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# Power System Integration of Electric Vehicles: A Review on Impacts and Contributions to the Smart Grid

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**Abstract:** In recent years, electric vehicles (EVs) have become increasingly popular, bringing about fundamental shifts in transportation to reduce greenhouse effects and accelerate progress toward decarbonization. The role of EVs has also experienced a paradigm shift for future energy networks as an active player in the form of vehicle-to-grid, grid-to-vehicle, and vehicle-to-vehicle technologies. EVs spend a significant part of the day parked and have a remarkable potential to contribute to energy sustainability as backup power units. In this way, EVs can be connected to the grid as stationary power units, providing a range of services to the power grid to increase its reliability and resilience. The available systems show that EVs can be used as alternative energy sources for various network systems like smart grids, microgrids, and virtual power plants besides transportation. While the grid–EV connection offers various contributions, it also has some limitations and effects. In this context, the current study highlights the power system impacts and key contributions of EVs connected to smart grids. Regarding the power system impacts in case of EV integration into smart grids, the challenges and difficulties are categorized under the power system stability, voltage/current distortions, load profile, and power losses. Voltage/current distortions like sags, unbalances, harmonics, and supraharmonics are also detailed in the study. Subsequently, the key contributions to the smart grid in terms of energy management, grid-quality support, grid balancing, and socio-economic impacts are explained. In the energy management part, issues such as power flow, load balancing, and renewable energy integration are elaborated. Then, the fault ride-through capability, reactive power compensation, harmonic mitigation, and grid loss reduction are presented to provide information on power quality enhancement. Lastly, the socio-economic impacts in terms of employment, net billing fees, integration with renewable energy sources, and environmental effects are elucidated in the present study.

**Keywords:** smart grid; electric vehicle; alternative energy source; power system impacts and contributions

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## 1. Introduction

The emissions of greenhouse gases from human activities amplify environmental pollution and cause climate change. To reduce these effects, it is necessary to make the best use of clean energy sources such as wind and photovoltaics (PVs) [1]. In addition, the power generation of these sources is directly proportional to the weather conditions and has an intermittent nature. The optimum use of alternative energy sources and the solutions to problems can be realized with smart grids. Smart grids have a great capacity to make power plants more flexible and encourage energy transition [2]. A smart grid is an electrical network that uses new technology to detect and respond to changes. A smart grid can continuously regulate supply to balance demand, keeping operations running while powering all the consumers [3]. With a smart grid, the remote instantaneous monitoring, analysis, and management of an entire network are performed. The smart grid integrates smart meters and smart devices with consumers and power distributors into a network, enabling them to establish two-way communication between them [4]. The smart grid can therefore improve users' energy demands and prevent possible failures. Smart grids can integrate alternative energy sources of various sizes, and their interactivity allows users to be both consumers and producers [5].

Smart grids carry information along with electrical power, providing the data needed to supervise the power system [6]. Smart grid operators have the crucial task of employing this information to ensure that the total electrical power supply consistently meets the electrical energy demand [7]. Continuous communication with dynamic electrical energy sources is essential while the power suppliers need to increase or decrease output to meet demand [8]. Owing to smart grids, the connection between the amount of energy demanded by users and the amount of energy supplied from alternative energy sources can be optimized [9]. In addition, it has the potential to ensure the storage of electrical energy during times when the generated electrical power from renewable energy is abundant. The utilization of the stored energy is high during times when there is demand for electrical energy. If a power plant is far away, a smart grid operator helps achieve this aim by ensuring key insight into energy markets. This process is accomplished through the internet, control systems, communication, and automation for smart grid applications [10].

A smart grid connects and supervises a variety of distributed energy resources to a common link. Due to environmental awareness, alternative energy sources such as PVs and wind play an active role in the smart grid [11]. The energy demand and environmental factors stimulate the integration of electric vehicles (EVs) with the grid as potential energy storage units. Environmentally friendly EVs, which are gradually replacing conventional fuel vehicles, have taken their place on the roads, the number of which has increased significantly in recent years [12]. However, most EVs spend an average of 90–95% of each day parked at facilities with charging infrastructures [13]. While these vehicles are parked, they can contribute to alternative energy solutions for stationary applications such as energy supply/demand. In recent years, the integration of smart grids with renewable power plants has increased the significance of EVs for grid integration as well as the transportation sector [14]. When EVs are parked, these structures play an essential role as critical components of smart grids with their energy charge and discharge features [15]. The integrated coordination of EVs will facilitate active consumer participation by supporting the smart grid with ancillary services [16]. EVs employ a variety of charging topologies to stock excessive energy produced from clean energy sources, supply electrical energy during times of power shortages, and use scheduling to consume grid loads more smoothly. Using EVs as a vital component of the smart grid ensures that the vehicles power the electric network and vice versa, making the smart grid more flexible, efficient, and balanced [17].

Most studies in the literature show that integrating EVs as an alternative energy source in smart grids is applicable and advantageous for a variety of ancillary contributions. For electrical grid connection, the available structures include various EVs like battery EVs, fuel cell EVs, and hybrid EVs [18]. In addition, many studies explain and detail the role of EVs in smart grids. Related to vehicle–smart grid integration, the system concepts are classified in terms of unidirectional/bidirectional charging and centralized/decentralized scheduling by researchers [19]. In one study, the researchers classified the concepts, frameworks, advantages, challenges, and optimization methods for the integration of EVs in smart grids [20]. In [21], the economic and reliability impacts of the vehicle–grid integration sector were explained. Also, it presented on-board/off-board charge infrastructures, challenges of energy storage technologies, and communication requirements for EVs [21]. A review of problems and their solution strategies regarding EVs connected to smart grids is explained in [22]. The charge scheduling, renewable energy integration, and infrastructure facilities of EVs have been clarified by researchers [22]. The authors examined the charging complication of EVs connected to smart grid technology and its interaction with sustainable energy [23]. A study focused on the feasibility of a smart vehicle-to-grid (V2G) system, the interaction of EVs in smart grids, and the integration of sustainable energy resources like PVs in [24,25]. The authors provided information about the service relationships between fleet operators and components in the smart grid [26]. In addition, battery dynamics and driving patterns, charging, and communication standards were provided in the study [26]. The researchers examined the identification and programming of charging stations suitable for individual EVs as an optimization issue [27]. This work introduced research results based on objective functions, solution methods, geographical situations, and demand-side management regarding the placement of charging stations [28]. The integration of plug-in EVs in smart grids such as V2G and grid-to-vehicle (G2V) systems has been described. Also, the work provided information about energy storage devices for EV charging [29]. In [30], multi factors affecting the EV charging load are presented. According to the study, policy, environment, market, infrastructure, user, and technology are significant parameters that affect the charging load [30]. The researchers indicated the frameworks, objectives, architectures, gains, and challenges of the energy management systems of several stakeholders and participants in the study [31]. Also, it provides a key analysis of the behavior of distributed energy generation and various programs like demand response, demand-side management, and power quality management used in energy management systems [31]. The impacts of EVs and sustainable energy resources were analyzed in terms of smart charging, coordinated scheduling, and energy management [32]. In [33], the impacts of EVs on power distribution networks are explained. Technical problems regarding modern power electronic converters, impacts on voltage/frequency, and challenges on supply/demand are detailed by the researchers [33]. Ref. [34] was dedicated to exploring and considering the challenges that EVs pose to the grid. The study dealt with the following subjects: power quality issues in conventional and modern power networks, EV topologies, power quality in conventional grids using EVs, and power quality improvement in smart grids using EVs [34]. The study examined the impacts of EV–grid integration on operating costs and the power demand curve for a distribution line with a high penetration of clean energy sources [35]. Studies on the integration of smart grids with EVs seem to focus on some issues. However, the lack of a detailed study describing the power quality effects and main contributions of EVs on smart grids is a shortcoming. For this, the current work aims to develop a detailed understanding of the impacts and contributions of EVs on a smart grid.

Compared to previous studies, the present study provides a comprehensive elucidation and analysis of the effects on the power system and the significant roles played by electric vehicles (EVs) integrated into smart grids. The main objectives and major contributions of this paper are given as follows:

- The effects of EVs on the stability of the power system are analyzed, focusing on both voltage and frequency stability. Subsequently, the impact of EVs on voltage and current distortions in the network resulting from their connection is assessed.
- The prevalent waveform distortions induced by integrating EVs into the grid, including harmonics, supraharmonics, overcurrents, sags/swells, imbalances, and fluctuations, are emphasized.
- A demand response program was conducted according to the load profile and power losses regarding the EV–smart grid connection to provide a perspective about the pros and cons.
- Energy management schemes for an EV–smart grid integration is elaborated on in terms of load management, supporting renewable energy resources, improving the

utilization efficiency of electrical energy generation, improving the system power factor, and energy saving.

- Subsequently, scheduling processes that preserve a stable grid operation are detailed to present a frame of reference for system operators.
- The potential compensation functions of EVs integrated into the smart grid are provided as power quality support functionalities.
- Finally, socio-economic impacts like greenhouse gas emission reduction, noise reduction, and the green environment are emphasized and clarified as possible contributions.

This remainder of paper is structured as follows. In Section 2, the power system influences of EVs on the smart grid are explained. Key contributions of grid-connected EVs to the smart grid are presented in Section 3. Finally, conclusions and discussion are presented in Section 4.

## 2. Power System Impacts of EVs

A smart grid including conventional and clean energy resources aims to provide electrical energy with higher reliability, a lower energy consumption, and lower cost. As presented in Figure 1, a smart grid includes a variety of conventional energy generation and clean energy sources, as well as consumers. On the other hand, it is emphasized that two-way energy exchange can be achieved when the role of EVs in smart grids is considered. The charging/discharging capabilities of EVs distinguish them from other energy units. However, the electronic equipment of EVs and their integration into the smart grid create some problems and effects in the network [36]. For this reason, the possible power quality effects of EVs on smart grids will be discussed in this section.

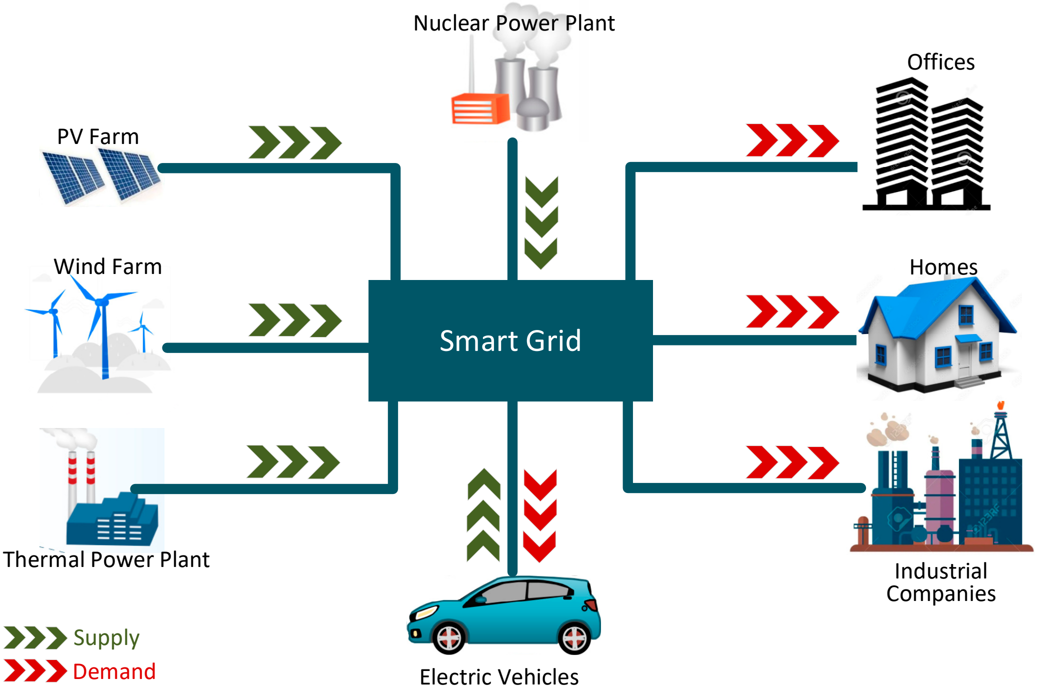


**Figure 1.** An illustration of the roles of EVs and other suppliers/consumers in the smart grid.

### 2.1. Impact on Power System Stability

Power system stability is defined as the return to a normal or stable operating state after a malfunction in the power system. Power outages in the power system have a significant impact on the stability of the smart grid. In addition, EVs have non-linear load characteristics in the power system and create various stability problems in the network. The fact that EVs have equipment such as a DC–DC converter and inverter power electronics causes some power quality deterioration, and this affects the grid. In addition, uncertainties such as the charging times, power ratings, and connection locations of EVs in the smart grid cause some difficulties in estimating the load behavior [37]. Therefore, connecting a large number of EVs to the smart grid causes significant concerns.

EVs are not only distributed energy storage devices but also power electronic converters and dynamic loads that affect the stability of the power system as an electrical load [38]. The power system stability effects caused by EVs in smart grids are summarized in Table 1. Among these effects, voltage instability occurs when the reactive power demand is not met and in overload situations [39]. System planning and the operation of EVs in smart grids are important in order to ensure the voltage stability of loads. It is known that EV load group characteristics connected to the network cause voltage instabilities [40]. Although EV loads tend to consume more energy in low-operating voltage situations, they also negatively affect the voltage stability of the system. In order to minimize voltage stability problems, the optimal placements, quantity, and power ratings of EV charging stations should be determined according to the network structure [41].

Frequency stability and its control are significant problems for system design and operation in smart grids. Various control loops serve to keep the system frequency at a constant set value. The general purpose of these control structures is based on a certain amount of power reserve that is kept ready against power deviations [42]. Variations in power supply and demand may have a significant impact on grid frequencies. For example, if more power is needed than that available, the frequency will be less than the nominal value. In the opposite case, injecting the excess power value to the system will cause the frequency value to increase. Electrical systems require real-time equality between generation and consumption to provide a stable grid frequency. Otherwise, the grid frequency deviates from the desired value. More power has to be generated and supplied to keep the grid frequency within the allowed range if a high-rated load from the EVs is placed on the grid. Additionally, there are uncertainties related to the EVs' departure and arrival times. As a result, the consumer side becomes more unpredictable for power systems [43].

**Table 1.** Impact on the power system stability of EVs.

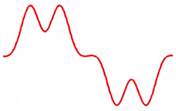
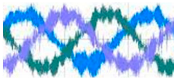
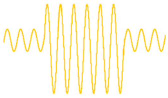
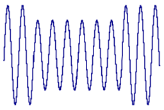
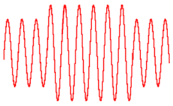
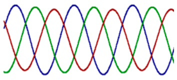
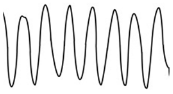
| Impact on Stability | Causes | Reference |
|---|---|---|
| Voltage | Placement, quantity, and power rating of EVSEs and integrating EVs as consuming loads | [40] |
| Frequency | Variations in power supply and demand | [42] |
| Oscillatory | The interactions between EV energy generation/consumption changes and system component controllers while connected to the smart grid | [44] |

Small-scale distortions that occur while trying to synchronize the power system are defined as oscillatory effects. The interactions between EV energy generation/consumption changes and system component controllers while connected to the smart grid cause oscillations. In the system, the capacity of synchronous machines to ensure the balance between electromagnetic and mechanical torques specifies the oscillatory stability of a smart grid integrated with EVs [44]. Oscillatory effects are classified under several modes like local mode, inter-area mode, and torsional mode. In local mode, the oscillating effects are limited according to a singular energy generation unit or a restricted local region of power generation systems. This mode is characterized by the oscillation of the local power generation unit against the rest of the entire power generation system. The frequency oscillation values occurring in this mode typically vary in the 0.7–2.0 Hz band. The oscillation of generators in one area relative to generators in another area is called inter-area mode. Typical frequency values change between 0.1 and 0.8 Hz in inter-area mode. Torsional mode pays attention to the energy generation unit and turbine rotating part in a power system. Sustained vibrations cause excessive aging and fatigue in power generation plant components and should be dampened. Additionally, if these vibrations are not properly controlled, these problems can lead to power outages [45]. Understanding the vibrational behavior of smart grids connected with EVs is critical to taking effective corrective action.

### *2.2. Voltage/Current Distortions*

In a smart grid, the generated electrical energy should be supplied to receiving-end users as a smooth waveform. Electrical quality also means that power companies have to supply power without nonstationary disturbances that may affect the operation of connected loads. In recent decades, electrical quality has become a major concern for both users and plants and grid operators. With more critical loads and sensitive devices in smart grids, users need a better quality of electrical power at all times. Differences in electrical current/voltage waveforms that are far from the ideal can be defined as the most important electrical power quality problems. The current/voltage problems that occur due to the EVs connected in a smart grid are characteristically different from each other. The effects of these problems cause different destructions and malfunctions in the other connected power loads [46]. However, the duration of the effect on the user's side also varies. Table 2 shows potential power quality influences and the electrical characteristics of EVs connected to a smart grid. The electrical characteristic properties of voltage/current distortions are explained in [47]. As shown in the power quality influences of EVs in a smart grid, the most common problems owing to EV–smart grid integration are presented as harmonics, supraharmonics, and overcurrents. Sags, swells, unbalances, and fluctuations are voltage distortions that affect the users in the smart grid.

**Table 2.** Potential voltage/current distortions due to EVs integrated with the smart grid.

| Distortion | | Causes | Effects | Duration | Magnitude | Waveform |
|---|---|---|---|---|---|---|
| Current | Current Harmonics | Non-linear characteristics of EVs and EVSEs | Overheating of components | Steady state | 0–100th |  |
| | Supraharmonics | Power electronic converters triggered above 2 kHz | Cause to overheat and shorten the useful life of the equipment | Steady state | 2–150 kHz |  |
| | Overcurrents | EV load alterations | Malfunction of switching components | >1 min | >>1.1 pu |  |
| Voltage | Sags | Start-up of EV loads | Data loss and damage | 0.5 cycle–1 min | 0.1–0.9 pu |  |
| | Swells | Switching off EV loads | Hardware damage | 0.5 cycle–1 min | 1.1–1.4 pu |  |
| | Unbalances | Unbalanced loading | Unequal overheating and (-) sequence currents | Steady state | 0.5–2% |  |
| | Fluctuations | Integration level and charging rate of EVs | | Intermittent | 0.1–7% |  |

EVs and charging stations contain a significant number of power electronic converters. These transducers provide them with a non-linear characteristic [48]. The non-linear behavior of these systems in a smart grid causes harmonic distortions on current waveforms. Due to the fact that household loads vary throughout the day and EVs charge only during specific times, current harmonics occur dynamically [49]. Serious issues might arise from the impact of current harmonics on electrically linked equipment. Moreover, the overall efficiency of the system would decrease, and malfunctions may occur if these harmonics are present in the grid. In an electric power plant, current harmonics can be a multiple of the fundamental frequency of the system [50]. The form or properties of a current waveform in relation to its fundamental frequency is a way to define the harmonics caused by EVs and charging stations. Harmonics are present in waveforms that depart from a sine wave appearance. The amount of harmonic distortion in the current waveform is estimated according to the concept of total harmonic distortion (*THD*) [51]. The *THD* value is defined as the ratio of the sum of the powers of the harmonic components to the power of the fundamental frequency [47]. For an ideal current shape, it is a complete sine wave consisting of only the fundamental frequency, and the *THD* value is zero. In systems without harmonic components, the *THD* value will not take any value. The *THD* value calculation in current waveform with harmonic components is expressed in Equation (1):

$$THD = \frac{\sqrt{\sum_{n=2}^{\infty} I_n^2}}{I_1} = \frac{\sqrt{I_2^2 + I_3^2 + .. + I_n^2}}{I_1} \tag{1}$$

where $I_n$ defines the nth harmonic component of the current, and $I_1$ defines the fundamental component value of the current signal.

Supraharmonics are known as distortions in the current waveform with a frequency range of 2 kHz to 150 kHz. The increasing amount of EVs and EVSEs with power electronic converters triggered above 2 kHz also significantly increases the amount of supraharmonic distortions in the current and voltage waveforms. These high-frequency harmonic distortions affect the operation of sensitive devices connected to smart grids. In addition, this increases the thermal stress in the devices and reduces their lifetime [52]. Since EVs are generally charged with high power and are more susceptible to supraharmonic distortions than other consumer electronics, the impact on low-voltage installations is more significant. Supraharmonics induce various effects on low-voltage networks and the electronic devices tied to them. For a weak network in a high-impedance situation, the system current has supraharmonic components with large amplitudes, this may also the increase voltage distortion. The voltage disturbances reproduce extra supraharmonic currents into the plant, influencing more equipment. Basically, the electronic equipment is generally not immune to distortions in the aforementioned frequency values, as the supraharmonic emissions have been partially standardized until now. These problems can cause them to overheat and shorten their useful lifetime [53]. The faulty operation of power line communications, audible noise, and electromagnetic incompatibility are other negative adverse effects of supraharmonics [54].

In smart grids, EV load alterations can cause overcurrent, which is defined as an increase in the current. When the typical load current is exceeded in the smart grid, this results in an overcurrent [55]. Overcurrents can cause the destruction of the switching elements. In addition, the overloading of EVs is the main source of these problems. Circuit breakers and fuses are used to safeguard electronic equipment from hazardous overcurrents [56].

The start-up of EV loads is one of the reasons for the voltage sag in the main voltage. When a voltage sag problem occurs, the nominal voltage value decreases to between 0.1 and 0.9 pu. The duration of the voltage sag varies between half a period and 1 min. In addition, faults in the power system are also known as the most important factor causing voltage sags. After this problem occurs, very high currents can be seen in the system. Voltage sag can create harmful effects such as data loss and damage to equipment. On the other hand, the disconnection of EV loads may cause a rise in the network voltage [57]. An increase in voltage value is called a swell. In this situation, the value of the increase in voltage is more than 0.1 pu. The time interval of the swell problem is half a period to one minute. Voltage swell can cause hardware damage in smart grid systems [58].

$$V_{grid} < 0.9 \text{ pu} \rightarrow Sag \tag{2}$$

$$V_{grid} > 1.1 \text{ pu} \rightarrow Swell \tag{3}$$

The single-phase connection of EVs with smart grids causes unbalanced loading. This is because smart grids comply with system stability limitations and have considerable loading requirements in most cases. As a result, voltage imbalances occur. In this case, the amplitude values in the three phases differ from each other [57]. In addition, the dissimilar characteristics and loading planning of EVs create unbalancing issues. Loading characteristics have a large impact on the smart grid's voltage reliability [59].

As shown in Table 2, voltage fluctuations are defined as random voltage variations occurring in the range of 0.9–1.1 pu. Excessive voltage deviation causes reliability problems that must be prevented to ensure a safe operating process of electrical equipment. In smart grids, periodic changes in the voltage can occur when using equipment or devices that require high EV loads or EVSEs. These problems can be described as a series of haphazard or permanent changes. The integration level and charging rates of EVs mainly cause voltage fluctuations in smart grids [60]. The duration of voltage fluctuations is intermittent, while the fluctuation magnitude changes from 0.1 percent to 7 percent [47].

### 2.3. Load Profile

The main factors affecting the load profile are examined under three main headings: charging region, charging level, and charging moment. These factors assist in estimating the EV load profile and impacts on the smart grid [61]. Figure 2 presents the main factors affecting the load profile and their individual properties.

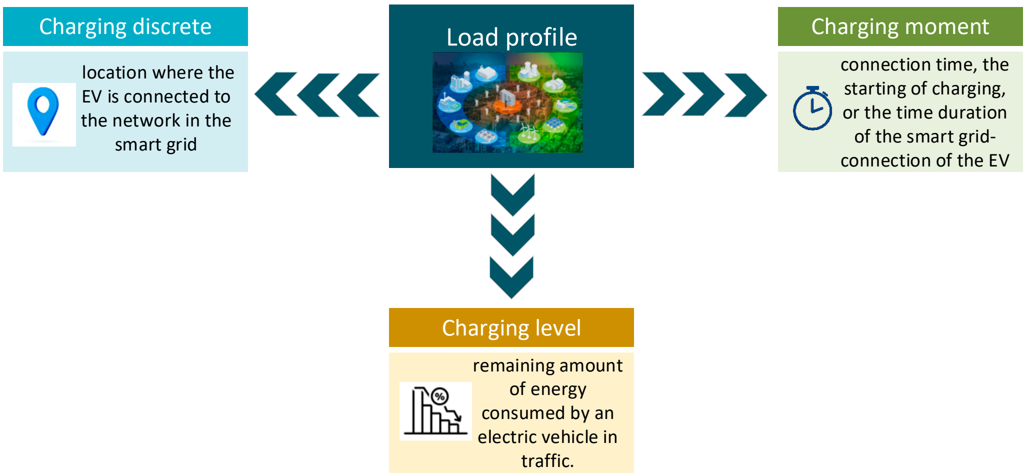


**Figure 2.** The main factors affecting the load profile in a smart grid integrated with EVs.

Charging region: It refers to the location where the EV is connected to the network of the smart grid. Generally, facility utilization is an important argument for a variety of private and public policies. When planning a parking lot, setting up a fire station, or setting up an emergency call center in a city, the question of optimal location arises. In addition, constant changes in population size, market trends, and peripheral factors necessitate the relocation, expansion, and adjustment of plants to keep them up to date [62].

Charging level: It defines the remaining amount of energy as a result of the amount of energy consumed by an EV in traffic. The electrical energy used by the vehicle is described in two ways: (1) energy consumed while driving and (2) energy drawn from the grid while the vehicle is charging. The amount of energy consumed while driving affects the charge level based on the travel distance, speed, and travel time [63]. When a vehicle is parked anywhere, its state of charge (SOC) provides information on the need for charging in the form of available energy capacity. While the vehicle is charging, the speed of the energy consumed from the grid varies according to the power rating of the EVSE. The power rating value of the EVSE determines the charging level duration [64].

Charging moment: It refers to the time that the vehicle's energy is charged. The charging moment can also be defined as connection time, the start of charging, or the time duration of the grid connection of the EV. In a study [65], the load time was predefined either with a specific start time or duration. In contrast, the start time was sampled using a probability distribution by the researchers in the study [66]. However, these approaches are limited to finding the time to recharge after the final drive or first commute. The researchers [67] also explored the possibility of connecting to car parks with charging facilities for recharging after each trip. In [68], charging times were based on stop-time statistics for commuting or non-shuttle driving trips, and charging times can also be shifted using external and/or charging strategies [61].

The impact between EVs and the power grid raises some uncommon problems. This means that vehicle loading needs to be predicted early to avoid undesired impacts on power grid operations. Without unique data on each vehicle's usage, it is not possible to fully investigate the desirable and detrimental impacts of vehicles on the smart grid [69]. In order to predict the overall ratings of EVs for the electrical energy demand profile, we need information about when each EV will start charging and the quantity of required electrical energy. The power taken by EVs poses a problem as it has a significant negative impact on the installment of the basic parameters of the smart grid, such as electrical generation, transmission, and distribution [69]. The load profile is the total amount of power that the EV requires at any given time within a certain range. Predicting the charge loading profile is compulsory for assessing how smart grids respond to EVs [70]. The load profile contributes to specifying some basic factors of the distribution network for influence assessments:

- Influences on local transformers;
- Distribution lines;
- Overloading and voltage unbalance;
- Power quality problems;
- Power losses and electrical efficiency;
- Power system stability and reliability.

### *2.4. Power Losses*

Power losses are defined as instantaneous losses, where the significant integration of EVs into the smart grid can result in significant efficiency reductions. Integrating a significant number of EVs into the smart grid requires enormous amounts of active power, leading to a poor performance in the electrical energy area [71]. With the integration of EVs into the grid, off-peak power losses increase to higher values. Researchers have explained that the uncoordinated charging of EVs leads to major increases in voltage deviation and power loss [72].

A particularly high number of EVs integrated into a smart grid will result in an additional load demand that requires energy generation and supply. Existing interface parts are not planned for the additional load, which can lead to the surcharging of the components and affect the transformer life [73]. Various systems have been proposed to solve the problem of EVs' influence on the smart grid. Coordinated charging improves the load factor and reduces power loss in the smart grid system. Energy loss from the power grid can be reduced by intelligently selecting the best locations and energy-filling capacities for energy storage stations. In a smart grid, power system stability can be developed by properly managing vehicle–smart grid integration. An efficient method for mitigating this impact is to combine domestic energy production with charging infrastructure such as sustainable energy resources [72].

In the smart grid connection, EVs generate current harmonics because they have several power electronic converter interfaces. According to the IEEE 519-2014 power quality standards, THD values have to be less than 5%. In several cases, individual THD levels are below 1% when the EVs are connected to the smart grid, but it may increase as the number of grid-connected EVs increases [74]. Many grid-integrated EVs require large amounts of active power, resulting in power losses in the energy area. Because EVs have non-linear load characteristics, they consume high amounts of active power in short time intervals, destabilizing the entire power grid [75]. With a large number of EVs integrated into the smart grid, the whole smart grid becomes very sensitive to interference, making it difficult to reach stability in a short time. Generally, the widespread adoption of EVs brings astonishing changes in the flow of electricity in the grid. At some point, the presence of a large number of EVs in a given area will peak the demand in the energy sector, increasing transmission line losses and reducing the voltage. In addition, voltage reduction can be tolerated up to a definite level, after which the grid will no longer supply electrical power [72].

According to grid operators, power loss is an economic issue while EVs are connected to the system. These losses should be diminished significantly, and transformers/feeders have to be prevented from overloading. Not only the power loss but also the quality of the network (voltage sags, unbalances, harmonic problems, etc.) are of great importance to both smart grid operators and network customers. In addition, night-time network connection can also induce base-load power plant utilization, smoothing the daily cycle or avoiding supplementary generator initiations that reduce the entire performance. From the EV owner's perspective, the EV's battery needs to be charged at night to have a fully charged vehicle before departure. This offers smart integration opportunities. Grid integration can be adjusted from a distance to change the demand to periods of low energy consumption to avoid high power consumption peaks [76].

## 3. Key Contributions to Smart Grids

Integrating EVs into the smart grid provides several contributions like energy management, scheduling, grid quality support, and socio-economic impacts, as expressed in detail in this section.

### *3.1. Energy Management*

Due to the increase in electrical energy consumption and the changeability of electrical loads, supply/demand can pose difficulties for smart grid operators. High peak loads are likely to be formed over many periods and can pose a danger to operational functionalities. To overcome this problem, smart grid operators have two options. The first way is to enlarge the scale of the electricity network. This way is expensive and time consuming to apply. The second way is to reduce the possibility of a high peak demand with energy management during peak usage hours. In recent years, energy management for smart grids has gained a great deal of importance. As illustrated in Figure 3, the main contributions of energy management for smart grids are as follows: (i) load management, (ii) supporting renewable energy resources, (iii) improving the utilization efficiency of electrical energy generation, (iv) improving the system power factor, and (v) improving the energy saving. All of these points will be explored in more detail in the following.

Load management: Smart grid–vehicle integration can supervise power loads by discharging energy storage units from EVs to supply the electrical grid during peak demand times and charging them from the grid during low demand. Load planning is used to handle peak loads and shift load curves [77]. The influences of an EV fleet on smart grids are smoothly mitigated through load shifting. This process can be accomplished through charge regulation. The main target of controlled EV chargers is to shift energy-consuming values and smooth peak loads. It is emphasized that peak power control is a significant cost-effective modality for load management [69].

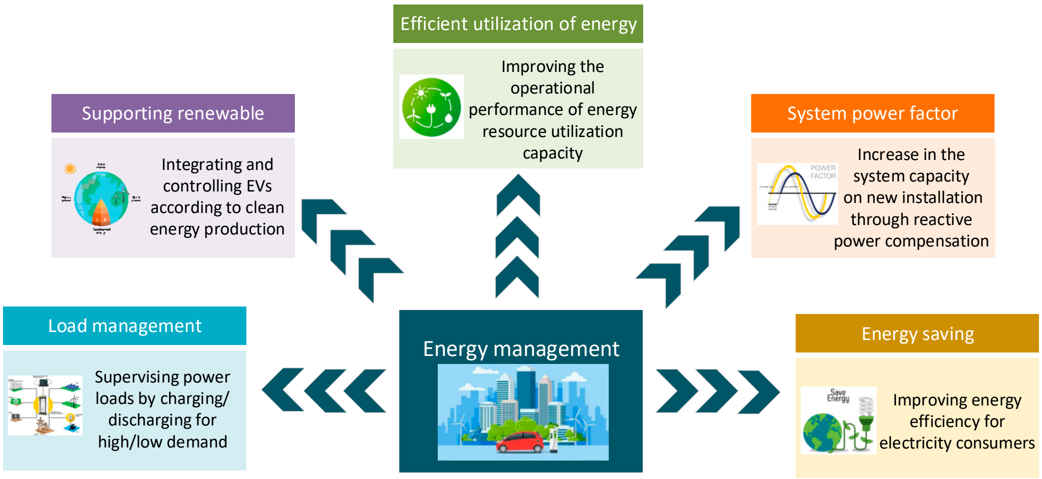


**Figure 3.** The fundamental contributions of EV–smart grid integration regarding energy management.

Supporting renewable energy resources: In smart grids, EVs function as alternative energy sources such as wind and PVs in the network. According to the production amount of other clean energy sources, the value of the amount of energy obtained from EVs can be controlled in a V2G system. Explained more clearly, in cases where the power produced in renewable energy sources is very high, the central power plant needs to reduce its energy production [69]. The balancing of production/consumption values with EVs is provided by the charge/discharge events of the vehicles. EVs can store surplus energy through renewable energy sources to meet transport requirements or feed the network when the electrical energy consumption from power loads increases [78].

Improving the utilization efficiency of electrical energy generation: Optimized scheduling techniques are widely used in cleaner productions like those of EV, wind, solar, and PV systems connected to a smart grid. Optimization plans can improve the operational performance of energy production resource utilization, increase the connected clean energy capacity, and diminish conventional fuel consumption at the source [79].

Improving the system power factor: The extension of the lines and the increase in the voltage levels also mean an increase in the reactive power level. Reactive loads connected to the network also cause this amount to increase even more. The reactive power flow occurring in the network causes a voltage drop. When the existing systems are examined, it is seen that there are existing structures for the realization of reactive power compensation through EV–smart grid integration. The compensation of reactive power improves the system power factor and reduces network losses [80]. Improving the system power factor increases the system capacity and saves costs on new installations [81].

Improving energy saving: Smart grids integrated with EVs improve energy efficiency for electricity consumers. These structures provide a variety of parameters for electricity consumers, such as real-time and previous power consumption values, the carbon footprint from their power consumption, the instantaneous demand, the ambient weather situation, moisture, and light intensity [82]. The power values are sent to the user, helping the user to determine their power consumption mode and switch the operational situation. EVs are more efficient and supportive of access to the smart grid to enable the intelligent interaction of alternative energy sources and clean energy savings [83].

### 3.2. Scheduling

In a smart grid, an EV is characterized as both an energy consumer and an alternative energy storage unit, as well as a power load. EVs connected to the smart grid are integrated with charge/discharge modes. EVs, which can be integrated with the clean energy system and reduce the utilization of traditional energy sources, draw attention to a balance between the amounts of energy produced/consumed in a V2G system [84,85]. Figure 4 presents a typical scheduling process for EVs integrated into smart grids. The proper scheduling process is achieved using the charging information of EVSEs, road information, and vehicle information [86]. The smart grid operators have to plan smooth electrical energy management based on the information necessary to schedule the EV loads. Bidirectional communication information exchange between smart grid operators and EVs/aggregators should be realized. The scheduling process of the V2G system is also achieved using consumption and generation power profile information [87]. The smooth planning of EV integration can preserve grid stability and provide a balance between power generation and consumption [88].

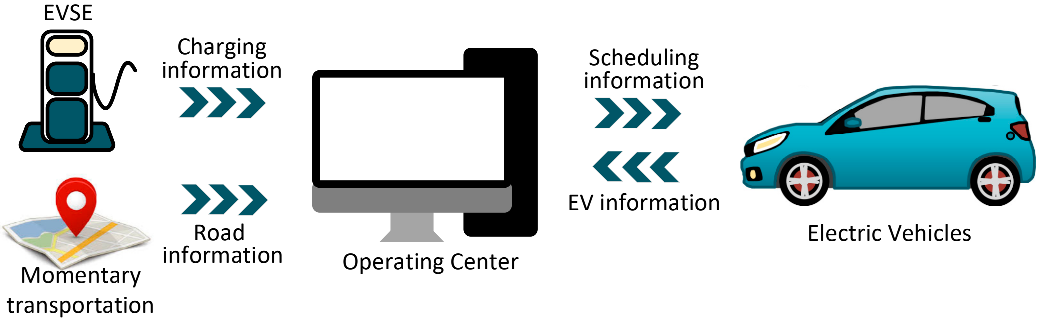


**Figure 4.** The scheme of a typical scheduling process.

Figure 5 summarizes the charging/discharging modes of EVs. The scheduling of EV charging/discharging can be classified under two headlines: control structure and mobility [89]. Figure 5 shows these scheduling types and their individual properties for the integration of EVs into the smart grid.

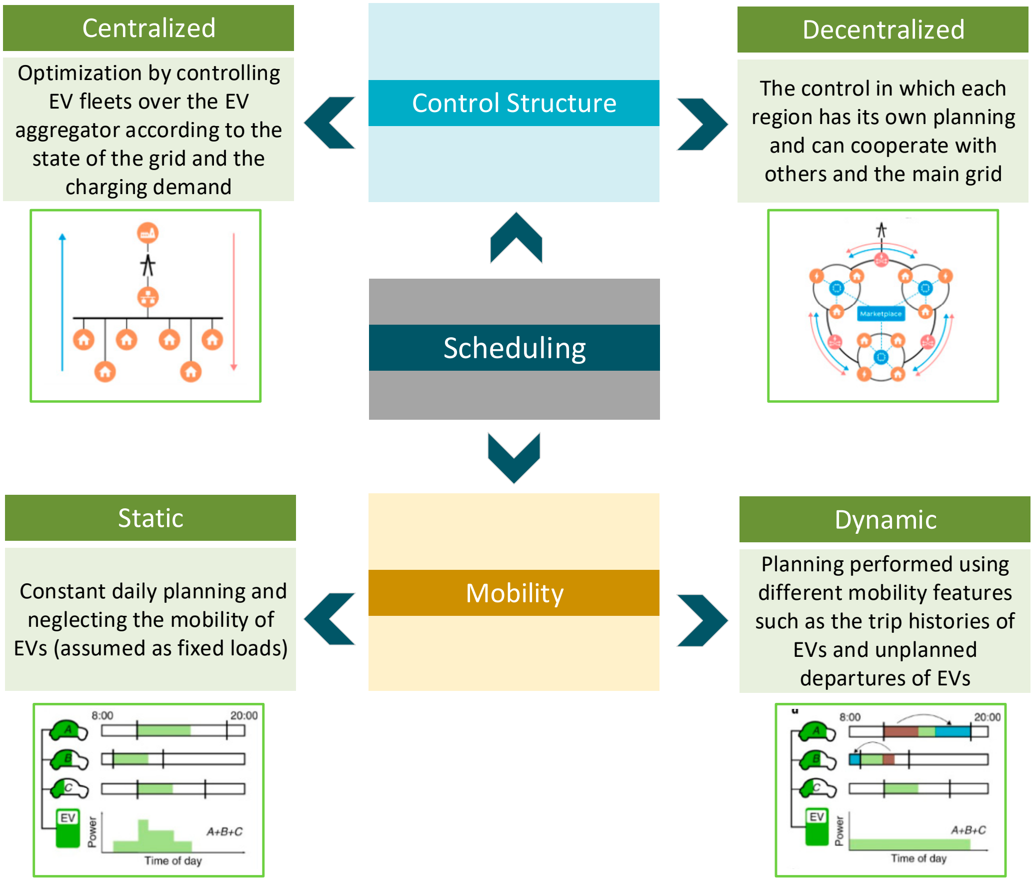


**Figure 5.** The classification of the scheduling process in terms of control structure and mobility.

As a control structure, centralized scheduling supervises the charging/discharging of EV fleets by taking information from the management center [90]. In the centralized programming method, EVs are optimized by controlling them over an EV aggregator according to the state of the grid and the charging demand. In order to determine the optimum loading/unloading strategy of the EVs, the aggregator is activated according to the loading demands and market behavior forecasts. EV aggregators charge their fleet of EVs according to the optimum load profile. In addition, each EV user is controlled by the aggregator through an online settlement system [91]. The control in which each region has its own planning and can cooperate with others and the main grid by exchanging electrical energy is called decentralized scheduling. Decentralized scheduling is more scalable and simple due to its lower computational and communication complexity compared to centralized scheduling [92]. EV owners can plan their charging according to their wishes in order to reduce the charging costs. Decentralized scheduling is an incentive approach in which the pricing behavior of EVs will be directly arranged by the electrical energy pricing program [93].

According to mobility, the scheduling process can be categorized as static and dynamic. Static scheduling refers to planning in which the mobility of EVs is neglected, assuming fixed loads, without the temporal characteristics of the mobility of EVs. Scheduling according to a natural vehicle entry–exit, where EVs come and go at any time, is expressed as dynamic scheduling. Dynamic scheduling is expressed as planning performed using different mobility features such as the trip histories of EVs and unplanned departures of EVs. For instance, charging demands can be predicted based on estimated arrival times at EVSEs; similarly, the unplanned departures of EVs and their effect on the smart grid can be investigated in dynamic scheduling. On the other hand, problem formulation in static planning is simpler than in dynamic planning [19]. A static schedule has constant daily planning that restricts the amount of electrical power for charging at different times of the day. In addition, it aims to reduce the load on a low-voltage grid by restricting the amount of power used to charge EVs [94]. According to dynamic scheduling, EV owners can park their vehicles at any time. Therefore, a parking lot operator needs a mechanism to supervise parked EVs in the smart grid integration. Various algorithms are employed to minimize the charging cost values for the EVs' dynamic scheduling schemes [95].

### 3.3. Power Quality Support

Power quality in smart grids is important for several factors. First of all, the equipment connected to the grid should be fed with uninterrupted energy and the supply/demand amount should be balanced. In addition, it is important that the systems operate at optimum energy levels. This is important for reducing electricity costs and contributing to the environment. Optimizing the electrical power means that the sensitive loads in the smart grid are less affected. Problems such as system malfunctions and overheating will be reduced. In addition, voltage problems on the network side and current problems caused by loads need to be compensated. Some power quality problems can be solved with the auxiliary functions of EV charging stations, such as harmonic reduction, voltage regulation, and reactive power mitigation [96]. In addition, EVs can be used as energy generation units for several concepts to mitigate power quality problems in smart grids. Figure 6 presents various concepts of EVs connected to a smart grid for the compensation of common power quality problems such as voltage sags and current harmonics.

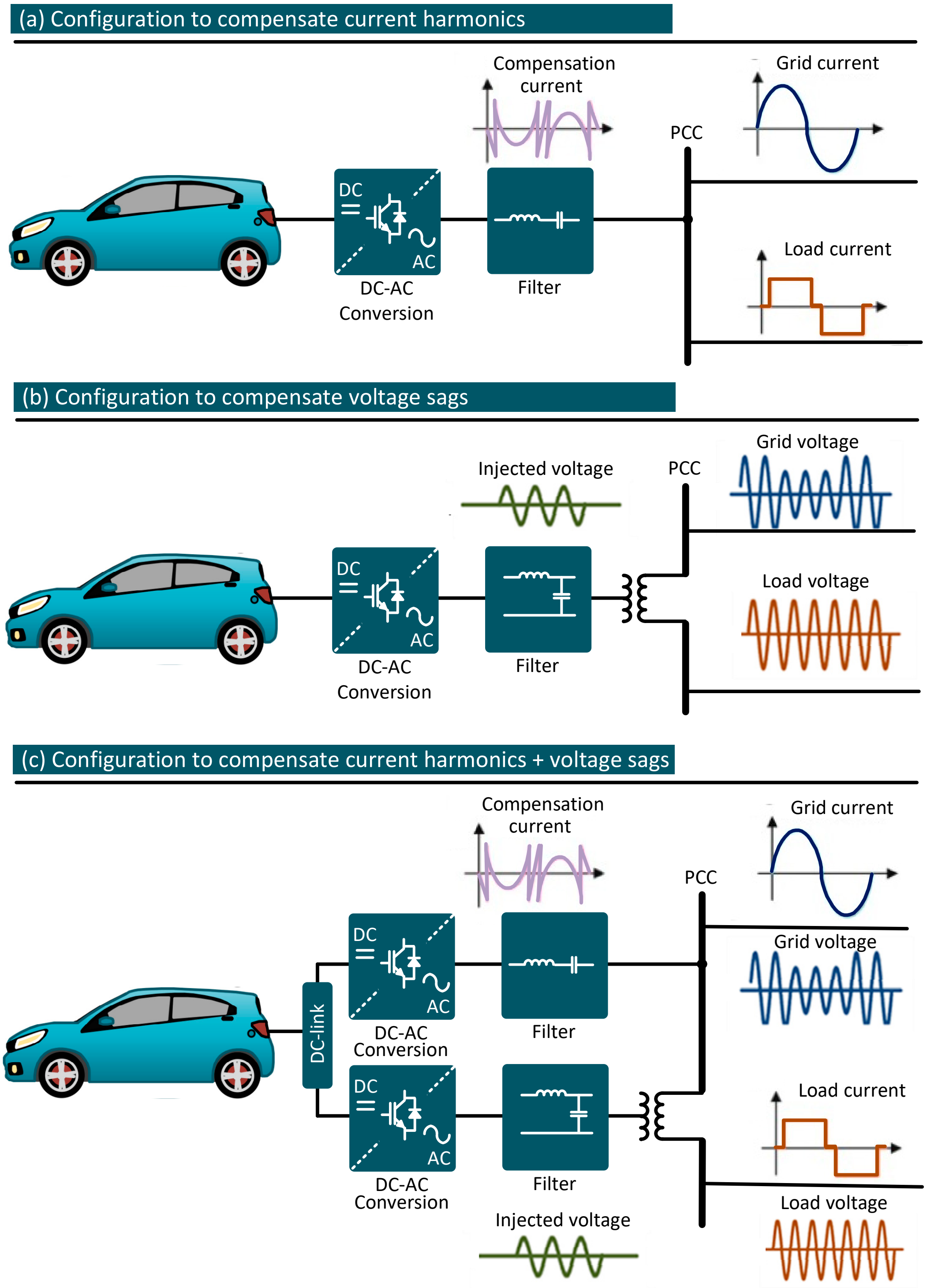


**Figure 6.** The potential compensation functions of EVs connected to a smart grid.

Smart grid-connected EVs can support the network during power quality problems. As shown in Figure 6a, EVs are connected to the point of common coupling (PCC) in order to compensate for the current harmonics caused by non-linear loads in the smart grid. The shunt connection of EVs through the converter interface is able to compensate for the current harmonics as well as for the power injection capability [97]. For instance, ref. [98] investigated EVs as a part of an active power filter to diminish THD values by less than 5% according to the IEEE 519-2014 power quality standards. The harmonic mitigating system behaves like a controlled current source, and the injected current is in phase with the system voltage. Common methods such as synchronous reference frame and instantaneous active power theory are used to extract the harmonic signals for the control process [99]. In case of short-term voltage sags in smart grids, it is desired that the electrical devices remain connected to the network during grid faults. This condition, which is necessary for system stability, is defined as the fault ride-through (FRT) capability [100]. As shown in Figure 6b, the voltage generated from an EV-based system connected to the smart grid is fed to the PCC by injecting series voltage in order to keep the constant voltage on the consumer side. This concept is also called dynamic voltage restoration [101]. In this concept, the injected voltage is computed as the difference between consumer-side and grid-side voltages. The system detects voltage sags to inject controlled series voltages from an EV energy unit through a DC–AC conversion interface. Then, the generated voltage is filtered and fed to the PCC by the transformer in order to provide the FRT capability during voltage sags [102]. In addition, the dynamic voltage restorer is able to compensate for the voltage swells in addition to voltage sags to protect sensitive loads against hardware damage. Figure 6c presents a hybrid concept for the compensation of both current harmonics and voltage sags. In the hybrid concept, called the unified power quality conditioner, an EV feeds both a series inverter and a shunt inverter with a common DC link connection. The unified power quality conditioner is an advanced custom power device that can also compensate for power quality problems like voltage swells, voltage harmonics, unbalances, and reactive power in addition to current harmonics and voltage sags [103]. Although it is a multifunctional structure, it has disadvantages in terms of cost and control complexity compared to an active power filter and dynamic voltage restorer.

EVs can play a significant role in the compensation of reactive power as well as in supporting active power in a smart system. In the smart grid, EVs are shunt-connected to inject reactive power for the compensation process. The compensation of reactive power in smart grids can contribute to diminishing power losses and improving the voltage profile [104]. The compensation helps to reduce the loading of distribution lines and transformers and allows to deliver more electrical power by reducing the overloading of smart grid components. Reactive power compensation is performed as an additional function by EVs in smart grids [105]. For instance, a vehicle can perform both the reactive power compensation function and charge. On the contrary, the vehicle can both supply power to the grid and eliminate reactive power.

### 3.4. Grid Balancing

Grid balancing represents the energy supplier's task of delivering the right amount of power to the network in a smart grid. Grid balancing has played a vital role recently with cheap, clean energy sources like EVs, wind turbines, and PV panels pouring power into the interconnected power infrastructure [106,107]. These clean energy sources rely on inherent phenomena, so smart grids are frequently underpowered or overpowered. If these undesirable situations are not properly stabilized, overvoltage can disturb electronic equipment tied to the smart grid [106]. In the absence of energy storage, it is not possible to store electrical energy, but the supply demand values must be equal for smart grids and conventional grids. For this, grid balancing becomes important in smart grids.

Grid balancing implies that power consumption always corresponds with power grid generation. Since electrical power is inherently difficult to store and must be available when needed, the supply must always be identical to the consumption, in spite of constant fluctuations in both. In an unregulated smart grid, the transmission system operator should provide the grid balance situation. Figure 7 summarizes three different scenarios according to the supply-and-demand situation. This discussion details what happens when the frequency of the system starts to drift away from the desired value (approximately 50 Hertz). The aim of grid balancing is to keep the power demand and supply in balance at all times, especially in the timeframe of seconds to minutes. If the supplied power is less than the demand, the grid frequency becomes less than 50 Hz (Figure 7a). If supplied power is higher than the demand, the grid frequency becomes more than 50 Hz (Figure 7b).

Frequencies must be kept within legal and operational limits. When the supplied power is equal to that consumed, equilibrium is achieved and the frequency value is equal to 50 Hz (Figure 7c). For grid balancing, grid operators realize positive balancing when the generation is low and consumption is high. In positive balancing, the generating source must produce more energy, or the consumer loads must consume less energy. In negative balancing, this process is conducted in the opposite way of positive balancing.

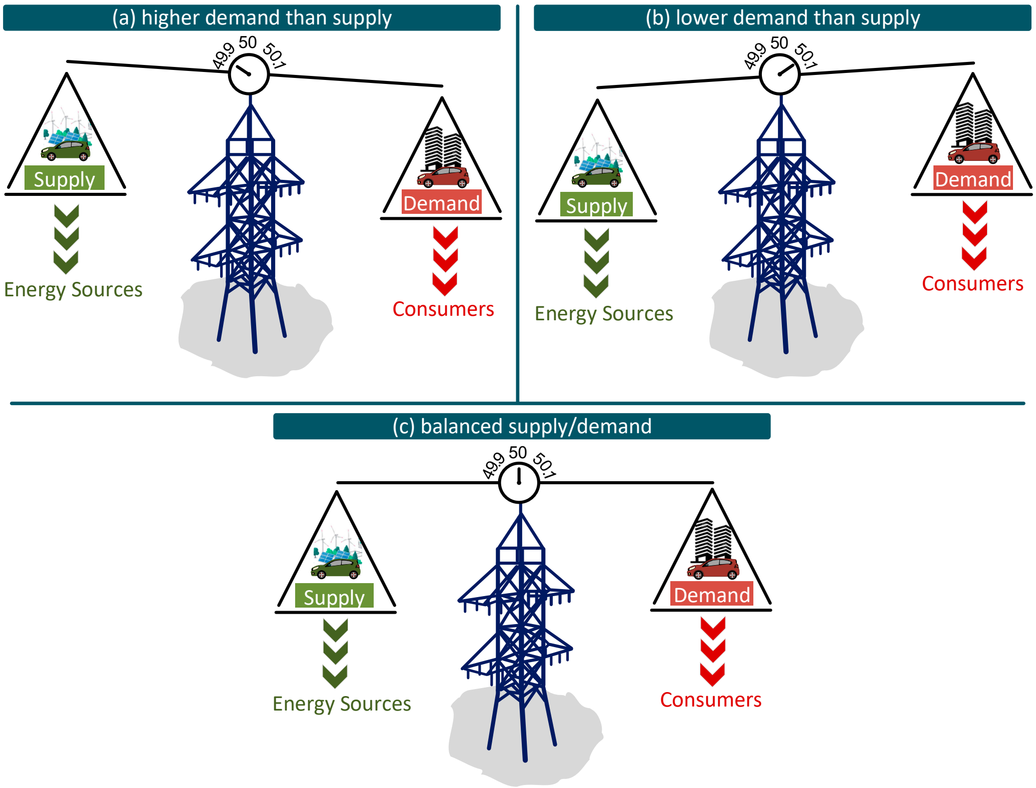


**Figure 7.** Frequency variation for supply/demand situations.

The smart grid operators rely on peak shaving and load shifting to avoid high consumption peaks, especially from high-rated consumer loads such as industrial vehicles and EVs. The smart grid has to be built to accommodate the highest demand for power during peak loads. EV loads may fluctuate as a result of the regular operation of multiple industrial companies, like starting or accelerating a production process. Peak shaving is a method for prohibiting peak load values, reducing grid development expenses, and providing saving costs [108]. If the electricity price and grid demand are low, load shifting defines a short-term reduction in electrical energy consumption followed by an increase in generation. If supervised properly, EV integration into the smart grid can greatly help to manage the supply/demand between consumers and producers [109].

Auxiliary services provide the smooth operation of smart grids. Grid balancing is handled by system operators (transmission system operators, distribution system operators). To supply controlled electrical energy, it is required to keep the frequency, voltage, and power within limited values. This process is achieved through an operating center [110]. A large cyclic generator can be employed for frequency control, but it is a relatively expensive solution. EV energy storage units offer fast charge and discharge rates in smart grid systems, making the power plant an effective option for grid balancing [69].

### *3.5. Socio-Economic Impacts*

Since EVs are alternative energy sources, owing to their storage capability, their integration with smart grids creates various prospects for future human life. With the integration of EVs into smart grids, they can have some social and economic contributions. Social changes will create new job opportunities, play an important role in environmental cleanliness, and indirectly affect human health. The environmental role of EVs in smart grids is to reduce carbon dioxide gas emissions and pave the way for the transition to low-carbon energy. It is known that EVs contribute to nature by reducing gas emissions in traffic. It is clear that conventional fuels significantly increase environmental pollution and affect the life expectancy and quality of life of people living in these environments. The influences of automobiles on environmental pollution will increase as the electrical network's carbon emissions decline. Because of this, it has been demonstrated that EVs have significant environmental advantages in an energy grid without carbon emissions [111].

Conventional energy sources such as fossil fuels and wind turbines in smart grids create noise pollution in the regions where they are installed [112,113]. For this reason, it is a serious issue to reduce this noise pollution for human health and living standards and to find new solutions. For this reason, the utilization of energy storage units such as batteries and fuel cells in EVs also contributes to reducing noise pollution [114].

Along with industrial and technological developments, energy production methods are developing and renewing. With the use of EVs, it is expected that new jobs and new occupational groups will be formed in the smart grid industry as well as in the automotive industry [115,116]. Current and potential jobs for the integration of EVs in smart grids can be listed as follows:

- Research and development engineers;
- EV charge point installer;
- Sales and marketing staff;
- Scheduling center director;
- İnstallation and maintenance staff;
- Charging analysis and control system researcher.

Smart grid technology improves the proportion of impermanent clean power generation sources like hydrogen, wind, and PVs, and increases the capacity of on-grid renewable generation in the network system. Furthermore, smart grids facilitate energy savings in power supply systems. A key benefit of smart grids is the ability to enhance the utilization and energy consumption efficiency of power systems [117]. Electricity consumed from the smart grid can be stored in EVs via charging stations for later use. The overall electricity bill can be diminished by charging an EV energy storage unit using the smart grid's energy resources together with optimally priced tariff schemes. By integrating communication, control, and software technologies into the system, it is also aimed to provide electrical energy with higher reliability and lower costs through smart grids connected with EVs. As a result, it reduces system costs related to energy production, storage, distribution, and facility maintenance through EV integration [118].

## 4. Discussions

In the literature, most studies have dealt with the integration of EVs as an alternative energy source in smart grids being applicable and beneficial for a variety of ancillary contributions. In addition, the existing studies explain and detail the role of EVs in smart grid integration. In vehicle–smart grid integration studies, researchers classify system concepts in terms of unidirectional/bidirectional charging and centralized/decentralized scheduling. In addition, the previous studies have classified the concepts, frameworks, benefits, challenges, and optimization methods for the integration of electric vehicles into smart grids. Some studies explain the economic and reliability implications of the vehicle–grid integration sector. Also, on-board/off-board charging infrastructures, challenges for energy storage technologies, and communication requirements for EVs have been presented in the literature. The charge planning, renewable energy integration, and infrastructure facilities of EVs have been clarified with the complexity of charging EVs connected to smart grid technology. Also, the existing studies provide information about the feasibility of a smart V2G system, the interaction of EVs in smart grids, and the integration of sustainable energy resources such as PVs and EVs. The integration of plug-in EVs in smart grids such as vehicle-to-grid (V2G) and grid-to-vehicle (G2V) systems has been another interesting topic for researchers. Some studies present the factors that influence the EV charging load in terms of policy, environment, market, infrastructure, user, and technology. In previous studies, researchers have presented the frameworks, objectives, architectures, benefits, and challenges of the energy management systems of various stakeholders and participants. Also, key analyses of the behaviors of distributed generation and various programs such as demand and response, demand-side management, and power quality management used in energy management systems have been presented. The impacts of EV–grid integration on operating costs and the electricity demand curve for a distribution line with a high penetration of clean energy sources have been examined in previous studies. Studies on the integration of smart grids with EVs seem to focus on some issues. However, the lack of a detailed study describing the power quality impacts and the main contributions of EVs to smart grids is a shortcoming. Therefore, the current work aimed to develop a detailed understanding of the impacts and contributions of EVs on smart grids. Compared to existing review studies, the current study clarified and explained in detail the power system impacts and key contributions of EVs connected to smart grids. With regard to the power system impacts of EVs, the effects on power system stability were first expressed in terms of voltage stability, frequency stability, and oscillation stability. The voltage and current distortions due to EVs connected to the grid were then expressed. This was followed by a discussion of the load profile and power losses associated with the EV–smart grid connection to provide information on the negative impacts. The key contributions of energy management for EV–smart grid integration were identified as load management, supporting renewable energy resources, improving the utilization efficiency of electrical energy generation, improving the system power factor, and energy conservation. Scheduling processes that maintain grid stability and balance power generation and consumption were then detailed for informational purposes. The potential balancing functions of EVs connected to a smart grid were presented as grid quality support. Grid balancing, i.e., the task of the energy supplier to supply the right amount of power to the network of a smart grid, was detailed in the current review. Moreover, socio-economic influences such as emission reduction, new business opportunities, noise reduction, and the green environment were highlighted and clarified as potential benefits.

In the end, the integration of EVs into the smart grid offers numerous potential benefits, including enhanced grid stability, increased renewable energy integration, and reduced environmental impact. However, realizing these benefits requires addressing challenges related to infrastructure, data management, policy, and regulation. Policy and regulatory frameworks, which play critical roles in incentivizing the integration of EVs into the smart grid, are highly required. On the other hand, ensuring data privacy and security is crucial to maintain the system operation. Distribution planning is also another significant area that needs to be focused on. Smart grid technologies can assist in managing this increased demand by implementing dynamic pricing mechanisms and load management strategies in case of using EV batteries as backup power sources during grid outages for enhancing grid resilience and reliability. The optimization of charging station deployment by identifying optimal locations based on factors such as demand patterns and grid capacity is another issue that needs to be focused on. Collaboration among stakeholders, including utilities, regulators, policymakers, and technology providers, is essential to successfully navigate the complexities of EV–grid integrations and maximize the potential contributions.

## 5. Conclusions

Increasing energy consumption and environmental problems in recent decades have brought developments and changes to the renewable energy and vehicle technology industries. The high-rated power units of EVs make them potential energy sources. In recent years, the integration of smart grids with renewable power plants has increased the importance of EVs for grid integration and the transportation sector. The evaluation of the energy units of these vehicles, which spend most of the day in parking lots, highlights several impacts on the sides of both the producer and the consumer. The integration converter interfaces of EVs into a smart grids provides different contributions like energy management, scheduling, grid quality support, and socio-economic impacts while their integration also poses several problems and implications for networks. The network contributions of EVs connected to a smart grid regarding energy management are load management, supporting renewable energy resources, improving the utilization efficiency of electrical energy generation, improving the system power factor, and energy saving. In addition, scheduling EV integration can preserve grid stability and provide a balance between the power generation and the consumption. In this study, the advantages and disadvantages of EVs as an ancillary service for the grid were extensively discussed to highlight the challenges and achievements for increasing grid reliability in the future. The additional capabilities of integrating EVs into smart grids can contribute to addressing notable power quality issues such as voltage regulation and compensating for reactive power. Moreover, in the current study, it is emphasized that the integration creates new job opportunities, a cleaner environment, and economical contributions for people. On the flip side, EVs have non-linear load characteristics in the power system and, therefore, pose various power quality problems to the network. EVs, which are equipped with devices such as DC–DC converters and inverters, lead to a reduced power quality and negative impacts on the smart grid. In addition, the current/voltage distortions occurring due to the EVs connected to a smart grid are characteristically different from each other. The most common current problems are current harmonics, supraharmonics, and overcurrents. Voltage sags/swells, unbalances, and fluctuations are known disturbances that affect the smart grid quality. The negative effects of these problems cause different destructions and malfunctions in the other connected consumer loads. The main factors affecting the load profile were expressed in terms of charging region, charging level, and charging moment in this study. Also, it was emphasized that integrating a significant number of EVs requires enormous amounts of active power, resulting in voltage drops and power losses in the smart grids.

The use of EVs in smart grid is still being studied and developed continuously. With the reduced cost of storage units, EVs are expected to become more common as a new vehicular technology in the practical implementations of smart grid integrations in the near future. The integration of EVs into the smart grid attracts a lot of attention with the improvements in the lifetime and capacity of the batteries. In this context, research studies on this vehicle–grid integration are going to focus on the following sections: (1) advanced charging systems, (2) energy management regarding a more efficient utilization of green energy sources, (3) the employment of EVs as auxiliary services for the reliable and secure operation of the grid, and (4) energy trading for vehicle owners. To this end, the challenges and findings discussed in this research can contribute to broadening the technical outlook for designers, researchers, and engineers who aim to address the use of EVs in smart grids.

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**Data Availability Statement:** The data presented in this study are available in the body of this paper.

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