





Review

# Charging Electric Vehicles Today and in the Future

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**Abstract:** It is expected that more vehicles will be electrified in the coming years. This will require reliable access to charging infrastructure in society, and the charging will include data exchange between different actors. The aim of this review article is to provide an overview of recent scientific literature on different charging strategies, including for example battery swapping, conductive- and inductive charging, and what data that may be needed for charging of different types of electric vehicles. The methodology of the paper includes investigating recent scientific literature and reports in the field, with articles from 2019 to 2022. The contribution of this paper is to provide a broad overview of different charging strategies for different types of electric vehicles, that could be useful today or in the coming years. The literature review shows that data utilized for charging or discharging includes for example information on the battery, temperature, electricity cost, and location. It is concluded that the preferred charging strategy for an electric vehicle may depend on the type of electric vehicle and when, where, and how the vehicle is used.

**Keywords:** charging infrastructure; electric vehicles; data; autonomous electric vehicle



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## 1. Introduction

There are more electric vehicles (EV) on the roads today, with a continuous charging need. It is expected that there will be a further significant increase in EVs on the roads, in the air, and on the water in the future, i.e., electric cars, trucks, aircraft, and boats. Thus, there is a trend toward the decarbonization of all modes of transportation [1]. This suggests a variety of future charging strategies, charging patterns, system types, and charging infrastructures to match the specific vehicle- and user requirements. The electricity available for EV charging locally can be generated to the grid from fossil fuels, nuclear power, or renewable energy sources (RES), such as hydropower. Intermittent RES can include e.g., solar [2], wind [3], or wave power [4]. The grids can be supported by battery energy storage (BES) for power balancing. In many countries, legislations, targets, or regulations to limit the amount of fossil fuels, internal combustion engine (ICE) vehicles, and pollutions will lead to a further enhancement of the amount of EVs in coming years [5], and installation of grid connected RES. The aim of this paper is to provide an overview of charging strategies available for charging of different types of EVs, now and in the future. Additionally, the information and data needed for the charging strategies will be presented, as well as the pros and cons of charging strategies for different vehicle types.

Thus, the idea of the paper is to map recent research in charging strategies for different types of EVs and identify the data utilized for the charging processes. The main contribution of this paper is to not solely analyze one type of charging for electric cars, but to map several different charging strategies for several different types of EVs that may be useful today or in the coming years to provide an overview of recent research in the area.

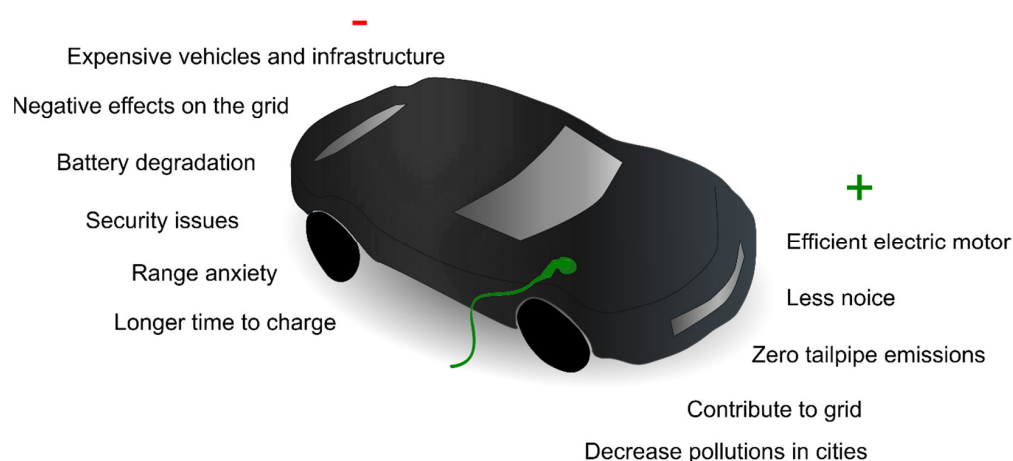
## 2. Methods

This review article is based on scientific literature and reports from 2019 to 2022, found mainly on ScienceDirect.com. The search phrases include, for example, the keywords

“charging”, “electric vehicle” and “data”. Scientific articles written before 2019 have not been included in the review. The paper is structured as follows: Section 3 provides a background to EVs and charging systems, Section 4 focuses on conductive charging, Section 5 describes controlled charging, Section 6 presents wireless charging systems, Section 7 describes battery swapping, Section 8 describes mobile (moveable) chargers, Section 9 focuses on renewable sources utilized to generate electricity for charging, and Section 10 concerns charging of autonomous or shared EVs. Section 11 concerns security aspects related to, for example, data sharing during charging. In Section 12, an overview of charging strategies is provided. Finally, the conclusions are presented in Section 13.

### 3. Background

There are both opportunities and challenges when it comes to a significantly more electrified transport sector. Some pros and cons of utilizing an EV instead of an ICE vehicle are summarized in Figure 1. The main benefits with EVs are related to the environment, with zero emissions from the EV itself (i.e., zero tailpipe emissions), no need for fossil fuels for driving EVs, and the vehicle is regarded as a zero-emission vehicle (ZEV) [6]. The air quality could be improved locally with more EVs in the cities. EVs are less noisy than ICE vehicles, and the electric motor is highly efficient [7]. Additionally, EVs can contribute with power discharge to the electric grid and therefore potentially support grid services. For most cases investigated, the total emissions (i.e., well-to-wheel emissions) are generally estimated to be lower for EVs than ICE vehicles, and the emissions related to EVs depend on the local electricity production [8,9]. In contrast, some negative aspects with EVs are that the new vehicles with batteries and charging infrastructures are expensive today, and the charging of EVs typically take a longer time than refueling an ICE vehicle. Moreover, EV drivers may experience range anxiety if they are worried about not being able to drive the desired distances with a charged EV [10]. When the EV reaches a charging station, there may be a long line of EVs waiting to be charged. Additionally, the local electricity demand would increase with additional EVs, and uncoordinated charging could result in power peaks, especially in the case of fast charging at high power rates. The charging of EVs may affect the grid and the power quality. While there are opportunities for balancing the grid with power discharge from EVs, using EVs for grid support may degrade the batteries faster, and drivers may also be reluctant to use their personal vehicle for stabilizing the grid. Furthermore, charging EVs and data sharing could enhance issues regarding cybersecurity.

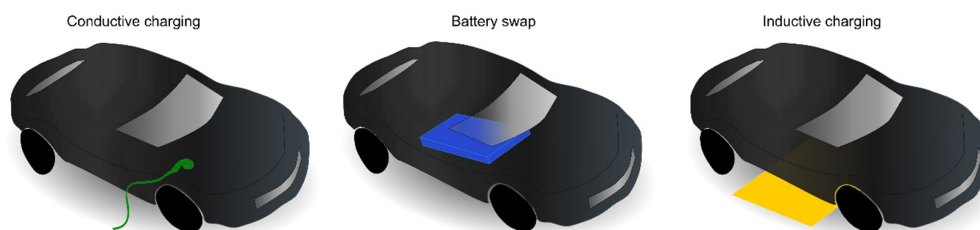


**Figure 1.** Summary of some potential pros (below the plus sign to the right) and cons (below to the left) with utilizing an EV instead of an ICE vehicle.

The vehicles with electric motors can be categorized as one of the following types: battery electric vehicle (BEV), plug-in hybrid electric vehicle (PHEV) or hybrid electric vehicle (HEV). PHEVs and HEVs include both an electric motor and an ICE. The PHEV is refueled with gasoline and recharged with electricity, whereas the HEV is only refueled

with gasoline. The BEV, in focus here, only includes an electric motor and needs to be recharged. The EVs could be categorized based on use and weight [6]: light-duty vehicles (LDV), medium-duty vehicles (MDV) and heavy-duty vehicles (HDV). LDVs are commonly electrified today, but more MDVs and HDVs are expected to be electrified. The heavier vehicles are often driven long distances to transport heavy loads. Specific requirements for MDVs and HDVs, including adapted charging infrastructure, should be met [6]. The EVs could be personally- or company owned, affecting the charging strategy. As an example, there could be regulations on how often a driver of a commercial HDV needs to stop to not get too tired on the road, and such regulated stops could be utilized for EV charging. Two possible charging strategies for commercial electrified trucks are on-route charging and return-to-base charging [11]. Commercial vehicles should be charged in an easy, fast and predictable way, and data that affect the charging behavior include the distance of the trip, length of the trip on a typical day, schedules, load on the vehicle, charging rate, parking time, available charging infrastructure, etc. [11]. In a recent report [12], it was highlighted for the case of Sweden that the number of heavy electrified trucks are expected to increase to meet the goals for fossil-free transportation.

A charging system for EV charging is called electric vehicle supply equipment (EVSE) [13]. As illustrated in Figure 2, an EV can be charged with AC or DC conductive charging, i.e., charging with cable (on-board or off-board charging), inductive charging (static or dynamic), or with battery swapping [14]. Chargers could be fixed or mobile. Moreover, EVs can recharge with regenerative braking [15], where the motor acts as a generator. The charging strategies can be differently applicable to different types of EVs and preferred in some situations or environments.



**Figure 2.** Illustration of three types of charging strategies for electric vehicles: conductive charging, battery swapping and inductive charging.

Easy access to charging is expected to support EV adoption. However, the cost for the charging infrastructure is not insignificant. Four different scenarios for the funding of EV charging are discussed in [16]; (i) the EV manufacturer pays for the charging infrastructure, (ii) the government pays for the charging infrastructure, (iii) the government provides an EV subsidy and the EV manufacturer pays for the charging infrastructure, and (iv) the government pays for both the charging infrastructure and an EV subsidy. In [16], the conclusion is that, to benefit social welfare, the government should pay for a subsidy of EVs, or pay for both the EV subsidy and the charging infrastructure. Purchasing an EV is already subsidized in some countries, and the potential of subsidizing charging and the installation of charging infrastructure was discussed in [17]. Many EV manufacturers are not part of the design of the charging infrastructure. However, business models, including the design of both EVs and the related charging infrastructure, may be beneficial in comparison to the independent design and production of vehicles and charging infrastructure [18]. EV drivers can install a private charger at home for a personally owned EV or share chargers in a neighborhood. The opportunity of community-owned charging stations was investigated in [19]. Access to a private parking space with a charger could increase the willingness to purchase an EV [20]. What may affect the willingness to buy an EV was discussed in [21], and it was found that there is a relation between EV customers and people with solar panels on their rooftop. Generally, EV owners could prefer access to both charging at home and publicly available charging stations, and data on public charging infrastructure

per capita may indicate local EV adoption [22]. The charging may take place in different environments. At airports, ground service equipment (GSE) could be electrified, including forklifts, shuttlebuses, and trailers for luggage [23]. As highlighted in [23], useful data for the electrification of airports with PV systems are electricity price, carbon taxes, solar irradiation, state-of-charge (SOC), info to identify the EVs at the airport, aircraft arrival and departure time (i.e., flight schedules), and investment costs.

#### 4. Conductive Charging

Today, charging with cables, i.e., conductive charging, is the most common charging strategy of EVs [24]. Conductive charging can occur at home or at other private or public charging stations. The opportunities of charging EVs at home, at work, or at a public facility, as well as utilizing a supplementary vehicle for some longer trips, were discussed in [25] for Seattle, based on GPS data. The charging stations for conductive charging EVs can be residential or non-residential, with fast or slow charging, with unidirectional power flow, or enabling a bidirectional power flow from the vehicle to the grid [7]. The AC or DC conductive charging can be classified in three different levels: Level 1, Level 2, and Level 3. In some cases, Level 3 is not included and denoted as DC charging instead. Level 1 is typically AC charging at low power levels; Level 2 is AC charging at slightly higher power levels; and Level 3, or DC fast charging (DCFC), includes higher power levels. The charging time is shorter with Level 3 charging and DCFC [7]. Slower charging is also known as destination charging, and fast charging is also called rapid charging [26]. A tool for modeling Level 3 charging stations was presented in [27]. The power level of DCFC could today be from around 50 kW, but the power levels could be increased in the future [28]. There is ongoing work on increasing the charging level to high-power charging (HPC) at about 350 kW to limit the charging time of a personal EV to about 15 min. This could, however, result in very high temperatures around the connector and safety issues [29]. Heavier vehicles could benefit from HPC. Charging at even higher power levels, around 400 kW, is known as extreme fast charging [28]. Thus, there are goals of reducing the charging time of EVs to be comparable to the refueling time of an ICE vehicle. This may lead to shorter battery lifetime [30]. Data on the battery system of the vehicle include, for example, weight, energy density, volume, degradation and the time it takes to charge, costs, and safety [31]. Data that could inform the EV driver of the charging time and driving range of (i.e., fast charging speed) are estimated in km/min [30]. On-board charging means that the charging system with a converter, etc., is mainly included inside the vehicle itself, whereas off-board charging means that the charging system with a converter, etc., is mainly inside the charging station [32]. AC charging is on-board charging and DC charging is off-board charging. The power electronic converters are discussed in [31]. Information on weight, size and space is more relevant for on-board charging, as the EV will include more equipment, whereas costs of the system are relevant for both on-board and off-board charging [33]. The on-board charging is more commonly used for slower charging rates, whereas faster charging can be done with off-board charging [24]. For AC charging, one single phase or all three of the phases could be used [26]. There are national and international standards to follow when charging an EV, affecting the design of the ports and connectors [7]. There are several strategies for battery charging proposed in different charging protocols, such as constant current constant voltage (CC-CV) [34]. As described in [35], in USA, EU, and Asia, the chargers used are for example of the types Tesla, J1772, GB/T, Mennekes, and CHAdeMO, an abbreviation for Charge de Move [26].

It has been highlighted that an Inconvenience in charging, due to a lack of Level 2 chargers at home, can contribute to the discontinuation of using EVs [36]. The placement of charging stations for conductive charging was discussed in [37], where information that could be used to optimize placement was, for example, the number of EVs charged, energy delivered to the EVs, infrastructure cost, distance to a charging station, degree of utilization of the chargers, and waiting time at charging stations. Cloud-based systems have been proposed for EV charging, to handle large amounts of data [38]. In [38], their framework

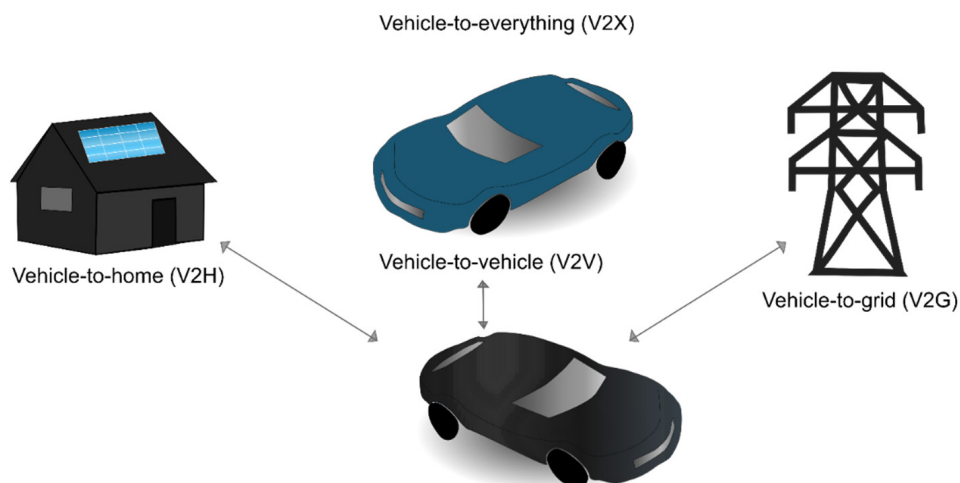
included data on SOC to describe the state of the battery, locations, energy of the charging, data on climate and on vehicle properties. Vehicle-to-cloud models have been proposed [39]. Charging clouds were used for data on the battery cell level in [40], including information on current, voltage, temperature and time. As highlighted in [41], apart from SOC, input data for the modeling of EVs generally include weather (e.g., temperature), travelling (time of the travel and estimated daily distance travelled, from either real data from GPS, data from travel surveys, or estimated patterns), date (time of the day, day of the week and season), and economy (e.g., gross domestic product and electricity prices). An overview of datasets available for studying charging of EVs was recently presented in [41]. Real datasets of residential charging of EVs for apartment buildings in Norway were presented in [42,43], with data on the energy use for garages with hourly resolution if an increasing number of EVs are charged there. It is noted that the EV charging times vary with personal access to a parking spot with a charging system [42]. It has been proposed that data could be simulated to emulate the charging of EVs, if real-world data are hard to receive [44], including data on the arrival of EVs, departure time, and need of charging. Additionally, although the number of EVs is increasing globally, there are not so many EVs in all cities where there are available larger data sets on the charging of similar EVs [45].

## 5. Controlled Charging

When the charging typically occurs, i.e., the charging profile, it varies with the season, time of the day, location, and if it is a workday or holiday [46]. How EVs are charged was the topic of [47], analyzing the travel data along with theories from behavioral economics. The charging demand can be estimated based on electricity price, patterns in driving, SOC values, where the charging station is located, charging time, type of charging, amount of people charging there, and the overall experience of the costumer [48]. To better understand to what extent different EV charging behaviors could affect the grid, increasing the peak-demand, non-preferred voltage levels, and system losses, a model and analysis for EV charging, with a case study of EVs in the UK, was presented in [49]. The charging of EVs can be coordinated to limit the load on the grid at certain times. The control or management of charging is known as smart charging, including the concept of V1G, where the (unidirectional) charging of the vehicle is coordinated in time, and vehicle-to-grid (V2G) with the coordination of bidirectional power flows between the vehicles and the grid, which is considered more complicated to implement [50]. The EV can be discharged to other systems as well, through vehicle-to-everything (V2X), vehicle-to-home (V2H), or vehicle-to-vehicle (V2V), and an overview is shown in Figure 3. EV owners can prefer to charge when the electricity price is low. A dynamic electricity price can enhance charging at certain times, to balance and coordinate charging from a grid perspective [51]. An EV aggregator is an actor between the grid owners and EV owners and could be useful for the implementation of smart charging or V2G, where the EV can both charge and discharge power to the grid. The aggregators would be part of coordinating V2G to ensure that it is beneficial for all actors [52]. As highlighted in [51], the data exchange between the EV and the aggregator could include SOC, charging time, battery capacity and location of the vehicle. The opportunity of utilizing V2G for a fleet of EVs was described in [53], utilizing DC-to-AC converters inside the EVs. An aggregator planned charging and discharging of the EV fleet to ensure the low cost of electricity, and the regulation of voltage and frequency, as well as not significantly decreasing the battery lifetime. The data used were current- and final SOC value, time of arrival and departure, cost of electricity, power availability and the preferred power regulation for the grid [53]. Some positive aspects with V2G are to support grid stability, power quality, good power factor, frequency regulation, reduce costs and limit voltage fluctuations [54]. Carbon emissions may be reduced by smart charging [55,56], and generally, purchasing a new EV rather than a new ICE vehicle may, in many countries, lead to lower life cycle emissions [57]. The control of EV charging could be designed to ensure a long lifetime of the technical systems, such as ensuring a long lifetime of the transformer connected to the grid [58]. Some downsides with V2G are that there could be



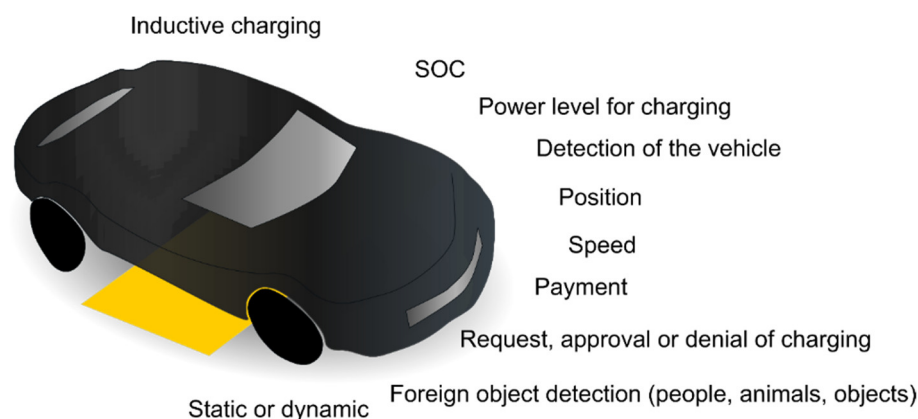
additional wear of the batteries, higher costs, and limited access to stations equipped and adapted for V2G [52]. The willingness of the vehicle owners and grid operators to use their EVs for smart charging or V2G can vary.



**Figure 3.** Sketch of concepts of V2X, with bidirectional power flow from the vehicle.

## 6. Wireless Charging and Dynamic Charging

The wireless charging of EVs, i.e., wireless power transfer (WPT), has been proposed as an alternative to cable charging. The EV can be charged wirelessly during the drive (dynamic charging) or when it stands still (static charging) [59]. Inductive wireless charging does not require a physical connection between the vehicle and the grid [33]. Bidirectional power flow is not relevant for WPT yet [7]. As described in [59], data sharing between the vehicle assembly (i.e., the system for wireless charging on the vehicle) and the ground assembly (i.e., the system in the road) is done through communication links, and the information necessary is e.g., SOC-value, and power level for charging. Other data transferred between systems are the detection of the vehicle and request, as well as the approval or denial of charging and ensuring that the vehicle is at the right position throughout the charging. If the charging is dynamic, the speed of the vehicle should be within a certain limit, and there may be additional vehicles on the road. The ground assembly must ensure that no other objects are on the charging area, i.e., ensure foreign object detection (FOD), including both people, animals, and objects, to ensure that no one will be harmed. Finally, the payment should be done. The charging of many vehicles with wireless charging was discussed in [60], proposing a system that would limit the need for transformers. Data suggested for dynamic charging are presented in Figure 4, and could include the arrival and departure time of EVs and unplanned or planned charging based on the historic data of driving [7], as well as the following: when and where to charge and when the charging should start and stop, when the connection is done, the cost of electricity in real time but also as expected in the future, potential cheaper prices at certain times, grid load, time of day, charging rate and power level, scheduling and location of the EVs to be charged, location of the charging stations, traffic on the roads to different charging stations and road conditions.



**Figure 4.** Sketch of some of the useful data during static or dynamic inductive charging.

There can be both inductive and conductive charging in the road for dynamic charging. Electric road systems (ERS) include inductive charging, power tracks in the road, and charging from overhead power lines, enabling dynamic charging. Thus, the dynamic wireless charging (DWC) can include a power track in the road to charge while the EV is driving over the power track [61]. The potential benefits with such a system could be a longer range of driving, a potential cost reduction, and improved use of the batteries. However, the too-small batteries for EVs with DW may have a shorter lifetime and be degraded, which could increase battery costs in the longer perspective, as discussed in [61], and there are the costs of installing and maintaining the power tracks.

## 7. Battery Swapping

Battery swapping could be a solution for fleets of electrified taxi cabs, where the discharged battery would just quickly be swapped to a fully charged one at a specific battery swapping station (BSS) [62]. The information includes the EV position in the station, info on requiring a new battery, how to dismount and mount batteries properly [63], the battery model and number of swaps per day at a station [64]. The possible locations of BSSs were analyzed in [64]. Battery swap could be an alternative to ensure a fully charged EV, with the benefit that it could take less time than cable charging. In [65], the infrastructure for EV charging is divided in three different categories; distributed infrastructure (i.e., small charging systems, at home or by the office, connected to the grid utilizing transmission lines, but adding on systems and functionality for V2G), fast charging infrastructure (i.e., with charging stations with use of high power rates from grid, but no functionality for V2G), and battery swapping infrastructure (i.e., battery swapping stations with many charged batteries and opportunity to recharge the battery at a central station). The consumers view on battery swap technology (BST), with regards to risks and usefulness, affect how much it will be implemented in the future [63].

## 8. Mobile Charging

In large cities, fixed charging piles may be expensive to install due to the high costs of land; the EV driver could spend a lot of time at charging stations, and parking places with charging piles could be hard to find due to the large amount of traffic. In such circumstances, mobile charging could be an interesting option for the driver [66]. Mobile charging or portable charging includes charging stations that can change its location. As described in [66], the mobile charging piles, including a van with battery to charge from, could be called to a specific EV for charging with the use of an app in a smartphone, and the payment of the charging, including a fee for the service, would be made afterwards using the phone. In [67], the problem of the high interest of EV drivers to charge during specific hours and demand on the power grid at these times was solved by including extra portable charging stations (PCS). The vehicles can be charged by mobile robots in a garage,

where the charger moves to the car that needs charging, either with a conductor or with inductive charging [68]. A mobile robot charger with energy storage and conductor in a parking area was proposed in [69], discussing that the cost of installing fixed charging piles at parking spaces could be reduced. Data in the model of charging robots in [69] included information of the size, overall outline and number of parking lots of the parking area, data on when the vehicles arrive and leave, how many of the vehicles that are EVs, EV charging requests, battery information, which parking lot the EV is placed on, when the vehicle should be done with its charging, and the EVs will be put in a line to fulfill the charging demand of several EVs. To communicate between EVs and chargers, internet-of-vehicle (IoV) was suggested in [70] for mobile charging solutions with data on charging stations and number of plugs, waiting time, cost of charging, GPS data on roads and traffic jams, data on EVs and charging need, budget for charging, etc.

Mobile charging stations were outlined in a recent review paper [71], dividing different charging strategies in the three main categories: mobile charging (including the subcategories: portable charging station, truck mobile charging stations and vehicle-to-vehicle (V2V) power transfer), fixed charging (private and public charging stations) and contact-less charging (battery swapping and wireless road charging). Data from the driver for mobile charging include the suggested location for the charging event, electricity need, and time to charge, and after a correct charging, the driver will receive information on total cost of the charging [71]. Some benefits of utilizing a mobile charging strategy are that it does not require building more new fixed charging stations with secure access to an electric grid, or new costly infrastructure, and the system could be charged during the times that are beneficial for the grid [71]. In general, mobile charging could become a complement, enable flexible charging, reduce traffic jams, and become a support to fixed charging stations during times with high demands. V2V charging was analyzed in [72], discussing that data are required from the driver in need of charging (consumers) to the driver who offers charging and sells it to the other vehicle (providers), and that vehicular ad-hoc networks (VANETs) could be used for data-sharing between the vehicles.

## 9. Renewable Energy Systems and Charging

Utilizing photovoltaics (PVs) on the EV itself could decrease the time at a fixed charging infrastructure. For agricultural machines, PV systems on-board vehicles were discussed in [73], including autonomous vehicles for agriculture and electric tractors for farming. Utilizing PV systems on the roof for generating electricity to directly power the propulsion system of tourist boats was discussed in [74]. This is to reduce the use of fossil fuels in powering the boats. Including RES in the charging of EVs has gained interest; an EV charging system with fast chargers, including, for example, a PV system, battery storage, and wind power, was modeled in [75], utilizing weather data (e.g., radiation, temperature and wind speed) to predict the power production from RES available to charge the EVs. A PV system for a stand-alone charging system was modeled and analyzed in [76]. Also, EV charging supported by PV systems and control was modeled in Matlab/Simulink in [77]. In [78], a charging station powered directly with wind power was discussed for the fast charging of EVs. While most charging systems powered by RES today include wind power or solar power, often combined with battery energy storage, there are future opportunities of utilizing, for example, marine current energy converters or wave power for EV charging systems, especially for applications in marine environments or near harbors. This area could benefit from future research, possibly with real-time simulations. The data needed for RES powered charging depend, for example, on the type of RES, the variability of the resource, the EV charging demand, information on the location, and if the system is connected to the grid or if it is a stand-alone system.

## 10. Charging Autonomous Vehicles, Shared Vehicles or Vehicle Fleets

In the future, EVs could be shared to a larger extent. Each vehicle would then be driven more and could result in a reduced number of EVs on the roads. In [79], the inductive



charging and conductive charging of shared autonomous electric vehicles (SAEV) were compared and discussed for a university shuttle. SAEVs may have different charging needs than personally owned EVs, due to increased use on the roads [80]. In some cities, there are business models for shared electric vehicles (SEVs), where the customer either picks up and parks the SEV anywhere or parks the SEV at a specified place [81]. Additionally, there may be more connected mobility (CM) in the future, including communication between different vehicles or between vehicles, pedestrians, and traffic lights [7]. The self-driving autonomous electric vehicles (AEVs) will need a specific charging strategy, as there is no driver there to enable the charging [82]. Data required when planning for charging strategies of shared AEVs are the physical charging infrastructures and their location in relation to the AEVs and status (i.e., occupied or unoccupied), current SOC value and preferred value, as well as the customer's request to travel [82]. AEV passengers would not need to take care of parking and the decisions of when and where to charge or discharge [7]. The use of a cyber-physical infrastructure, including hubs for the controlled charging of shared autonomous electric vehicles (SAEVs), electricity generated from PV, energy storage, and EV discharging, were discussed and investigated in [83]. Information included electricity price, the charging demand of AEVs, the number of SAEVs and hubs, the design of the hub, including the PVs and batteries, previous demand for transportation, etc., and the authors highlighted that some of these data may be publicly available in some countries [83]. Self-driving cars may improve the safety of the pedestrians and other vehicles. More connected and autonomous vehicles and infrastructure could have several socio-economic effects [84], suggesting that some sectors may either benefit economically (e.g., car manufactures, digital services and electronics) or may not benefit economically (e.g., insurance companies and repair stations due to safer driving) from an increased amount of connected AEVs. Access to charging stations affects how beneficial the SEVs can be [81]. In [85], a model for the planning of fast charging for ridesharing was presented for a limited EV idle time, with a case study of buses in Luxembourg.

The charging infrastructure can be planned to be adapted to a large amount of electrified taxi cars in the urban environment [86]. Taxis in large cities are driven more often than a personally owned EV, and the charging infrastructure should enable fast and available charging to not let the customers wait for their ride. The authors propose a method for deciding the locations of charging stations for electric taxi fleets based on the driving range of EVs and driving routes of ICE taxi drivers based on GPS data, with a case study for Istanbul [86]. Due to many driving hours, taxi fleets can reduce the pollution in cities by using EVs instead of ICE vehicles. Additionally, electric taxis and the planning of a fast-charging infrastructure in a city, specifically in Singapore, were analyzed in [87]. The taxi driver wants to limit the time waiting for an EV to charge, to drive customers continuously, and this affects the charging strategy and suitable infrastructure. Thus, if using cable charging, fast chargers would be the most time efficient [88]. The charging of EVs for ride pools could be controlled via time to ensure that the vehicles are available in service when the travelling demand is typically the highest, or to ensure charging with a low cost of electricity [89]. The ride-pool service may utilize information on the pickup place, driving path, drop-off place of passengers, time that the customers wait until pickup and any delay, the total time of the ride, how many shared the ride with other passengers, and data on the state of the EV [89].

## 11. Safety Aspects

The EVs and EV charging stations (EVCS) are sometimes described as cyber-physical systems, including one physical part, including the electrical system, and one cyber part for communication [90]. The safety of charging is highly important. This includes the safety of the vehicle, including batteries and electrical systems, fire, electrical shocks, cyber-security, and the safety of EVCS [91]. The cyber-security issues and vulnerabilities related to EVs, the power grid and the EVCS were highlighted in [90]. Risks could be that the EVs are controlled to cause power instability of the grid, a remote attacker may take control of

charging to include falsified data for the vehicles (such as GPS data) and damage the power grid through taking control of the interfaces between the EVs and EVCSs, and the data available for the public on EV systems and the grid could be used for planned attacks. Data transferred between the EV and EVCS could be authentication and control, SOC value, and preferred charging current [90]. Looking at future AEVs, these may be able to communicate with traffic lights and other vehicles. Data for the EVCS could be control of the quality of AC power from the grid. Information on the EVCS could be regarding payment, charging level, which type of connector to be used, and the charging time, charging prices and energy use via grid or aggregator, etc. [90]. Additionally, data on which vehicles have been charged by the EVCSs, their charging status, authentication, data beneficial for the customers, etc., can be presented in an app, or shared to the manufacturer, the power grid company, an aggregator and so on. The EV charging and information sharing from different vehicles demand security and would have to follow current legislation, such as general data protection regulation (GDPR) with systems for deleting information about the drivers, etc. [92]. Taking regulations, such as GDPR, into account when handling data from energy systems was discussed in [93], including data on RES and EVs in Denmark. GDPR and similar legislations will be relevant to consider for connected vehicles [94]. In the future, the increased number of connected vehicles, such as AEVs, would require the management of a lot of data as well as considerations of the privacy of the users.

Charging EVs in emergency situations, e.g., during wildfires or hurricanes, can be complicated [95] and needs planning. Data utilized in [95] for modeling charging under emergencies were historical data on mass evacuations, vehicle model and level for charging, EV arrival time to the charging station, number of vehicles and how much the EVs are charged when they arrive at the station and number of charging station locally. Data on temperatures (e.g., temperature rise and temperature differences) during a charging process with cables were discussed in [96], from a safety perspective. During the charging events in experiments [96], the data exchange between the charging pile and EV included, for example, the highest and lowest temperatures of the battery, SOC-value, current, voltage, and charging power. Issues related to EV charging and temperatures could lead to battery damage or thermal runaway, and both too high and too low temperatures can cause problems [96].

## 12. Overview

Based on the literature review, analysis, and information on the charging of electric vehicles, Table 1 presents an overview of the likely and possible ways to charge electric cars, boats, heavy road vehicles, aircraft and agricultural- or working machines. The most common types of EVs today are electrified cars. Electrified cars utilized used for different purposes and with different charging strategies, are analyzed and presented in Table 2.

**Table 1.** Overview of different charging strategies and EVs, highlighting the possibilities of implementation as likely (green, X), possible (yellow), not likely (red, -), or requiring more research and development (blue, \*).

Charging Strategies of EVs	Cars	Boats	Heavy Road Vehicles	Aircraft	Agricultural- or Working Machines
AC cable charging	X	X	X	X	X
DC cable charging	X	X	X	X	X
High power charging	*	*	X	X	*
Static inductive charging	X	-	X	-	-
Dynamic inductive charging	X	-	X	-	-
Battery swap	X	*	X	X	X
Mobile charging	X	*	X	*	*
Regenerative braking	X	X	X	X	X

Table 1. Cont.

Charging Strategies of EVs	Cars	Boats	Heavy Road Vehicles	Aircraft	Agricultural- or Working Machines
Overhead lines			X	-	X
PV system on vehicle		X	*	*	X
V2G	X	*	X	*	X
V2X	X	*	X	*	X

**Table 2.** Different types of electric cars and charging places affect the likelihood of utilizing different charging strategies, from likely (X, green), limited likelihood (yellow), and more research and development are needed (\*, blue).

Charging Strategies of EVs	Personally Owned Chargeable Cars at Private Charging Places (Households)	Personally Owned Chargeable Cars at Public Charging Places	EV Fleets Charged at Public or Private Charging Places (Taxis, Fleets of AEVs, Car Sharing Pools, Delivery Services etc.)
AC cable charging	X	X	X
DC cable charging	*	X	X
High power charging			
Static inductive charging	X	X	X
Dynamic inductive charging		X	X
Battery swap		*	X
Mobile charging		X	X
Regenerative braking	X	X	X
Overhead lines			
PV system on vehicle			
V2G		*	X
V2X	*	*	X

### 13. Conclusions

In this study, it is concluded that there are several different charging strategies for EVs described in recent scientific literature, and that the strategies have both pros and cons. The benefits and challenges can be related to the data needed for the charging, for example, when it comes to safety and security. Three charging strategies that could be relevant in the future are conductive charging, inductive charging, and battery swapping, and the charging strategies may include mobile or fixed systems. From the literature review, it is concluded that which charging strategy that is the most suitable for an EV in the coming years depends on when and where the charging is needed, the type of EV, and how the vehicle is used. It is concluded that some charging strategies may not likely be utilized for certain EVs or may require more research before utilization.

Data on the batteries are crucial for all charging strategies (SOC, temperature, etc.) to not cause thermal runaway or other failures for the battery system and to know how much the EV needs to charge. Certain ways of charging may be more interesting from a security perspective, as they require less data sharing. Additionally, some charging strategies may be more relevant for fleets than for personally owned EVs. Certain data could be needed in specific situations, such as weather data during bad weathers, to ensure secure charging. It is concluded that some areas could benefit from more research in the coming years, such as HPC, mobile charging and V2X. Future research could also include the analysis of different types of RES to support the charging of EVs, such as wave-powered or marine-current-powered charging systems for electric boats. Future research can include a techno-economic perspective on all charging strategies for different EVs.

It is concluded that EV charging will result in information sharing that should be considered from security perspectives. One main conclusion from the literature review is

that there will likely be many different types of EVs in society in the coming years, requiring access to an available charging infrastructure and different suitable charging strategies.

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