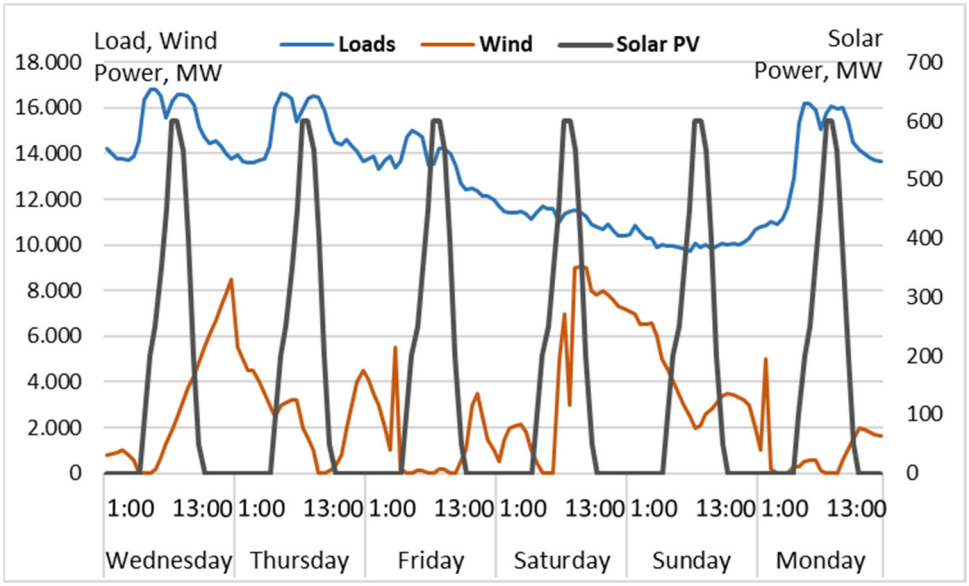


Figure 3. Loads, solar, and wind power profile (26–31 October 2022).

A day is divided into 24 h to find the optimal generation schedule for the entire load profile, assuming the load is constant during these one-hour periods. The question to be asked is which power plants should be committed to generating at minimum cost for each time period. In order to solve the problem, the minimum value of the objective function under the determined constraints is attempted to be found.

Electric vehicles are considered one of the important solutions to balance power fluctuations caused by higher integration of unstable and unpredictable renewable energy sources [35]. However, the integration of electric vehicles acts as additional loads to the electricity grid during battery charging, and these additional loads can create unwanted congestion, frequency ripple, and various negative effects on the distribution grid in Istanbul. All these issues create new challenges for power system operators. Therefore, it is imperative that electric vehicles provide a Managed Charging Strategy (MCS) instead of a simple traditional load.

In this study, the 24-h time frame was examined in 1-h periods. According to the demanded load values, the most suitable unit combinations and the total cost of the system were calculated. The results of all solution methods were compared. Estimated demand values in the system and total operating costs for the three scenarios are summarized in Table 3.

Table 3. Operating costs of scenarios (in $ million).

Scenario	Natural Gas Unit Cost	Coal Unit Cost	Reserve Capacity Cost	Start-Up Cost	Total Cost
MCS	57.1	5.7	1.03	1.35	65.18
UCS	58.1	5.9	1.19	1.52	66.71
WEC	56.4	5.5	1.12	1.31	64.33

Compared to the uncertain charging strategy, managed charging saves 2.3%, reducing the total cost from $66.71 million to $65.18 million. This is because some of these facilities can be considered flexible and their power output can be adjusted within some limits according to the data. When dealing with unit commitment, it is important to realize that not all manufacturing facilities are the same. Thermal generation units such as oil-fired units, coal-fired units, gas-cycle turbines, combined-cycle plants, and storage hydro plants are highly flexible as their condition and power output can be optimized.

On the other hand, there are plants that are inflexible or much less flexible, and these are plants whose output cannot be adjusted for technical or commercial reasons. Renewable energy sources such as wind and sun can only be generated when the wind blows or the sun shines. Combined heat and power plants are often driven by the need for heat rather than their ability to generate power, or their ability to generate power is constrained.

Also, the Uncertain Charge Strategy results in higher evening peak demand than the Managed Charge Strategy and then results in higher load shedding. In the Managed Charging scenario, most of the charging power occurs between 11:00 p.m. and 05:00 a.m. when electric vehicles are charged at home, which decreases the evening peak demand from 17.8 GW to 16.4 GW (7.2% decrease) in the Uncertain Charging scenario. Using the Managed Charging scenario, most of the evening charging demand is optimized to switch to off-peak hours after 01:00 a.m. Thus, a smoother load profile is obtained than using an Uncertain Charging strategy. As seen in Figure 4, Managed Charging also increases the operating efficiency of a fossil fuel-fired power plant.

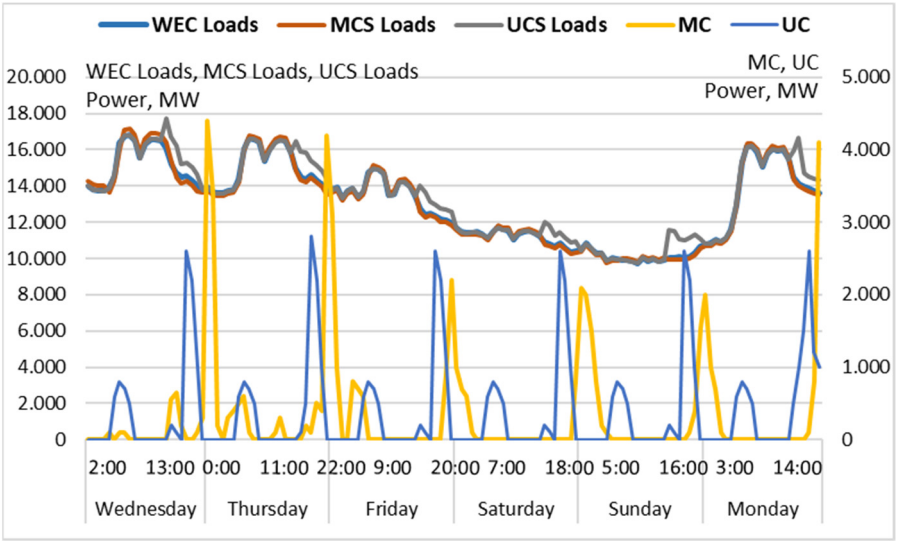


Figure 4. Electric cars' charging profile in the simulated days (26–31 October 2022).

Therefore, proper energy management is a necessary prerequisite for the energy transition. In order to efficiently integrate electric vehicles into it and make their technical flexibilities usable, a systemic approach is required that not only considers the requirements of electric vehicle users, but also the framework conditions of the distribution grids and an energy market oriented towards regenerative generation. Managed charge integration

addresses all of these topics and proposes a feasible concept for the intelligent charging of many electric vehicles in private spaces at the low-voltage level, at the same time meeting the requirements of the smart city concept.

5. Conclusions and Discussion

Creating a map for achieving zero-emission road transport in cities is a huge task in the coming years [36–38]. An important postulate in this concept is the development of electromobility processes [39,40]. As many researchers emphasize, one of the determinants is the integration of energy systems with the vehicle and renewable energy sources [15,41].

With the arrival of more electric cars in Istanbul in 2030, the individual commitment model presented in this paper can be used to analyze the interaction between electric car charging and power plants. The uncertain charging strategy coincides with peak electricity demand during the day, while the managed charging strategy is implemented during off-peak hours and during times of low electricity prices to avoid peak demand. This study highlights the importance of charging electric vehicles in a timely manner so that the charging process does not burden the grid. The results of simulations indicate that managed charging is an appropriate strategy for the proper operation of the power system in Istanbul due to its flexibility in reducing peak load and reducing operational costs. In particular, a significant reduction in the operating costs of power plants may result in a decline in electricity prices in the future. The research results presented will provide useful insight into assessing the impact of electric vehicles on the power grid and the use of renewable energy in the process. However, it should be noted that the results depend on the renewable energy generation profiles and from several other factors including the driving behavior of electric vehicles—energy consumption.

In the current unreliable charging method, it has been shown that the temporary charging output overlaps the already peak power output during the day. This worsens the situation in the power grid, which relies on already existing energy peaks, which contributes to greater differences between peaks and valleys in the power curve from the Istanbul grid station. This overlap can cause power quality problems in the future as grid load increases. This situation will certainly result from the need to charge more electric cars at the same time.

However, this does not change the state of affairs that, as the authors have shown, managing the charging of electric vehicles can be a solution and a potential alternative to energy system solutions based on fossil fuels, such as stationary energy storage or peak generators.

It should be emphasized that the presented research focused on assessing the possibility of implementing solutions based on the integration of electric vehicle energy systems by analyzing the impact on selected networks—a case study of a selected city. It is important, both from a scientific and practical point of view, to answer the question of whether the project itself and the research conclusions can be directly implicated or compared with other cities. According to the authors, the implementation of this category of projects should be individual. It is not possible to indicate assumptions and patterns because each of the possible implemented projects is based on different starting assumptions. This does not change the fact that in each case, the implementation of a possible project must include a comprehensive analysis resulting from the impact of the use of electric vehicles on selected energy networks and systems, which are increasingly based on energy from renewable sources. It should therefore be remembered that a possible comprehensive assessment of all consequences resulting from the integration of energy systems will only be possible several years after the implementation and possible launch of individual projects in selected cities.

In the discussion on the integration of energy systems of electric vehicles, economic issues regarding the costs incurred for this process seem to be no less important [42,43]. The current energy transformation is based on the higher use of energy from renewable sources. It is estimated that the introduction of a larger fleet of electric vehicles will certainly lead to an increased demand for energy, i.e., an increase in financial outlays for the construction

of appropriate transmission infrastructure, charging stations, and energy storage facilities. However, over time, in the authors' opinion, these costs will be optimized.

The authors support the thesis promoted in the literature that the integration of energy systems in relation to the development of electromobility is an inevitable process and all these activities certainly fit into the currently promoted smart city concept [44,45].

At this stage of the summary, it should be noted that, like every study, the one presented above also has its limitations. The authors focused their research on preconceived data and selected research methods and scenarios described in Sections 2 and 3 of this study. Verification and assessment of the validity of the adopted model assumptions will take place in the coming years. This does not change the fact that the discussed topic certainly requires further in-depth research in the areas of simulation efficiency, identification of limitations, challenges, and the selection of specialized software to analyze changes taking place in this area.

So, the future research in this matter should focus on identifying all barriers in the relationship between renewable energy sources—technical infrastructure—vehicles, taking into account the benefits for all stakeholders of this relationship.

To summarize the presented considerations regarding the integration of energy systems of electric vehicles—the analysis of the impact on selected networks does not fully exhaust the essence of the research problem. They are only an encouragement for research in this matter. This topic certainly requires further in-depth research to fully understand both the essence of the impact of energy transformation on the modern concept of smart city, as well as the role that electromobility and renewable energy sources play in this process. Hence, these types of analyzes will be the subject of future work aimed at determining and identifying key factors for the implementation of plans for the development of the smart city concept based on the development of electromobility and renewable energy sources.

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References

1. Van Aalst, M.K. The impacts of climate change on the risk of natural disasters. *Disasters* **2006**, *30*, 5–18. [CrossRef] [PubMed]
2. Nema, P.; Nema, S.; Roy, P. An overview of global climate changing in current scenario and mitigation action. *Renew. Sustain. Energy Rev.* **2012**, *16*, 2329–2336. [CrossRef]
3. Rogelj, J.; den Elzen, M.; Höhne, N.; Fransen, T.; Fekete, H.; Winkler, H.; Schaeffer, R.; Sha, F.; Riahi, K.; Meinshausen, M. Paris Agreement climate proposals need a boost to keep warming well below 2 °C. *Nature* **2016**, *534*, 631–639. [CrossRef] [PubMed]
4. Telli, A.; Erat, S.; Demir, B. Comparison of energy transition of Turkey and Germany: Energy policy, strengths/weaknesses and targets. *Clean Technol. Environ. Policy* **2021**, *23*, 413–427. [CrossRef]
5. Şahin, Ü.; Tör, O.B.; Kat, B.; Teimourzadeh, S.; Demirkol, K.; Künar, A.; Yeldan, E. Türkiye'nin Karbonsuzlaşma yol Haritası: 2050'de Net Sıfır. 2021. Available online: https://ipc.sabanciuniv.edu/Content/Images/CKeditorImages/20211026-23105368.pdf (accessed on 1 January 2023).
6. Turkish Statistical Institute. Turkish Greenhouse Gas Inventory 1990–2020. April 2022. Available online: https://unfccc.int/documents/461926 (accessed on 20 January 2023).
7. Minelli, F.; D'Agostino, D.; Migliozzi, M.; Minichiello, F.; D'Agostino, P. PhloVer: A Modular and Integrated Tracking Photovoltaic Shading Device for Sustainable Large Urban Spaces—Preliminary Study and Prototyping. *Energies* **2023**, *16*, 5786. [CrossRef]

8. Li, J.; Liu, F.; Li, Z.; Shao, C.; Liu, X. Grid-side flexibility of power systems in integrating large-scale renewable generations: A critical review on concepts, formulations and solution approaches. *Renew. Sustain. Energy Rev.* **2018**, *93*, 272–284. [CrossRef]
9. Minelli, F.; Ciriello, I.; Minichiello, F.; D'Agostino, D. From Net Zero Energy Buildings to an energy sharing model—The role of NZEBs in Renewable Energy Communities. *Renew. Energy* **2024**, *223*, 120110. [CrossRef]
10. Turkey Projected to Have 2.5 mln Electric Cars by 2030. *Hurriyetdailynews*. 2019. Available online: https://www.hurriyetdailynews.com/turkey-projected-to-have-2-5-mln-electric-cars-by-2030-150242 (accessed on 1 January 2023).
11. Neaimeh, M.; Andersen, P.B. Mind the gap- open communication protocols for vehicle grid integration. *Energy Inform.* **2020**, *3*, 1. [CrossRef]
12. Li, M.; Lenzen, M.; Wang, D.; Nansai, K. GIS-based modelling of electric-vehicle–grid integration in a 100% renewable electricity grid. *Appl. Energy* **2020**, *262*, 114577. [CrossRef]
13. Sovacool, B.K.; Kester, J.; Noel, L.; de Rubens, G.Z. Contested visions and sociotechnical expectations of electric mobility and vehicle-to-grid innovation in five Nordic countries. *Environ. Innov. Soc. Transit.* **2019**, *31*, 170–183. [CrossRef]
14. Li, B.; Ma, Z.; Hidalgo-Gonzalez, P.; Lathem, A.; Fedorova, N.; He, G.; Zhong, H.; Chen, M.; Kammen, D.M. Modeling the impact of EVs in the Chinese power system: Pathways for implementing emissions reduction commitments in the power and transportation sectors. *Energy Policy* **2021**, *149*, 111962. [CrossRef]
15. Das, H.S.; Rahman, M.M.; Li, S.; Tan, C.W. Electric vehicles standards, charging infrastructure, and impact on grid integration: A technological review. *Renew. Sustain. Energy Rev.* **2020**, *120*, 109618. [CrossRef]
16. Brown, M.A.; Soni, A. Expert perceptions of enhancing grid resilience with electric vehicles in the United States. *Energy Res. Soc. Sci.* **2019**, *57*, 101241. [CrossRef]
17. Hildermeier, J.; Kolokathis, C.; Rosenow, J.; Hogan, M.; Wiese, C.; Jahn, A. Smart EV Charging: A Global Review of Promising Practices. *World Electr. Veh. J.* **2019**, *10*, 80. [CrossRef]
18. Nour, M.; Chaves-Ávila, J.P.; Magdy, G.; Sánchez-Miralles, Á. Review of Positive and Negative Impacts of Electric Vehicles Charging on Electric Power Systems. *Energies* **2020**, *13*, 4675. [CrossRef]
19. Coban, H.H.; Lewicki, W.; Sendek-Matysiak, E.; Łosiewicz, Z.; Drożdż, W.; Miśkiewicz, R. Electric Vehicles and Vehicle–Grid Interaction in the Turkish Electricity System. *Energies* **2022**, *15*, 8218. [CrossRef]
20. Fei, L.; Shahzad, M.; Abbas, F.; Muqeet, H.A.; Hussain, M.M.; Bin, L. Optimal Energy Management System of IoT-Enabled Large Building Considering Electric Vehicle Scheduling, Distributed Resources, and Demand Response Schemes. *Sensors* **2022**, *22*, 7448. [CrossRef]
21. Naderi, E.; Asrari, A. Integrated Power and Transportation Systems Targeted by False Data Injection Cyberattacks in a Smart Distribution Network. In *Electric Transportation Systems in Smart Power Grids*; CRC Press: Boca Raton, FL, USA, 2022; pp. 447–472. [CrossRef]
22. An, K.; Song, K.-B.; Hur, K. Incorporating Charging/Discharging Strategy of Electric Vehicles into Security-Constrained Optimal Power Flow to Support High Renewable Penetration. *Energies* **2017**, *10*, 729. [CrossRef]
23. Colmenar-Santos, A.; Muñoz-Gómez, A.-M.; Rosales-Asensio, E.; López-Rey, Á. Electric vehicle charging strategy to support renewable energy sources in Europe 2050 low-carbon scenario. *Energy* **2019**, *183*, 61–74. [CrossRef]
24. Zhu, X.; Xia, M.; Chiang, H.-D. Coordinated sectional droop charging control for EV aggregator enhancing frequency stability of microgrid with high penetration of renewable energy sources. *Appl. Energy* **2018**, *210*, 936–943. [CrossRef]
25. Zhong, J.; He, L.; Li, C.; Cao, Y.; Wang, J.; Fang, B.; Zeng, L.; Xiao, G. Coordinated control for large-scale EV charging facilities and energy storage devices participating in frequency regulation. *Appl. Energy* **2014**, *123*, 253–262. [CrossRef]
26. Coban, H.H.; Lewicki, W. Daily Electricity Demand Assessment on The Example of The Turkish Road Transport System-A Case Study of The Development of Electromobility on Highways. *Transp. Geogr. Pap. PGS* **2022**, *25*, 52–62. [CrossRef]
27. Richter, M.; Oeljeklaus, G.; Görner, K. Improving the load flexibility of coal-fired power plants by the integration of a thermal energy storage. *Appl. Energy* **2019**, *236*, 607–621. [CrossRef]
28. Jha, A.; Leslie, G. Dynamic Costs and Market Power: Rooftop Solar Penetration in Western Australia. *SSRN Electron. J.* **2020**. [CrossRef]
29. Van den Bergh, K.; Delarue, E. Cycling of conventional power plants: Technical limits and actual costs. *Energy Convers. Manag.* **2015**, *97*, 70–77. [CrossRef]
30. YTBS—Load Dispatcher Information System, "Electricity Statistics of Türkiye". Available online: https://ytbsbilgi.teias.gov.tr/ytbsbilgi/frm_hakkinda.jsf (accessed on 1 January 2023).
31. Nandi, A.K.; Chakraborty, D.; Vaz, W. Design of a comfortable optimal driving strategy for electric vehicles using multi-objective optimization. *J. Power Sources* **2015**, *283*, 1–18. [CrossRef]
32. Sanguesa, J.A.; Torres-Sanz, V.; Garrido, P.; Martinez, F.J.; Marquez-Barja, J.M. A Review on Electric Vehicles: Technologies and Challenges. *Smart Cities* **2021**, *4*, 372–404. [CrossRef]
33. BloombergNEF, Electric Vehicle Outlook 2022. 2022. Available online: https://about.bnef.com/electric-vehicle-outlook/ (accessed on 1 January 2023).
34. Cedric, D.C.; Messagie, M.; Sylvia, H.; Thierry, C.; Joeri, V. Electric Vehicle Use and Energy Consumption Based on Realworld Electric Vehicle Fleet Trip and Charge Data and Its Impact on Existing EV Research Models. *World Electr. Veh. J.* **2015**, *7*, 436–446. [CrossRef]

35. Kurucan, M.; Özbaltan, M.; Yetgin, Z.; Alkaya, A. Applications of artificial neural network based battery management systems: A literature review. *Renew. Sustain. Energy Rev.* **2024**, *192*, 114262. [CrossRef]
36. Brdulak, A.; Chaberek, G.; Jagodziński, J. Development Forecasts for the Zero-Emission Bus Fleet in Servicing Public Transport in Chosen EU Member Countries. *Energies* **2020**, *13*, 4239. [CrossRef]
37. Pietrzak, K.; Pietrzak, O. Environmental Effects of Electromobility in a Sustainable Urban Public Transport. *Sustainability* **2020**, *12*, 1052. [CrossRef]
38. Lojano-Riera, B.P.; Flores-Vázquez, C.; Cobos-Torres, J.-C.; Vallejo-Ramírez, D.; Icaza, D. Electromobility with Photovoltaic Generation in an Andean City. *Energies* **2023**, *16*, 5625. [CrossRef]
39. Adenaw, L.; Lienkamp, M. Multi-Criteria, Co-Evolutionary Charging Behavior: An Agent-Based Simulation of Urban Electromobility. *World Electr. Veh. J.* **2021**, *12*, 18. [CrossRef]
40. Tundys, B.; Wiśniewski, T. Smart Mobility for Smart Cities—Electromobility Solution Analysis and Development Directions. *Energies* **2023**, *16*, 1958. [CrossRef]
41. Patil, H.; Nago Kalkhambkar, V. Grid Integration of Electric Vehicles for Economic Benefits: A Review. *J. Mod. Power Syst. Clean Energy* **2021**, *9*, 13–26. [CrossRef]
42. İnci, M.; Savrun, M.M.; Çelik, Ö. Integrating electric vehicles as virtual power plants: A comprehensive review on vehicle-to-grid (V2G) concepts, interface topologies, marketing and future prospects. *J. Energy Storage* **2022**, *55*, 105579. [CrossRef]
43. Lewicki, W.; Niekurzak, M.; Sendek-Matysiak, E. Electromobility Stage in the Energy Transition Policy—Economic Dimension Analysis of Charging Costs of Electric Vehicles. *Energies* **2024**, *17*, 1934. [CrossRef]
44. Hertel, D.; Bräunig, G.; Thürer, M. Towards a green electromobility transition: A systematic review of the state of the art on electric vehicle battery systems disassembly. *J. Manuf. Syst.* **2024**, *74*, 387–396. [CrossRef]
45. Rivera, S.; Goetz, S.M.; Kouro, S.; Lehn, P.W.; Pathmanathan, M.; Bauer, P.; Mastromauro, R.A. Charging Infrastructure and Grid Integration for Electromobility. *Proc. IEEE* **2023**, *111*, 371–396. [CrossRef]

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