Rooftop Photovoltaic Parking Lots to Support Electric Vehicles Charging: A Comprehensive Survey

Gerardo J. Osório [a,*], Matthew Gough [b, c], Mohamed Lotfi [b, c], Sérgio F. Santos [a,c], Helena M. D. Espassandim [b], Miadreza Shafie-khah [d], João P. S. Catalão [b, c,]

[a] *Portucalense University Infante D. Henrique (UPT), R. Dr. António Bernardino de Almeida, 541, Porto Portugal*
[b] *Faculty of Engineering of the University of Porto (FEUP), R. Dr. Roberto Frias, 4200-465, Porto, Portugal*
[c] *INESC TEC, R. Dr. Roberto Frias, 4200-465, Porto, Portugal*
[d] *School of Tech. and Innovations, University of Vaasa, 65200 Vaasa, Finland*

Abstract

Due to technological advances, the growing need for a decarbonized economy, and the desire to reduce urban air pollution, electric vehicles (EVs) are seen as promising developments for the progressive decarbonization of the transport sector. The potential for large scale integration of solar photovoltaic (PV) systems has not been explored fully, compared to other renewable energy uses in power systems. One of the proposed paths for the sustainable integration of EVs and solar exploitation in power systems involves the creation or installation of parking lots fitted with solar PV systems on their rooftops. This concept increases the reliability and robustness of the power system, as studies show that EVs are parked for the vast majority of the time. The EVs can then be optimally managed to assist the network in critical moments. The solar parking lot would then serve as a backup to manage the EVs' state-of-charge (SoC) which would guarantee the owners' comfort and help to accelerate the decarbonization of the economy. The present work presents a comprehensive survey of the state-of-the-art concepts of photovoltaic (PV) panels, EVs and batteries, and how the different associated technologies can be applied in the concept of solar parking lots.

Highlights

- A solar photovoltaic (PV) survey is presented considering PV technologies, efficiencies, market, and integrated support strategies.
- Available electric vehicle (EV) technologies and integration targets are reviewed.
- Comparisons of battery technologies are comprehensively reviewed.
- The interactions between PV systems, EVs and parking lots is addressed considering relevant studies.

Keywords: Electric vehicles, photovoltaic panels, power grid, rooftop photovoltaic parking lot, smart technology.

1. Introduction

Global energy systems are facing a paradigm shift caused by concerns around energy supply, climate change, and economic competitiveness. Most countries have recognized climate change as the most serious threat for the coming decades. For example, the European Union (EU) has set ambitious targets [1] to reduce greenhouse gas emissions (GHG) and in the process accelerating the decarbonization of the economy. Recently, the EU has developed a long-term road map to foster a low-carbon European economy by 2050 and as the main objective of this roadmap is a reduction of Europe's GHG emissions by 80% relative to 1990 levels [2].

*Corresponding author
E-mail address: gerardo@upt.pt (G.J Osório).

As a result of decarbonization plans, renewable energy sources (RES), energy efficiency and new transport technologies will require widespread exploitation, incentives, and improvements in integration to contribute to reducing GHG emissions. Therefore, the improved rollout of these technologies utilizing green energy solutions is of utmost importance. Solar energy is the most plentiful renewable energy resource. It is expected that solar photovoltaic (PV) resources may provide 5% of global energy usage in 2030, rising to 11% in 2050 [3]. Additionally, the EU also has environmental targets for the transport sector requiring reductions in GHG emissions by the end of 2050 [2].

Consequently, new opportunities and efforts are already available, or under development, for the integration of environmentally friendly electric vehicles (EVs) or the reduction of the investments or development incentives for conventional internal combustion vehicles (ICVs) [4]. EVs not only offer the possibility of minimal GHG emissions during their lifecycle, but they also reduce both air and noise pollution relative to ICVs [5].

Despite these advantages, both PV and EV have significant issues related to their integration such as: power stability (voltage and frequency) and flexibility (from conventional generation, energy flow, and grid limits) problems and these problems may threaten grid reliability. The main disadvantages of PV generation are its variability and uncertainty [6]. While, EVs could degrade power quality, and destabilize the conventional power system by increasing power demand thus overloading power systems [7].

These issues can be minimized by using PV generation for EV charging. As EVs spend a large amount of time stationery so utilizing car parking lots may be a critical point to consider in this process [8].

Typically, EVs are charged either at home or at work. The first situation generally occurs during the night, while the second situation normally takes place during the workday and it does not require a personal charging facility station. In this situation, daytime charging represents a supplementary load that may jeopardize the grid's stability [9]. Integrating RES with EV charging infrastructure, such as EVs' parking lot with RES infrastructure (EVSPL) can be a successful combination to mitigate the problems in the grid. This is especially important as EVs are parked over 90% of the time [10].

In this context, charging EVs through RES, such as PV, is a highly effective solution that provides several practical and economic opportunities while mitigating the concerns to the grid [11]. EVSPLs also emit zero GHG emissions during operation and reduce the need for additional land to be developed [12]. EVSPLs may accelerate the acceptance of EVs by providing charging infrastructure. Directly charging the EVs from PV facilities reduces the need for the integration of large PV capacities (or other RES) and this may reduce the need to reinforce the physical infrastructure to account for increasing EV integration [13].

When carefully designed and managed, the EVSPL contributes to environmental goals by using PV capacity and helps to accelerate the electric mobility expansion and in doing so overcoming possible ecological and technical problems [14]. The need for greener alternatives that simplify the integration of RES in power systems has become more evident. The replacement of conventional vehicles by EVs can help the reduction of GHG and pollutant emissions and considering the EVs capabilities to store and transport energy across both time and distance increases the power systems' flexibility [15]. Some successful examples exist, such as [16] where a combination of PV and EVs presenting an EVSPL may promote further research and efforts in this matter.

After describing the background, this manuscript provides a necessary overview of the large-scale integration of both PV and EVs, including the positive and negative effects on power systems, when the systems act independently or are combined. This is done by presenting a literature survey of relevant works in the subject areas is presented. This manuscript aims to provide a thorough foundation for future research in understanding the most common technologies and expected advances in EVSPLs to help realise their full potential to accelerate the clean mobility transition.

The remaining manuscript is presented as follows: Section 2 describes the PV principles, technologies, and markets. Section 3 presents concepts, incentives, features, and associated technologies of EVs. Section 4 shows the different battery and charging technologies used in EVs. Section 5 describes the interactions between the power systems, EVs and RES. Section 6 describes the combination of features of EVs and PV which provide the potential for the successful implementation of EVSPLs. Section 7 describes relevant studies in the field of EVSPLs and other relevant studies considering EVs, PV systems and demand response approaches. Section 8 provides the main findings of the proposed survey.

2. Survey of solar photovoltaic energy

The exploitation of the abundant solar energy resource to generate electricity is extremely dependent on factors such as geographical position, orientation, season, time of day, and weather conditions [17].

Despite its intermittent nature, solar energy is still considered a highly attractive energy resource. The exploitation of solar energy does not significant negative impacts on the environment. Power systems based on solar energy generation are also more accessible and applicable, especially in industrialized and urban/commercial areas [18]. Solar PV systems will be an important and growing industry in a low-carbon future [19]. Typically, a typical PV system is composed of the following four components:

- The PV module, composed of photovoltaic cells (semi-conductor cells), which when exposed to sunlight generates electricity [20].

- The optional charge controller, responsible for energy flow and charging of batteries (if batteries are included in the system), i.e., avoiding overcharging, so guaranteeing the proper state-of-charge (SoC) [21].

- The inverter, responsible for converting the direct current (DC) electricity, generated, or stored, into alternating current (AC), i.e., grid voltage and frequency AC levels [22].

- An additional or supplemental energy storage system (ESS) based on batteries may be used to store any excess power from the PVs, making it possible to use the stored energy during periods of insufficient generation to meet demand or to exchange energy with the grid [23].

From the previous description of the components of a traditional PV system, the focus of this survey is the PV module. Thus, the technical aspects of the remaining components are not included in this manuscript. The following sub-sections will try to further describe PVs and the importance to further exploit the potential for PV integration in power systems.

2.1 PV technologies

There are two main types of PV cells which are classified according to the raw material used and the level of commercial maturity of the technology which is further divided into three different groups:

- The first-generation PV cells use crystalline silicon technology (c-Si), more specifically monocrystalline (mc-Si), polycrystalline or multi-crystalline form (pc-Si), and ribbon and sheet defined film growth (ribbon/sheet c-Si). This group is the most widespread and advanced technology representing nearly 95% of the current market. Regarding efficiency, monocrystalline cells are the most efficient with rates between 16% to 22%, while for multi-crystalline cells efficiency ranges between 14% and 18% [20].

- The second PV generation uses thin-film technology and is typically divided into three categories:
    1. amorphous silicon (a-Si) and micro amorphous silicon (a-Si/μc-Si),
    2. cadmium telluride (CdTe),
    3. copper indium selenide (CIS) and copper combined with indium gallium diselenide (CIGS).

    Currently, thin-film technology is considered the principal candidate to replace crystalline silicon; however, it has lower efficiency, lower stability, and less durability [24]. The CdTe PV panels are the cheapest to manufacture among thin-film PV technologies [25].

- The third PV generation [20] consists of novel thin-film devices, e.g., organic PV technologies which are still at a demonstration phase [24], or are not at commercialized large-scale level, along with new concepts under development [25].

Fig. 1 illustrates the efficiency of each generation of PV module. As can be observed, the first-generation technology has a higher efficiency than second-generation technologies. However, the first-generation has a considerably higher cost per square meter (m^2), which implies that the first-generation is typically more expensive than the second-generation per watt-peak (W_p) of the module's power [20].

Turning back to the PV technologies, in worldwide PV integration, pc-Si PVs represented 60.8 GWp, mc-Si PVs had a capacity 32.2 GWp, and thin-film PVs accounted for 4.5 GWp. Moreover, c-Si PV technology leads the world market. Amongst thin-film technologies, CdTe modules accounted for an annual output of 2.3 GWp, followed by CIGS modules with 1.9 GWp, and a-Si modules with 0.3 GWp. In terms of production per year, thin-film PV technologies had a 5% market penetration in 2017 [13].
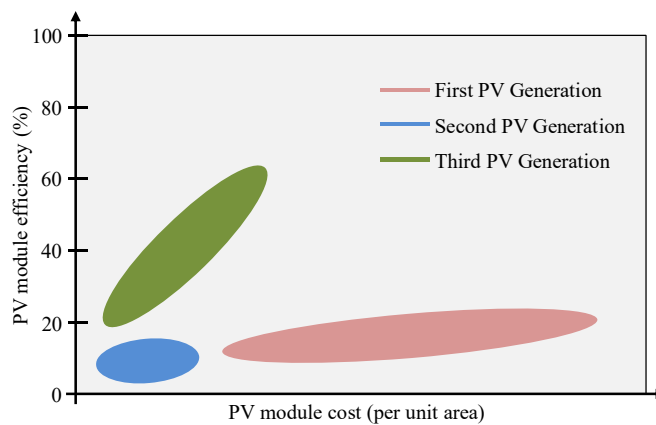
Figure 1
Distribution of cost and efficiency PV technologies [20].
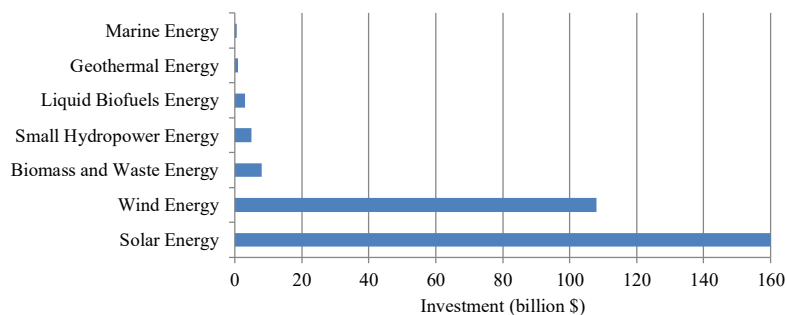
2.2 PV market

In recent years, the global PV market has grown incredibly quickly. For example, the global installed PV capacity increased from 8 GW in 2007 to approximately 402 GW in 2017 [27]. Currently, as shown in Fig.2, five countries lead the PV market, with a market share above 10%. However, several countries are experiencing significant market growth, such as India that had installed nearly 17 GW of PV by 2017, up from near zero in 2007. China is the prime example of the evolution of the PV sector; at the end of 2017, China had an installed capacity of approximately 131 GW, surpassing the government's planned target for 2020 which was 105 GW, and this goal was only set in 2016 [19]. The growth in the PV market has been mostly due to growth in China, despite the increase in new capacity in Europe [27].
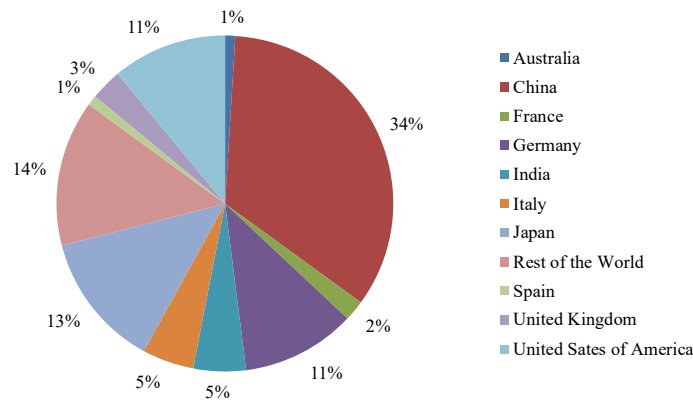
Figure 2
Countries' share in the PV global integration capacity [27].

Additionally, the growing recognition of environmental problems caused by CO_2 emissions combined with the rising demand for electricity in developing countries has also been key factors in the PV market expansion. In terms of investment in RES, it is also evident that new solar PV projects have been gaining interest. According to [28], more money was invested in PV in 2017 than in coal, gas, and nuclear power. As an example, Fig. 3 illustrates how solar (and wind) stand out from the remaining sources of RES in terms of investment. In 2017, investment in new PV facilities reached 160.8 billion USD, an increase of 18% when compared to the previous year.

The PV market is expected to continue its rapid development due to the implementation of global policies to support feed-in tariffs, tax incentives or tradable green certificates. The main purpose of these incentives is to increase the cost competitiveness of PV systems relative to conventional forms of generation [29].

Figure 3
Worldwide RES global investments by sector [28].

Fig. 4 demonstrates that most of the PV market is dependent on supporting strategies. Additionally, Table 1 summarizes the different types of support schemes in selected countries. These support schemes can be applied to many power systems and according to the local requirements [30]. It is expected that such schemes will go a long way to mature the PV market. Five of the most common types of support schemes are listed below:

- Competitive power purchase agreements (PPA) are long-term contracts (typically for 5 to 15 years) between two stakeholders to transact a specific quantity of energy, for a certain price, and a certain amount of time, to reduce cost uncertainties and profits. Typically, RES generators using PPAs are project developers or independent power producers that own the technology [30]. The buyers are usually utilities that have to fulfil the regulatory requirements associated with the renewable portfolio standard (RPS) [31]. The PPA will define the commercial terms for the sale of electricity between the stakeholders, including when the RES project starts commercial operation [29].

- Feed-in tariffs (FIT) are a type of PPA regime to encourage and accelerate investment interest in green energy technologies. It is a policy that offers a purchase contract for an extended period for RES energy sales. This is usually preferred for smaller-scale projects with sizes typically under 5 MW [29]. The RES investor will be remunerated by selling the electricity considering the terms of the contract besides the income for each unit of energy that is generated, regardless of whether energy is consumed locally [29].

- Tax incentives, associated with tax exemption, tax credits or carbon tax. This tool is used as an incentive measure to enhance both the development of RES in different countries, i.e., tax credits are used to facilitate the RES integration into the electricity market and for operations, e.g., for the purchase and installation of RES equipment. A carbon tax provides an incentive to increase investment in RES by imposing a higher cost on burning fossil fuels [30].

- Tradable green certificates, defined by the regulatory services, creates a tradeable certificate for each specific unit of energy generated from RES sources. These certificates may be traded to other agents who are required to reach certain mandates or requirement for the use of RES generated electricity. This incentive increases the financial reward for generating green electricity [31]. Finally, the self-consumption and net-metering (or smart metering), is a strategy that grants the owner of the PV system the opportunity to offset some of their electricity use through self-consumption [30].
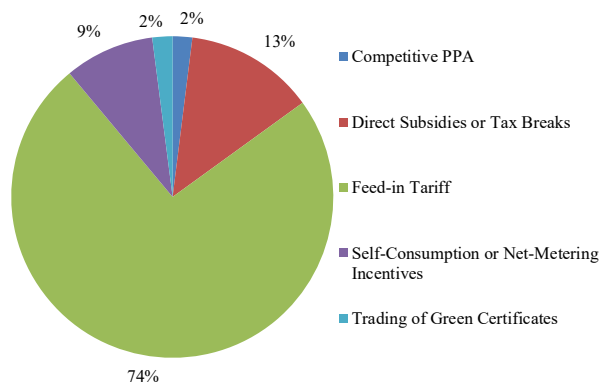
Figure 4
Overview of the integrated support strategies (in percentage) for the PV market [30].

Table 1
Overview taxonomy considering the support of RES strategies in some countries [30].

| Country	Tax Incentives	Feed-in Tariff	Self-Consumption	Net-Metering	Green Certificates
Australia		X	X	X	X
Belgium			X	X	X
China		X	X	X	
Italy	X		X	X	X
Portugal		X	X		
France		X	X	X	X
USA	X	X	X	X	X

2.3 Technology efficiencies of PV Systems

As previously stated, the efficiency of the PV cell is influenced by factors such as temperature, solar irradiance, and dust cover. The temperature may affect the PV cells' performance because as the temperature increases, the PV cells' efficiency decreases [32]. During use, dust accumulates on the surface of the PV module which reduces efficiency. This can be mitigated through frequent cleaning [24]. In a laboratory setting, the record for the highest PV cell efficiency record is 26.7% for monocrystalline silicon PVs and 22.3% for silicon multi-crystalline based technology. When considering the entire module, these efficiencies decrease to 24.4% and 19.9%, respectively [25].

In terms of thin-film PV technology, the highest cell efficiency reached in the laboratory is 21.0% for CIGS. This decreases to 19.2% when considering the PV panel and 19.6% for CdTe PV panels. An overview of this information is available in Fig. 5 [25]. Hence, the best performing modules in laboratory settings are based on monocrystalline silicon PV with an efficiency of 24.4% per PV panel [26]. Fig. 6 illustrates the laboratory efficiency of PV multi-junction concentrator cells reached 46.0% [25].
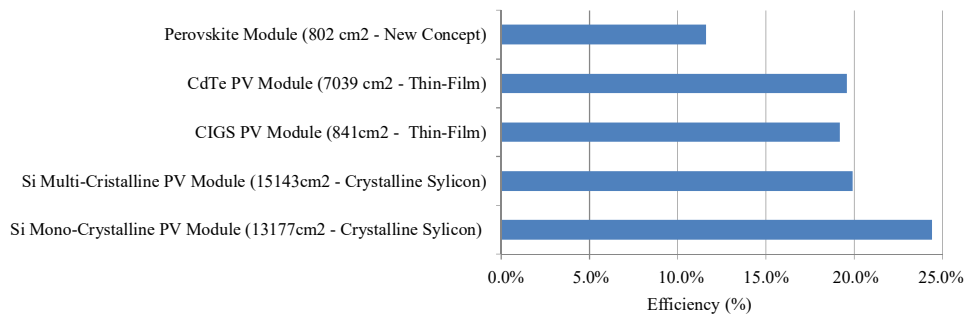
Figure 5
Laboratory comparison results between PV modules technologies [25].
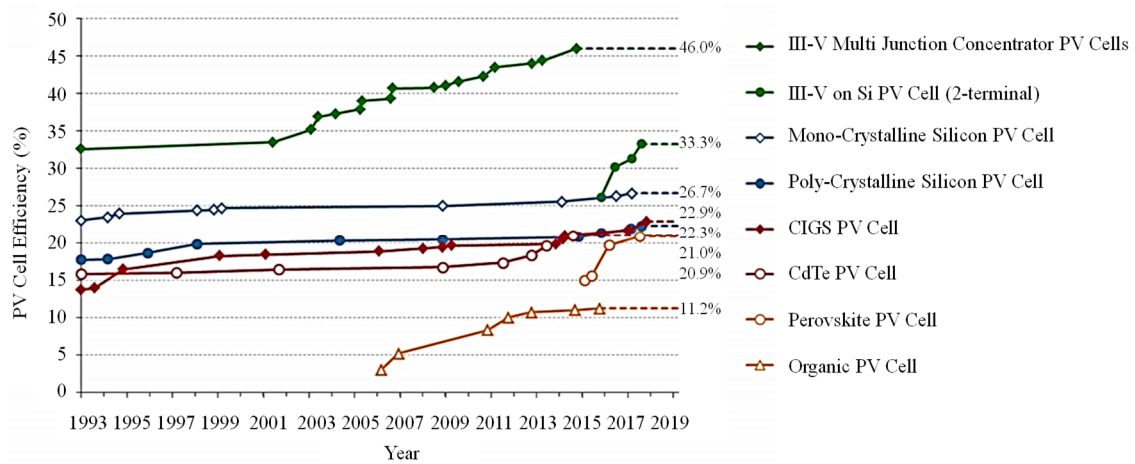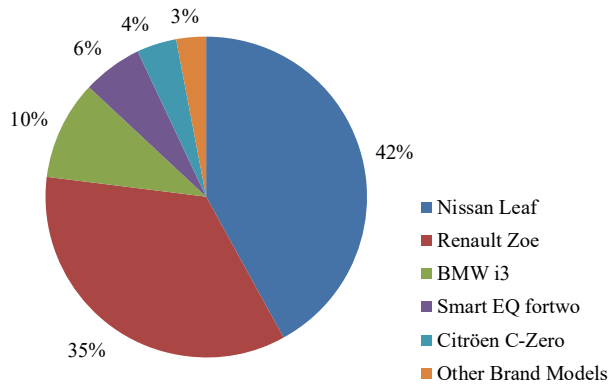
Figure 6
Laboratory PV cells efficiency [25].

3. Survey of current status of EVs

EVs are seen as a fundamental aspect of a low-carbon transport sector. Currently, 25% of worldwide GHG and pollutant emissions are from the transport sector. Therefore, electrification of the transport sector is essential for achieving decarbonization and energy security targets. This shift to clean mobility is the main pillar of various countries' policies for deep decarbonization of the transport sector, through the gradual and sustainable switch to EVs from conventional combustion vehicles [32].

China is the world's largest EV market with nearly 1.1 million EVs sold in 2018, having more than 2.3 million EVs, representing 50% around the worldwide EVs fleet. Europe is the second-largest market, with more than 1.2 million EVs, followed by the United States of America with more than 1.1 million EVs. Regarding the EVs market share, Norway is the market leader in Europe with a share of 46% of new EVs sales [33]. Following a similar trend, but fewer total sales, Portugal reached an annual record of 8200 EVs sold in 2018, representing a 95% growth compared to sales of EVs sold in the previous seven years. Furthermore, in terms of the EV models sold in Portugal, the Nissan Leaf represents the most popular, followed by Renault Zoe (due to their relatively low acquisition cost relative to other brands). Fig 7. Shows the five most popular EVs sold in Portugal [34].

Portugal has set the target for EVs to represent 33% of the transport sector fleet by 2030, mirroring similar policies from other European countries [35]. Table 2 shows examples of targets for EV integration in various countries [36]. However, EVs still struggle to be competitive relative to conventional vehicles due to the high purchase cost and limited charging infrastructure, and in this perspective, supportive mechanisms and policies are fundamental to increase interest and integration of EVs [36].

Despite increasing sales of EVs, and in some countries these sales surpass the sales of conventional vehicles, higher integration of EVs is difficult to achieve. As stated before, high initial investment, limited battery range, a prolonged recharging time, and uncertain availability of charging stations are some of the main obstacles facing increased EV integration and these concerns or limitations are expressed in Fig. 8 [37].

Figure 7
Overview of the EVs sold in Portugal by brand/model [34].

Table 2
EVs integration target examples according to some countries [36].

Country	2020-2030 EVs Target
China	5 million EVs by 2020.
Finland	250,000 EVs by 2030.
India	30% EVs sales by 2030.
Ireland	500,000 EVs and 100% EVs sales by 2030.
Japan	20-30% EVs sales by 2030.
Netherlands	10% EVs market share by 2020.
New Zealand	64,000 EVs by 2021.
Slovenia	100% EVs sales by 2030.
United Kingdom	100% EVs sales by 2030.
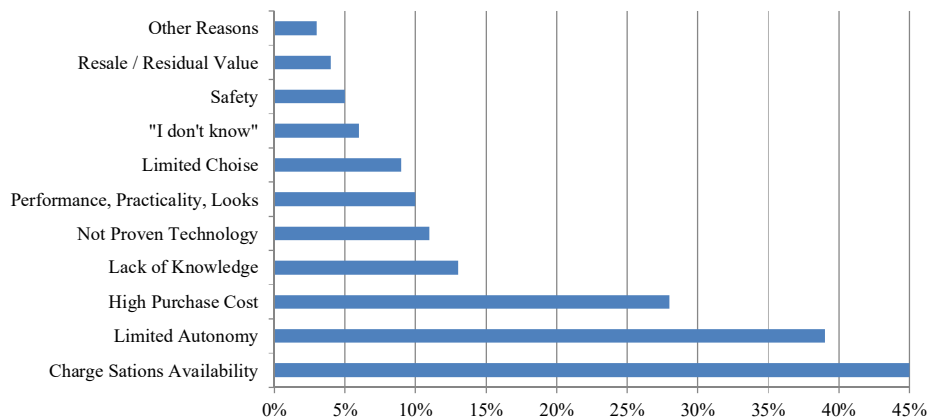
Figure 8
Main barriers for the EVs purchase (resulting from survey) [37].

Therefore, to grow the nascent EV market, support mechanisms are required. Several EU countries have established incentive instruments to reduce the high purchase cost of EVs. Table 3 summarizes some of the policy instruments that have been implemented in the EU. There are three main policy instruments currently in use [38]:

- Registration or sales tax reduction: this is applied to reduce the purchase cost of EVs for consumers. Typically, these taxes are applied at different levels depending on the vehicles' CO_2 emissions and this type of tax is one of the most important decision factors concerning the purchase of EVs.

- Circulation or motor tax: this is paid on a monthly or annual basis and is indexed to the engine power, number of cylinders, or fuel consumption. It is considered as a less effective mechanism compared to the registration or sales tax because consumers are more sensitive to an initial purchase price than to an annual or monthly tax.

- Fuel tax: this makes EVs more attractive for consumers because it increases the operational costs of a conventional car by increasing the cost of fuel.

Table 3
Policies instruments examples to support EVs integration in some EU countries [38].

Country	Economic Instruments to Support EV Interest
Austria	Exemption from fuel consumption tax.
	Exemption from monthly vehicle tax.
	Up-front purchase price bonus of 500 €.
Belgium	Purchasers of EVs receive a personal income tax reduction of 30 % of the purchase price (with a maximum of 9000 €).
Finland	Exemption of fuel tax.
Italy	A tax incentive of 800 € and a two-year exemption from annual circulation tax is granted for the purchase of an EV.
Spain	Several regional governments grant tax incentives for the purchase of alternative fuel vehicles including EV, around 6000 €.
Portugal	Exemption from registration tax.
United Kingdom	Exemption from annual road tax.

EVs are divided into two main categories: hybrid EV (HEV) and full EV (FEV). HEVs are categorized into full hybrid EV (FHEV) or plug-in hybrid EV (PHEV). FEVs are categorized into two types: battery EV (BEV) and fuel-cell EV (FCEV). The following Sub-sections will describe each type of EVs in detail.

3.1 Full hybrid EV

Full Hybrid Electric Vehicles (FHEV) use a combination of two different propulsion sources: the conventional combustion engine (CCE) and a battery with an electric motor. This last component is applied to improve the vehicle fuel economy or to increase performance relative to a conventional vehicle. FHEVs allow for the cooperation between the CCE and the electric motor to offer the maximum possible range [7].

The combination of the CCE with a battery pack and an electric motor allows for the FHEV to switch between using either the CCE or electrical motor for propulsion [39]. In this type of vehicle, recharging of the battery is not a major concern as FHEVs keep the SoC of their batteries within a narrow band while travelling. The recharging process only occurs from on-board electricity generation by the CCE or from the conversion of the vehicle's kinetic energy into energy stored in the battery through regenerative braking. For these reasons, conventional FHEVs are charge self-sustaining [40]. FHEVs typically use a nickel-cadmium (NiCd) battery. Regarding the distance that the FHEV can travel, the range is typically between 900 and 1200 km [7].

3.2 Plug-in hybrid EV

Another type of EV gaining increasing relevance in the automotive market is the Plug-in Hybrid Electric Vehicle (PHEV) as it is seen as high potential technology. Their operating principle is similar to FHEVs so as much as PHEVs also have a CCE combined with a battery and an electric motor. Typically, PHEVs have three flowing features [7]:

- a battery storage system of 4 kWh or more,
- possibility of an external charging connection,
- the possibility to operate in electric mode for a distance of 16 km or more.

The major difference between FHEVs and PHEVs is that the latter can recharge its battery by connecting to an external electric power source. PHEVs can operate with either conventional fuels or electricity, or a combination of both simultaneously. This ability grants the PHEVs important advantages such as reduced dependence on conventional fuels, a decrease in GHG and pollutant emissions, and the emergence of a new concept, vehicle-to-grid technology (V2G) [41], which will be further discussed in the next sections. Hence, according with the needs and main usage, PHEVs engines configuration can be designed in three different ways: series, parallel or series/parallel [42]. Despite the design, PHEVs can operate in two different modes to manage the vehicle's battery discharge strategy [43]:

- Charge-depleting – This occurs when the battery's SoC is depleted to a predefined level, this mode allows a fully charged PHEV to operate only on electric mode. When this predetermined level is reached, the vehicle's CCE starts. This procedure is also used in FEV (detailed in the next section).

- Charge-sustaining – This is a combination between CCE and the battery/electric motor to achieve maximum efficiency without allowing the battery SoC to exceed a predefined narrow range.

Concerning batteries, there are two types of battery systems that are adequate for PHEVs operation: NiCd batteries and Lithium-ion (Li-ion) batteries. NiCd batteries provide lower energy and power densities relative to Li-ion batteries and this leads to an inferior travelling range and a lower maximum vehicle speed. Also, NiCd batteries can be more durable and can withstand a higher number of deep discharging cycles [44]. Despite these differences, currently, PHEV batteries consist of Li-ion battery technology. The reason is not only related to the promising features of the advanced Li-ion battery technology, which is under substantial development, but also for the fact that this type of battery provides higher energy densities and life expectancy [7].

3.3 Full EV

In contrast with the previously presented types of EVs, the Full Electric Vehicle (FEV) or battery EV (BEV) relies solely on the electric motor as the propulsion system rather than a combination of electric motor and CCE. Electricity can be generated by two different methods: by on-board rechargeable battery packs (the most common method) or through the use of capacitors or flywheels [7]. The FEV's batteries may be charged either by conventional outlets within the owner's residence or by dedicated external charging stations. The most recent batteries for FEVs consist of improved Li-ion battery packs. As opposed to NiCd batteries or older Li-ion batteries, the FEV's performance is greatly improved when using advanced Li-ion battery technology, allowing FEVs to reach a trip range of up to 390 km or more, and a top speed over 200 km/h [45].

FEVs need to be able to operate at differing speeds which place special requirements on the battery packs. Additionally, the batteries need to have high energy potential to ensure an adequate trip range. Consequently, the battery pack requires both high-power and high-energy-density [46]. Increasing the battery energy density implies greater charging time which may lead to higher costs. Typically, only NiCd or Li-ion batteries are suitable for this type of EV [47]. Some of the technical features of the three types of EVs described are summarized in Table 4 [7].

Table 4 shows that as HEVs have an electric motor with a battery system and a CCE, they have higher autonomy ranges compared to PHEVs and FEVs; also, PHEVs can operate either using on-board charging or using charge depleting or charge sustaining method. This characteristic of PHEVs allows for less stringent battery's requirements compared to FEVs batteries. PHEVs can use either Li-ion or NiCd batteries. Finally, FEVs rely solely upon their battery so charge depleting mode is always active (guarantying the batteries SoC requirements and lifetime), demanding high power that can be offered by Li-ion batteries.

Table 4
Comparison between different EV types [7].

Vehicle Type	Operation Mode	Battery Type	Max. Autonomy (km)
Hybrid Electric Vehicle	Charge-sustaining	NiCd	900 – 1200 (Hybrid)
Plug-in Electric Vehicle	Charge-sustaining	NiCd	20 – 60 (Electric)
	Charge-depleting mixed mode	Li-ion	900 (Hybrid)
Full Electric Vehicle	Charge-depleting	Li-ion	120 – 390 → (or more)

3.4 Fuel cell EV

The Fuel Cell Electric Vehicles (FCEV) belongs to the FEV family; however, it uses compressed hydrogen gas (H_2) as its fuel source. There are two options for using the generated electricity; it is either applied to drive the vehicle or it is stored in an energy storage device, such as a battery pack. In contrast with CCE vehicles, FCEVs produce no GHG or harmful pollutant emissions during operations so they are considered zero-emission vehicles. Due to a lack of infrastructure for hydrogen production and storage coupled with technical limitations of the fuel cells, FCEVs are not as widespread as FEVs [45].

4. Features of EV batteries and charging strategies

The batteries represent a fundamental role in the performance of an EV and represent the major barrier to the successful integration and development of EVs in the transport sector [48]. This section discusses and compares different battery technologies. Five important characteristics of batteries have been identified and these are [49]:

- The energy density of the battery is the ratio between the total energy stored and battery mass (Wh/kg) or (kJ/kg). It is considered the most important parameter for an EV since it directly influences the trip range of the EV.

- Power density defines the battery's efficiency and refers to the amount of power that the battery can deliver per mass (W/kg) without jeopardizing battery health.

- Safety is the characteristic defining the level of protection being offered against anomalous operating conditions such as over-voltage, thermal variation, and mechanical shock.

- Battery lifetime depends on both the time and the number of charge/discharge cycles. Apart from battery use, temperature and SoC during storage can strongly influence the battery lifetime. Additionally, both deep charge and shallow charge cycles affect the battery lifetime [50].

- The cost of the battery is a major part of the EV's final price and so it is the most important factor which influences the commercial deployment of EVs.

The cost to manufacture an EV is 1.5 to 2.5 times higher than a comparative CCE vehicle due to currently available batteries [42]. However, it is expected that battery costs will continue to decline considerably in the coming years due to economies of scale. It is estimated that battery costs will be below $200 per kWh by 2030 [50].

The charging of EVs is classified according to power levels or modes. There are several established international standards for charging EVs, such as the Society of Automotive Engineers (SAE), the International Electrotechnical Commission (IEC) and the CHAdeMO EVs charging standards. The aforementioned standards are published in regions with large EV sales volumes, i.e., North America, the EU, and Japan. Each of the EV charging standards will be described in the following sections.

4.1 SAE standard

SAE charging standard uses the term "level" to categorize the charging levels into three charging levels, which are Level 1 defined as "slow charging" and Level 2 and Level 3 are "fast charging" for AC and DC operations respectively. Table 5 illustrates the different SAE charging levels and charging rating according to SAE Electric Vehicle Conductive Charger Coupler Standard (SAE J1772) [50].

While AC charging is performed via an onboard EV charger, DC charging occurs by using external EV charging equipment, which is a dedicated charging station located at a permanent location, defined as EV service equipment (EVSE). AC Level 1, known as "slow charging", is the lowest voltage level for residential and commercial facilities. It is specifically appropriate for overnight charging. The expected charging time is up to 17 hours to charge a BEV from SoC of 20% to BEV fully charged [51].

AC Level 2 is designed to use 240 V_{AC} with a charging current up to 80 A and charging power up to 19.2 kW. For type 2, the time required to go from a fully depleted PHEV to fully charged is 22 minutes using a 20-kW charger [52]. For DC Level 1 charging is 200–450 V_{DC} with charging current up to 80 A and charging power up to 36 kW.

DC Level 2 charging is designed for 200–450 V_{DC} with a charging current up to 200 A and charging power up to 90 kW. As illustrated in Table 5, both AC Level 3 and DC Level 3 charging levels are yet to be determined [53].

4.2 IEC standard

While the SAE standards use the term "level" to categorize charging rates, the IEC standards use the terms "types" and "modes" for charging classification.

Four charging modes are specified in the IEC 61851-1 depending on four main factors: the type of power received by the EV, the voltage level, the presence or not of a control device (which allows a unidirectional or bidirectional communication flow between the charging station and the EV), and the integration of protective equipment. Moreover, Modes 1 to 3 utilise onboard EV charging [54], whereas Mode 4 [55] refers to the utilization of an external charger [51]. In this sense:

- Mode 1 refers to slow charging from a typical household connection in AC. There is neither protective equipment nor communication with the vehicle. It is typically used for light vehicles such as electric motorcycles [54].

- Mode 2 consists of slow charging from a typical AC residential socket equipped with a cable protection device.

- Mode 3 allows for both slow or fast charging using a dedicated EV socket equipped with control and protective equipment installed in AC mode [55].

- Mode 4 refers to fast charging using an external charger in DC. The charging station integrates control, communication, and protective functions [55].

Table 5
Charging power level types based on SAE standard [55].

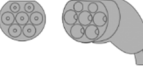| Charging Level	Charging Rating	Charging Time
AC Level 1	120 V; 1.4 kW (12 A) 120 V; 1.9 kW (16 A)	PHEV: 7 h (SoC–0% to full)
		BEV: 17 h (SoC–20% to full)
AC Level 2	240 V; up to 19.2 kW (80 A)	**Considering 3.3 kW Charger:**
		PHEV: 3 h (SoC–0% to full)
		BEV: 7 h (SoC–20% to full)
		Considering 7 kW Charger:
		PHEV: 1.5 h (SoC–0% to full)
		BEV: 3.5 h (SoC–20% to full)
		Considering 20 kW Charger:
		PHEV: 22 minutes (SoC–0% to full)
		BEV: 1.2 h (SoC–20% to full)
AC Level 3	>20 kW, 1-Phase, and 3-Phase	To be determined
DC Level 1	200–450 V_{DC}; up to 36 kW (80 A)	**Considering 20 kW Charger:**
		PHEV: 22 minutes (SoC–0% to 80%)
		BEV: 1.2 h (SoC–20% to full)
DC Level 2	200–450 V_{DC}; up to 90 kW (200 A)	**Considering 45 kW Charger:**
		PHEV: 10 minutes (SoC–0 to 80%)
		BEV: 20 minutes (SoC–20 to 80%)
DC Level 3	200–600 V_{DC}; up to 240 kW (400 A)	**Considering 45 kW Charger:**
		BEV: < 10 minutes (only) (SoC–0 to 80%)

4.3 CHAdeMO standard

The CHAdeMO EV standard is a Japanese national standard published in October 2012. It is a DC fast charging standard aiming to increase EV deployment and to solve one of the major problems related to EV driving, range anxiety [50]. This method can charge an EV battery to 80% SoC in 30 minutes via DC charging using a 50-kW charger. The charging is performed through dedicated external EV charging equipment, which is built-in dedicated locations [56].

As described in the previous sections, both "level" and "mode" are used to describe the types of charging. The existing standards must converge around charging technology so that charging facilities become more common [57]. This trend will increase the EV drivers' satisfaction with the charging technology and manufacturing costs can be reduced. In addition to rating terms, there is also a great diversity among the plugs or connection types due to a lack of standardization in this area [58]. Table 6 illustrates the different types of connectors available.

Table 6
Different EVs plugs types [50].

Connector Type	Diagram	Charging Level	Charging Mode	Region
SAE J1772 (Type 1 AC)		Level 1	-	North America and Japan
		Level 2	-	
IEC 62196 Type 2 "Mennekes"		-	Mode 1	Europe
		-	Mode 2	
SAE J1772 DC Combining Charging System (CCS) (Combo 1 Connector Type 1)		Level 3	-	North America and Japan
EU DC CCS Combo 2 (Connector Type 2)		-	Mode 2-4	Europe
Chademo Yazaki		Level 3	Mode 4	Europe, Japan and North America
Tesla Charging		Level 1	Mode 1	Worldwide
		Level 2	Mode 2	
EU DC CCS Combo 2		Level 3	Mode 3	
		-	Mode 2-4	

4.4 Battery technologies for EVs

Currently, several battery technologies are being used in EVs. These include:

- Lead-acid batteries are a well-known and mature technology. Their most significant disadvantages are the management of their acid constituents, the existence of lead in their construction, their low energy to weight ratio, and their low stored energy to volume ratio [36].

However, Pb-acid batteries represent a relatively low-priced option with high electric power to weight ratio [48].

- Nickel-Cadmium (NiCd) batteries typically have the longest lifetime as expressed by the number of charge/discharge cycles. However, their construction implies the use of Cadmium, a heavy metal, which has a significant disadvantage in terms of damages to the environment, human and animal populations [49].

- Nickel-Metal-Hydride (NiMH) batteries are similar to NiCd batteries regarding their technology and operation. The most significant advantage is the absence of the memory effect, which influences the maximum load capacity of the battery. When compared with Li-ion batteries, NiMH batteries have an inferior energy storage capacity [51].

- Lithium-ion (Li-ion) batteries are known for their high-power storage capacity with a high energy density to weight ratio. Li-ion batteries do present three main disadvantages, namely high costs, concerns relating to thermal runaway and a limited lifespan. Despite these drawbacks, Li-ion batteries are considered to be the most highly promising technology in the short term [51].

- Sodium-Nickel-Chloride (NaNiCl) batteries, also known as the "Zebra Battery", have the major advantage of a high stored energy density. However, there are concerns related to operational safety and longer-term storage prospects [36].

A summary of the characteristics of the different battery technologies is presented in Table 7 [48]. Table 8 provides the charging characteristics and infrastructure parameters for several types of commercially EVs available in worldwide fleets [52].

5. Interactions between EVs and the grid

5.1 Grid-to-vehicle charging

The process of EVs using the electricity grid to charge their battery systems is defined as grid-to-vehicle (G2V) charging. Typical household outlets are the most common method to charge the vehicles' battery [59]. However, public charging stations are becoming more popular to long charging times and the need for EVs charging in external locations for more frequent and faster charging. These stations can be integrated into the existing charging network or independent from the network [7]. These networks may compose of planned infrastructure developments composed of public-accessible charging stations and battery switch stations to charge EVs [60].

Considering the current trips ranges for EVs, it is evident that until a substantial charging infrastructure, EVs will be at a disadvantage for long trips, rather they will be better suited to shorter trips.

Table 7
Batteries technologies comparison and main characteristics [48].

Battery Type	Energy Density (Wh/kg)	Specific Power (W/kg)	Volume Energy Density (Wh/L)	Memory Effect	Production Cost ($/kWh)
Lead-acid (Pb-acid)	35	180	1000	No	60
Nickel-Cadmium (NiCd)	1.2	200	2000	Yes	200–300
Hybrid-Nickel-Metal (Ni-MH)	1.2	200–300	< 3000	Rarely	200–250
Sodium-Nickel-Chloride (NaNiCl)	2.6	155	> 1200	No	230–345
Lithium-ion (Li-ion)	3.6	200–430	2000	No	150
Lithium-ion Polymer (LiPo)	3.7	260–450	> 1200	No	150

Table 8
Charging characteristics and infrastructures of some manufactured EVs [52].

EV Model	Li-ion battery capacity (kWh)	Electric Range (km)	Level 1		Level 2		DC Fast Charging	
			Demand (kW)	Charge Time (h)	Demand (kW)	Charge Time (h)	Demand (kW)	Charge Time (minutes)
Toyota Prius	4.4	23	1.4	3	3.8	2.5	N/A	N/A
Chevrolet Volt	16	64	0.96-1.4	5-8	3.8	2-3	N/A	N/A
Mitsubishi i-MiEV	16	154	1.5	7	3	14	50	30
Nissan Leaf	24	161	1.8	12-16	3.3	6-8	50	15-30
Tesla Roadster	53	394	1.8	30 +	9.6-16.8	1-12	N/A	N/A

Thus, for the widespread integration of EVs, a large network of charging points is needed. This is beginning to emerge, for example, there are more than 100,000 EV charging points in the EU, of which around 30% are located in the Netherlands [61]. Germany has around 22%, with France at 14%, and the UK having 12% of these chargers. However, this still lags in other countries such as Romania which only has 0.1% of the charging points [60].

Typically, during off-peak hours there exists significant electricity generation capacity which sits idle. In these periods, this available electricity generation capacity may be utilized by charging PHEVs and FEVs. This shift can help to reduce the large changes between peak and off-peak periods which allows for more efficient operating strategies [7]. However, EV charging may also introduce several problems to the network such as an increase in transformer loading, network unbalance, voltage levels reduction, power losses and harmonic distortion [62]. Concerning the last two problems, the situation is made worse when EV charging is done during peak periods and especially with fast charging [63].

5.2 Vehicle-to-grid concept

Vehicle to grid (V2G) electricity is a concept which describes the flow of electricity from the vehicle to the grid to supply energy demand and supply ancillary services. The V2G power flow can be either unidirectional or bidirectional, although in unidirectional V2G only ancillary services such as regulation, are provided to the grid [64]. The main concept of V2G is that the EVs deliver power to the grid while parked [56].

There are three main advantages of V2G: EVs may charge when it is best suits the system operator, allowing for the EVs to displace some of the need for stationary energy storage systems (ESS), EVs can provide ancillary services, and finally, EVs can supply electricity to the grid, replacing traditional power generation [65].

V2G concept was first introduced in 1997 and it is illustrated in Fig. 9 [66]. The term was conceptualized by considering the case where EVs would have a bidirectional and computer-controlled connection to the electrical grid. A study in [66] concluded that, if a small portion of the USA's vehicle fleet were EVs, the real-time matching of supply and demand in the electrical power systems would be made easier. This would allow for the increased integration of intermittent renewables to the power system.

In Fig. 9, the interactions between EVs and the power grid are illustrated. Traditionally, the electricity flows unidirectionally from the generators to end-consumers. However, considering the existence of EVs equipped with V2G technology, the electricity may also flow back to the grid shown in Fig. 10 with the bidirectional arrows [46].
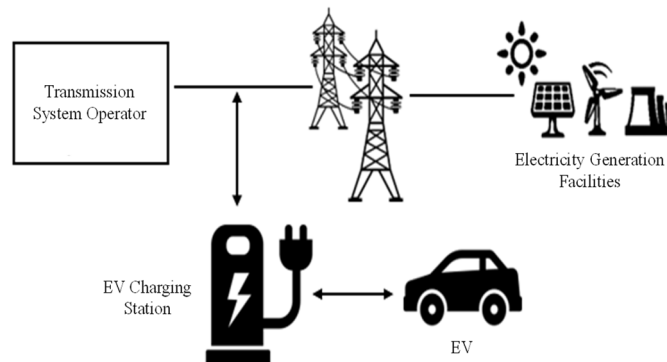
Figure 9
V2G general concept [66].
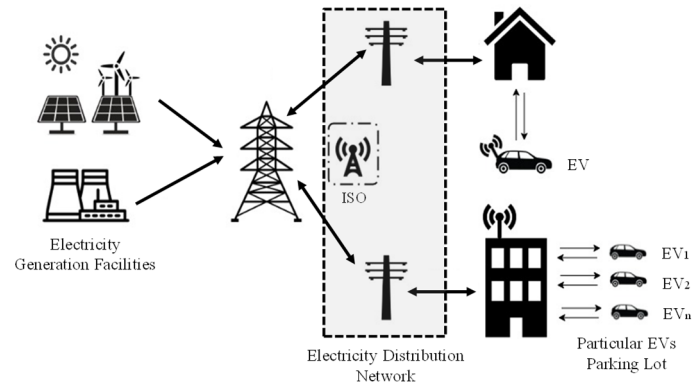
Figure 10
Illustrative schematic and control connections between EVs and the electric power grid in V2G mode [46].

There may also be control signals from the grid operator (defined as Independent System Operator (ISO)) which can request power from a large number of EVs. This signal may go directly to each EV, schematically illustrated in the upper right of Fig. 10, or to a fleet's operator, who alternatively controls the EVs in a particular parking lot, schematically illustrated in the bottom right of Fig.10 [46].

The V2G concept can be a valuable solution for both ISO and EVs owners as it motivates them to operate in V2G mode. The EVs owners may profit while their EVs are parked in a parking lot. This profit may depend on factors such as the length of time that EV is connected, the BEV size, the available power chargers, and the EV's daily mileage. The ISO is concerned about the impacts that higher numbers of EVs can have on the distribution grid [65]. Despite the increased challenges, EVs can be a good solution in terms of absorbing generation from RES or frequency regulation and other ancillary services (regulation and spinning reserves). There are four power markets in which V2G can participate [66]:

- Base-load, these generators provide power to meet the almost constant demand throughout the day. Due to the limited energy storage and high energy cost associated with EVs, this market is not suitable for V2G.

- Peak power is provided by flexible generators to meet the peak power demanded for short periods of the day. In some situations, V2G can be competitive in these markets as the prices paid for peak power are higher than baseload.

- Spinning reserves are provided by generators who are operating but not connected to the grid. These generators can quickly be connected to account for unexpected fluctuations in both supply and demand. Usually, this type of generation is activated for a short period a few times per year and is renumerated according to the time available. These types of markets may be particularly attractive for V2G.

- Frequency regulation is provided by several generators spread across the power system to stabilize the frequency and voltage of the grid. Usually, these generators are activated for a few minutes several times per day. This market is extremely attractive for V2G. From the point of view of an electrical utility, this market allows for increased efficiency and power quality improvement and from the point of view of the EV owner, it may be a source of revenue that incentives the purchase of an EV.

There has been previous research in each of these four power markets. The simultaneous operation in these two V2G markets was studied in [67]. The results have shown that the different uses of V2G in the various types of energy markets are not mutually exclusive and can operate simultaneously. Also, the study showed that it is particularly lucrative for PHEVs owners to use V2G for regulation services daily and peak reduction in days of unusually high electricity demand.

The feasibility of EVs participating in ancillary services markets was analyzed in [68]. The study demonstrated that using the V2G mode for peak-load and regulation services is more profitable than when used for other ancillary services. It also demonstrated that V2G is not profitable as a spinning reserve. Hence, the authors concluded that the structure of electricity markets will have a significant impact on the economic value derived from V2G.

Most studies focused on bidirectional power flows however, some studies address unidirectional V2G. For example, an analysis of the cost-effectiveness of regulation service offered by unidirectional and bidirectional EV charging is presented in [69]. The results show that EVs can contribute to the energy market, even when only operating in a unidirectional mode. Additionally, the study observed that unidirectional power flow can achieve nearly all the V2G benefits of bidirectional power flow, considering the requirement for double the EV integration to deliver a guaranteed level of regulation services.

The implementation of optimal charging strategies using unidirectional V2G was studied also in [64]. The study developed an algorithm for unidirectional regulation to be used by an EV aggregator, utilizing several EVs to participate in energy markets. The study demonstrated that the algorithm simultaneously maximizes the BEV charge while minimizing the owners' charging cost. The profits of the aggregator are maximized while providing extra flexibility to mitigate fluctuations of RES thus improving the operation and control of the system.

5.3 Interaction between RES and EVs

Unpredictably and intermittency are two of the fundamental characteristics of RES, especially wind and PV. Despite the challenges that high levels of RES integration can introduce into power systems, power systems need to rapidly increase the amount of RES generation to combat the worst effects of climate change [70].

To accomplish this idea, the adoption of Battery Energy Storage Systems (BESS) or dispatchable loads is necessary. Storage systems allow for the excess RES production to be stored and released when it is needed. However, these storage systems do have high capital costs. Considering these factors, there is significant interest in using BEVs as BESS [71].

If there is excess generation from RES, EVs can absorb the excess through different charging strategies. In times of supply shortages, EVs can apply V2G technology to deliver power to the grid. In short, EVs may be an efficient answer to the integration issues that arise with high levels of RES by active storage devices which can help smoothen out grid operations. This will require both long-term and short-term planning and will not be a rapid process [52].

The majority of the literature concerning interactions between RES and EVs has mainly been dedicated to the study of wind and solar energy. Several studies analyze the EV's ability to support the integration of wind energy into power grids. For example, when 50% of the vehicle fleet are PHEVs and are combined with smart charging strategies, the potential for higher levels of wind generation increases to be around 6% of total generation [72].

In [73], an analysis of the benefits of large-scale EV and wind power interactions in Inner Mongolia was presented. The study assumed 100% penetration of EVs, which corresponds to 2.6 million EVs. The study tested five different charging strategies: uncontrolled, night, morning, afternoon, and bidirectional smart charging (V2G). The results demonstrate that EVs can balance the electricity demand and supply and thus increase wind power integration by 8%. Additionally, the study showed that EVs were able to reduce both the cost of the energy system operation and the fuel cost.

Regards to charging modes, EVs with afternoon charging were found to be the most favourable since EVs have the most excess electricity reduction potential as well as EVs allow a slightly higher integration of wind power than bidirectional smart charging. The study concluded that EV integration with low integration of wind power only slightly decreases CO_2 emissions. In other words, by simply expanding EVs while still relying on fossil fuel dominated power system, the potential benefits are minimized.

A study investigating the potential for using excess wind power to power EVs was carried out by [74], considering Germany's 2020 and 2030 decarbonization scenarios, corresponding to 1 million and 6 million EVs, respectively. The analysis based the EV models on real driving and car ownership behaviours and considered a controlled charging strategy, i.e., shifting the charging into off-peak times. The study only modelled home charging and it was divided considering the grid with and without restrictions.

The study showed that in 2020, the share of excess wind energy that can be used for controlled charging of EVs is limited to 7.5% by grid restrictions, compared to 8.4% with no grid restrictions. For the same conditions, in 2030 that share increases to 8% and 15% as the grid connection capacity increase along with the increase in wind power capacity installed.

The results have shown that in 2030, with grid restrictions, about 30% of EV demand can be met by excess power; without grid restrictions, the value increases to 50%. The study concluded that 1 million EVs have a very limited effect on Germany's energy balance. However, if this increases to 5 million EVs, the impacts increase considerably.

6. PV enabled EV parking lots

As has been stated previously, EVs are parked for the majority of their lifetimes and this is shown by the fact that 26% of worldwide EVs charging stations are located in parking lots, shown in Fig. 11 [76]. If the roofs of these parking lots could have solar PV installed on them, this may present an innovative solution for EV charging. These could be installed in places such as workplaces, shopping centers, restaurants, supermarkets, hotels, hospitals, airports, among others [77].

Combining solar energy production with EV charging has some challenges such as the innate variability of solar irradiation, parking duration, SoC of each EV parked, and electricity prices. To maximise the benefits of a solar EV parking lot, the generation from the solar PV systems and the EV charging requirements must be matched as closely as possible. This can be done through two approaches [78]:

- Uncontrolled charging is a simple approach that consists of fully charging EVs immediately after parking. It brings technical and economic challenges to distribution systems. From a technical point of view, it can cause several problems such as frequency and voltage oscillations, and grid overload, jeopardizing power quality and stability. From an economic perspective, it may result in a suboptimal generation dispatch and efficiency losses.

- Controlled charging consists of optimizing charging according to an objective function that is formulated to achieve an optimal charging schedule and charging power through active control of the EV charging. This approach will be discussed in depth in the following sections.
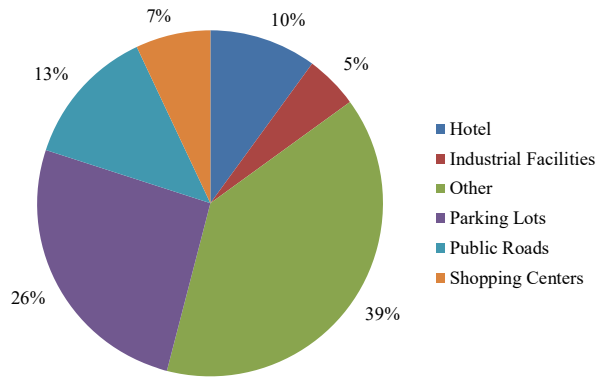
Figure 11
General distribution of EVs charge points by location type [76].

6.1 Environmental and other benefits

The environmental impact of EVs is determined by the source of the electricity used for charging. If charging is carried out using PV systems, there are negligible operating emissions associated with charging. Additionally, PV systems do not emit noise or pollutants during operation. Electric vehicle solar parking lots (EVSPLs) can also encourage owners to charge their EVs during the day causing less anxiety in terms of the vehicle's daily driving range which helps increasing market acceptance by EVs.

Using EVSPLs will also increase the development of charging infrastructure which is a critical aspect that consumers consider when deciding to purchase an EV [91]. EVSPLs may also be located in densely populated areas which increases both the visibility of charging infrastructure as well as the utilization factor of the charging equipment [2]. A further benefit of EVSPLs is that it provides shade for the EVs parked underneath thus protecting them from sun damage. Finally, EVSPLs may bring advantages regarding local employment and the local economy [80].

6.2 Configuration and operation

In an EVSPL, the EVs can be connected in two different ways, either linked to a DC link after a DC/DC converter or connected to an AC link after a DC/AC converter. The management of the system management is under the control of the EVSPL management and so are additional power sources (wind power or local batteries) [81].

The DC/DC converter transforms the current from one voltage level to another. Additionally, a maximum power point tracking (MPPT) system is used to maximize the power delivered from the PV panels. Any electricity generated is first used to charge the EV batteries and if there is an excess of generation, this is exported to the grid. When the output from the PV system is insufficient to completely charge the EVs, the grid provides the remaining power. The architecture of an EVSPL is conceptually described in Fig. 12 [82].

6.3 Smart parking lots

As opposed to the conventional parking lot, the smart parking lot offers new alternatives for owners of EVs as well as a utility grid. These types of parking lots have an energy management system that can communicate with the EVs to smart decisions relating to the charging/discharging schedule [83]. The basic idea of a smart EVSPL is the integration of EVs as a group of energy storage devices to maximize both the EVs owners' and parking lots' benefits, as well as the stability of the distribution power system.

EV owners can also define the price ranges for the selling of energy stored in the BEV and ranges for the purchase of energy from the grid [83]. Energy can flow in multiple directions in an EVSPL [84] and these are shown in Fig. 13 [85]. The most frequent flow is from the PV to the vehicle (PV2V) and PV to grid (PV2G). Bidirectional V2G and vehicle-to-vehicle (V2V) energy flows also occur which may occur when there is insufficient PV generation and the cost to buy electricity from the grid is higher than the predefined ranges [86].
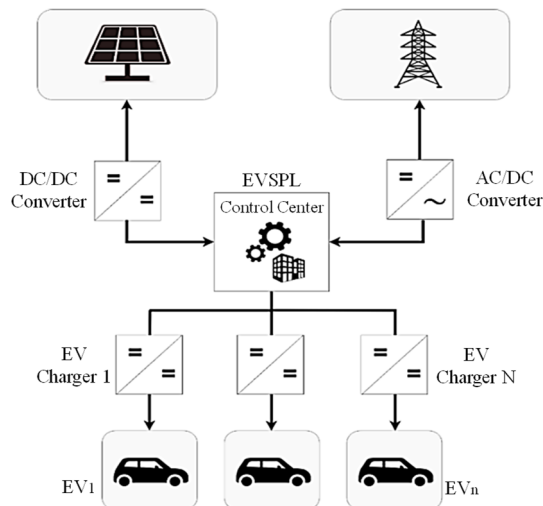
Figure 12
General overview of a PV standalone EVSPL configuration (DC charging) [85].
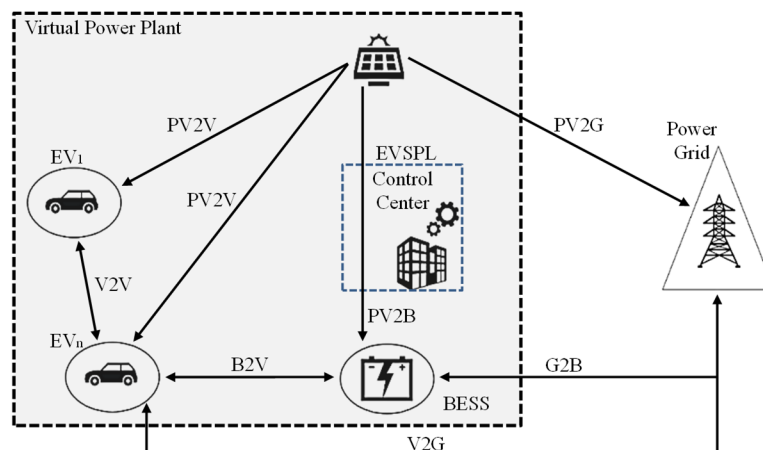
Figure 13
Virtual power plant concept: energy fluxes in a smart EVSPL with central energy storage (BESS) [85].

When the EVSPL also has a local BESS, there may be additional energy flows, namely PV to the battery (PV2B), battery to the vehicle (B2V) and grid to battery (G2B). The first two are unidirectional while the last one is bi-directional [86].

Smart parking lots are based on an energy management system that establishes communication between its different components, allowing information flows between the EVs and the parking lot. A smart EVSPL can aggregate many EVs to simplify the communication between the different elements: utility grid, electricity markets, and the EVs owners. Through this strategy, it is possible to fulfil customer's needs as well as improve the grid reliability and flexibility. Additionally, smart EVSPL can represent an integral part of a larger smart microgrid as observed in Fig. 14 [87].
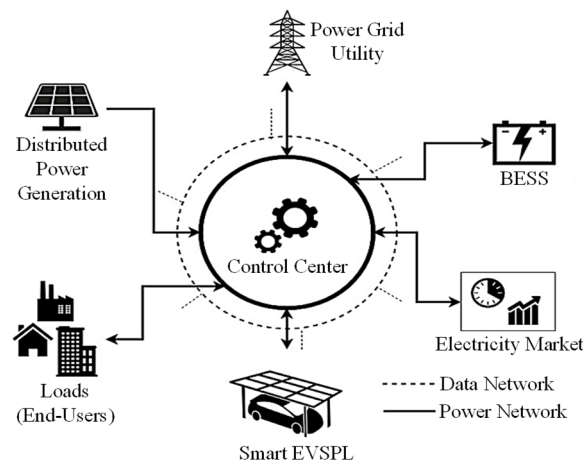
Figure 15
A smart EVSPL in a microgrid context [87].

7. Relevant studies

7.1 Power systems and PV integration

In [88] the effects of large-scale PV integration in a conventional electric power system were analyzed. It was shown that PV generation might be the key in terms of reducing demand during peak hours, mitigating the deviation between PV generation and demand.

The impacts of PV integration in various low-voltage network configurations were studied in [89]. The results show that higher levels of PV integration led to three main problems: overcurrent, reverse power flow and overvoltage. The study also showed that urban areas can integrate a higher level of PV integration although rural LV networks demonstrate a good interaction between PV. Finally, industrial areas do not present any overvoltage issues for all integration levels considered.

7.2 Integration of EVs into power systems

Analysis and quantification of the impacts of different levels of EV integration in distribution networks considering reinforcement and energy losses were presented in [73]. The study analyzes two distribution areas and three EVs penetration scenarios: 35%, 51%, and 62%. The results show that a 19% increase in the grid's investment at peak hours is required. However, this investment can be reduced by between 60% and 70% through the implementation of smart EV charging strategies.

The impact of PHEVs charging in a classic distribution feeder was analyzed in [91]. The network includes five residences and two PHEVs using two charging schedules. The results showed that the first scenario represents an increase of the transformer load by 68% and 52% in winter and summer, respectively. The second scenario results in a growth of the transformer load by 58% in winter and 52% in summer.

The impacts of PHEVs on a distribution grid in Belgium were discussed in [92]. The study considers three different scenarios of uncontrolled charging and high load scenarios (in both summer and winter), assuming four different integration levels of PHEVs: 0%, 10%, 50%, and 100%. The results showed that the integration of PHEVs has significant effects on the power losses and voltage fluctuations in the distribution grid. Thus, to safeguard the security of the electric grid, the impacts of PHEVs on the distribution grid must be evaluated and quantified.

The impact of EV charging strategies (non-smart, smart and V2G) on the Portuguese transmission grid, considering a 100% electric vehicle integration was analyzed by [93]. The results showed that the implementation of a non-smart charging strategy might cause a very high-peak demand in the grid, around 8 GW of demand. By using a smart-charging mode, the maximum power that the EV fleet absorbs is approximately 4.5 GW. Finally, it was observed that in the V2G mode, the vehicles spend time charging and not supplying energy to the grid.

7.3 Interaction between PVs and EVs

A discussion on the interactions between PV generation and EVs was presented in [94]. They used three charging strategies: uncontrolled charging, smart charging, and V2G. The analysis showed that an uncontrolled charging strategy with a high level of EV integration can lead to grid problems related to higher demand peaks. A high level of EV integration does not imply any additional peaks to the demand profiles when smart charging or V2G strategy was used. V2G can be a valuable grid asset as it helps to stabilize the grid, especially through peak-load shaving, reducing peaks by up to 35%.

In [95] an analysis on the impacts of large-scale PHEV and solar PV deployment using Texas as a case study was conducted. The study assumed a 30% integration of PHEVs and 15% of the system's annual electricity being generated by solar PV. The results demonstrated that the integration of PV either reduces or eliminates the growth in peak capacity requirements due to PHEV demand, also reducing the curtailment of PV generation. Another finding is that the trip range of the EVs was increased by allowing mid-day charging.

In [96], a study on the energy and environmental impacts of PV integration in future electricity systems considering EVs and heat-pumps under smart control strategies were presented, using a region of Japan as a case study. Different scenarios considered the combination of different integration levels of PV, EVs and heat-pumps, respectively 0 to 30 GW of installed PV, 0 to 5 million EVs and 0 to 5 million houses equipped with heat-pumps. The results demonstrate that the combination of 1 million EVs with 1 million heat-pumps can reduce electricity curtailment by 3 TWh, i.e., 2% of total electricity. Additionally, considering the upper level of integration for all three technologies, emissions were reduced by 11.6 Mt of CO_2, representing 43% of total CO_2 emissions for the area.

The practical feasibility of directly charging BEVs through PV panels was investigated by [97] and [98]. An advantage of this strategy is that there is no need to perform a power conversion as the DC electricity generated can charge the BEVs directly, preventing a 10% energy loss. The practical feasibility and effectiveness of the integration of PV systems into parking lots were presented in [99]. The study concluded that the installation of PV in parking lots has significant advantages relative to home installation because it is likely that the PV systems can be optimally positioned in parking lots.

The potential of 48 parking lots to meet the charging requirements of 14,000 EVs was discussed in [100]. Each parking lot was categorized according to its solar generation potential and compared to the production of an equivalent non-shaded optimally positioned parking lot. The study concludes that 29 of the parking lots were financially viable and shows that the solar parking lots produce approximately 5 GWh annually.

The authors of [101] examined 11 EVs and 23 charging stations in Western Australia. The results show that 79% of charging occurs at work and home locations, and charging stations are only used 33% of the time. The study showed that the aggregated daily charging power profile of the EVs is similar to the curve from solar PV generation which shows that PV systems can meet EVs charging demand.

A grid-connected parking lot equipped with PVs and BESS was designed in [102]. The model controlled the charging station through a change of voltage level in the DC link, considering four operation modes. Each mode is represented by a voltage range according to a typical EV battery and a 5.5 kW PV panel.

Three different EVSPL optimization models were presented in [83], [84], and in [85]. These studies assumed different levels of parking lot occupation and considered the routines and preferences of the EVs owners, such as parking duration and limits on charging and discharging prices. Degradation of the BEVs, prices in the day-ahead electricity market were considered, as well as parameters such as time of arrival or departure, EV capacity, and different objective functions. However, in all three models, the intrinsic goal was to exploit the benefits for EVs by maximizing the SoC through the use of lower energy prices as well as maximizing the benefits of any energy exchange with the existing grid.

In [78] a model for a smart parking lot for PHEVs, considering wind, PV, and a diesel generator was presented to optimize the charging rate of EVs. The study used three optimization functions: optimal generation sizing, optimal EVSPL sizing, and optimal PHEVs charging, considering uncertainty. Optimizing the charging rate considered the maximum energy required by the PHEVs while considering the power constraints and the number of PHEVs in the parking lot. For the optimization of the BEVs SoC, constraints considered included the PHEVs arrival-time, the number of charging PHEVs, the start and end time of charge and the up-to-date grid and the load situation.

7.4 Battery ageing process, EV modeling and aggregated V2G with demand response

In [103] it is stated that the impacts of EVs on the electrical network, also considering the presence of PV sources with/without ESS, is a problem that requires in depth analysis. To this end, the authors of [103] presented a power analysis study considering different integration levels of EVs, energy storage systems and PV sources. A techno economic analysis was also conducted considering the losses through a fuzzy logic control system together with the Matlab Simulink toolbox, presenting a new outlook for further research considering EVs, storage and renewable energy integration.

Another example can be found in [104] where it is assumed that the large integration of rooftop PV and EVs in urban areas could help to reduce emissions and help to meet environmental targets. To this end the only restriction identified was that it was about the largest implementation of EVs in the short-term period. However, in terms of the benefits from the combination of rooftop PVs and EVs show the potential for emissions reduction of about 60% and energy cost reductions by 22% in Kyoto, Japan by 2030.

The potential for EV batteries to be a flexible reserve for providing regulation electricity markets was discussed in [105]. However, due to the stochastic nature of EVs and the power grid, realizing this potential is challenging.

The authors used historical data of the charging behavior of EVs and electricity system's regulation signal, to propose a data-driven approach to optimize the participation of EVs in the regulation market considering a statistical approach to analyze the uncertainty from the EVs together with a scheduling approach comparing three EV aggregators under a regulation market.

A data-driven framework for the large-scale forecasting of EV charging demands was presented by [106]. To this end an intelligent approach was considered using a low proportion of training data to increase the performance despite the complexity of the linear and non-linear networks. Also, several characteristics of EVs such as the state of charge, weather conditions, charging rates and driving styles were taken into consideration. The results show improved outcomes compared with other intelligent approaches, suggesting that the model can be further utilized for cloud-based battery diagnoses and large-scale forecasting of the energy demands of EVs.

A coordination management scheme for controlling devices in distribution systems was proposed by [107], considering uncertainties of the EVs, and PV integration through a double-layer metaheuristic optimization approach. The IEEE 1547:2018 standard was also considered. The comparison showed the capability to maximize the capacity of PVs, respect the constraints and increase the capabilities of EVs integration.

Considering the EVs behavior, the authors of [108] presented a micro-traffic flow model for EVs by considering the acceleration/braking features to represent and analyze the movements of EVs in traffic flow, especially in congested traffic. To this end a real case study was implemented in China to model the calibration and corroboration with the data collected. The results have shown that the proposed EV behavior model, based on R-squared values analysis, outperformed the traditional behavior models for both several driving modes, providing detailed resources to replicate trajectories, energy consumption and other uncertainty data required to integrate with another systems.

The authors of [109] proposed an approach for the statistical assessment of the potential of PHEV to provide V2G ancillary services considering the PHEV availability, flexibility, and behaviour. The flexible interval was computed considering a stochastic global optimization technique called Free Pattern Search, together with a probabilistic method to quantify the impacts of uncertainty around the PHEV's availability using the Gaussian mixture model, and the interdependency of stochastic variables by a multivariate modeling with Copula function. A real case study from France was considered showing that the proposed approach can effectively analyze the V2G potential of PHEVs as supplier of ancillary services.

The authors of [110] developed a model that studied the effects of power exchanges between the grid and EVs on the demand profile of the power system, the operational stability index, and reliability indices, considering a real environment and data. To this end, the operational instability indices were considered through the variety and standard deviation of the load factor for evaluating the system stability, together with reliability indices for various V2G and G2V integration levels to estimate the impact of different levels of power exchange on the system reliability. Also, an EV charging scheduling approach was considered to analyze the EV batteries' degradation and lifetime, to provide the power exchange profile for V2G at different levels and conditions. The model was validated through the IEEE 33-Bus system.

A methodology to analyze the impacts of the EVs and V2G on reliability, cost, and emissions with respect to the power grid was developed by [111]. The authors presented two novel indexes, stochastic and constant power supply, for measuring the reliability of the power grid based on the availability of renewable energy. Also, based on different integration levels of EVs and V2G, charging modes, locations and schedules were defined and analyzed by a Monte Carlo simulation approach. The results have shown that the integration of the EVs and V2G systems considering a grid with high integration of renewable resources improves the power grid's efficiency in terms of decreasing the total cost and emission rate.

Considering the demand response problem integrating the behavior of EVs in EVPL, some recent research can be found. For instance, in [112] a hierarchical approach was presented for simultaneously modelling the scheduling of a microgrid using the concept of a virtual power plant, where the demand response program and EV integration level are some of the uncertainty inputs, together with the demand. The authors used a multiple market tariff under a scenario-based method, optimized through a stochastic mixed-integer linear programming model. The results demonstrated that the coordinated operation of microgrids can improve the load restoration and reduce the load supply costs under demand response and EV integration.

A reliability-constrained demand response-based method to maximize the permissible penetration level of EVs at power grid was formulated by [113]. In this paper, the behaviour of EVs was analysed and implemented through a demand response program considering penalties, incentives and differing EV integration levels in the power grid. Monte Carlo simulation was used to evaluate the well-known reliability indices of power systems, showing that the integration of a high level of EVs is possible by utilizing the proposed approach.

The authors of [114] presented a model considering a shared EVPL between two buildings with random behaviour and considering a peer-to-peer operation to simulate modeled power outages at different time horizon and periods. Also, the buildings were supported by energy management systems to handle all the uncertainty introduced. The goal of the approach was to minimize the energy cost and maximize energy resilience. The results demonstrated that the designated energy management system, considering the EVs, has minimized the energy cost by 25% and improve the energy resilience under 7 hours of power outage.

Recently, in [115] the authors have presented a critical analysis considering the EVs providing the necessary demand response thus helping with the integration of RES. It was noticed that demand response programs may cause unwanted negative effects that the authors have called the avalanche effect, particularly beyond 2030, when integration of EVs will higher. Some recommendations were made such as suggesting a more proactive demand response signal and clear incentives about when the EVs can charge batteries, especially moving to hours of low or negative residual loads, reducing the peak and variance of residual load, and helping the power system flexibility and higher integration of renewable sources.

6. Conclusions

A comprehensive review of a rooftop PV system to support the large-scale integration of EVs was presented. This review has shown that EVs can become a vital part of power systems, with consequent air pollution reduction, augmented system reliability and economic benefits. EV owners can also benefit in several ways, economically, for instance, since they can decide on the prices to buy and sell electricity. By parking the EV under the EVSPL, damage to the EV due to solar UV radiation is minimized [116].

Privately owned garages are often used for activities other than vehicle storage [117], which may increase the need for publicly available EV charging infrastructure such as EVSPLs. To accomplish this, the joint planning of EVs and power grid infrastructure will be required. Since EVs are parked during most of the time, exposed to solar irradiance, and 26% of worldwide EV charging stations are in parking lots, a convenient and viable solution emerges in terms of EV charging – through PV covered rooftops above parking lots becoming EVSPLs.

An EVSPL may have financial and technical benefits to both the power system and the EVs. Finally, EVSPLs can bring environmental benefits such as increased RES usage, while minimising the GHG and other pollutants. As this survey denotes, further studies should analyse how the EVSPL concept can have an active and profitable role in power systems.

Furthermore, additional investments, economic and government incentives, population education and information, and supporting policies [118] should be put in place by countries to meet their targets. A comprehensive review of a rooftop PV system to support the large-scale integration of EVs was presented. This review has shown that EVs can become a vital part of power systems, with consequent air pollution reduction, augmented system reliability and economic benefits.

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Furthermore, additional investments, economic and government incentives, population education and information, and supporting policies should be put in place by countries to meet their targets. This work has shown that EVs are emerging as a central technology for the decarbonization of the transport sector. The coupling of EVs with parking lots covered by PV panels can help address some of the challenges associated with expanding the integration of EVs.

These challenges may include the lack of suitable technology (both from EVs and in terms of charging infrastructure) as well as a lack of suitable business models for EV charging. Future research may focus on identifying business models and using the findings to develop pilot projects to help demonstrate the viability of EVSPLs. These pilot projects, supported by regulatory environments, can help to increase the potential market for EVSPLs and their integration with smart electric networks.

The interaction of these EVSPLs is an important area for future research. For example, services such as V2G impact both the EV's battery as well as the physical distribution network and these impacts need to be understood. Both the transport sector and the electricity sector are rapidly evolving and becoming increasingly intertwined. EVSPLs offer an intriguing bridge between these two sectors as they evolve to meet the needs of a decarbonized economy.

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