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Review

Charging and Discharging Strategies of Electric Vehicles: A Survey

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Abstract: The literature covering Plug-in Electric Vehicles (EVs) contains many charging/discharging strategies. However, none of the review papers covers such strategies in a complete fashion where all patterns of EVs charging/discharging are identified. Filling a gap in the literature, we clearly and systematically classify such strategies. After providing a clear definition for each strategy, we provide a detailed comparison between them by categorizing differences as follows: complexity; economics and power losses on the grid side; ability to provide ancillary services for integrity of the power grid; operation aspects (e.g., charging timing); and detrimental impact on the EV, the power grid, or the environment. Each one of these comparison categories is subdivided into even more detailed aspects. After we compare the EV charging/discharging strategies, we further provide recommendations on which strategies are suitable for which applications. Then, we provide ratings for each strategy by weighting all aspects of comparison together. Our review helps authors or aggregators explore likely choices that might suit the specific needs of their systems or test beds.

Keywords: charging strategies; optimization; electric vehicles; power grid; ancillary services

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1. Introduction

1.1. Motivation and Background

The world is encountering a reduction in fossil fuel reserves for the next few decades. For example, the worldwide production of oil is expected to expire in 53.3 years, that of natural gas is expected to expire in 55.1 years, and that of coal is expected to expire in 113 years [1]. The energy consumption is increasing each year [2], and the CO_2 emission is also increasing [2]. It is estimated that 32.2 Gt of CO_2 are produced in 2013 compared to 15.5 Gt in 1973 [3]. The global temperature of the Earth is increasing each year, and it is predicted to rise by about 3.6 °C by 2040 compared to 2014 [4]. The fuel oil consumption in the transportation sector overpassed 63.8% in 2013 with respect to the total consumption in the world, according to the International Energy Agency (IEA) [3]. The natural gas consumed by the transportation sector overpassed 6.9% in 2013 [3]. Meanwhile, the electricity used for the transportation sector did not reach 1.5% in the whole world, which is negligible compared to the oil consumed in the sector [3]. All these reductions in the worldwide reserves have encouraged researchers, organizations, and governments to shift their source of energy to Renewable Energy Source (RESs) and to introduce Electric Vehicles (EVs), which use electric/hybrid motors as an alternative solution to the Internal Combustion

Engine (ICE), which is used in most of the vehicles. The share of RESs in total power generation is expected to rise to 33% in 2040 [4]. The market production and demand for EVs are increasing every year. They reached 740,000 vehicles in 2014 [5], and it is expected to reach 20 million EVs in 2020 [6] (In fact, the number of customers who purchase EVs increases by 10% every year [7]). According to a study done by Electric Power Research Institute (EPRI), a PHEV sedan might cost annually $175 (assuming average residential price of 11.4 cents per kWh, all currencies are in USD in this paper). Assuming a gasoline price of $3 per gallon assumption and that a conventional car would travel the same distance, the EPRI concludes that the average American driver might save up to $600 annually by using a PHEV [8]. Thus, the utilization of EVs is economical. Other benefits also are obtained from EVs. Many studies have been done to integrate them into the Power Grid (PG) in an optimized fashion to benefit from their integration. In addition to the many advantages of EVs, they also have limitations. Thus, to reduce the negative impact on the network, it is crucial to choose an optimized charging strategy.

1.2. Literature Review

A Plug-in Hybrid Electric Vehicle (PHEV) consumes energy from two sources: the fossil fuel and a battery, while a Battery Electric Vehicle (BEV) is supplied only by a battery. Both types might interface electrically with the grid, which allows them to charge and (when technically possible) discharge their stored energy [9]. In this paper, we use 'EV' to refer to both types (i.e., PHEV and BEV). Over 90% of homes, workplaces, and public places might provide chargers for EVs, which means they might be connected to the grid most of the time [10–13]. Furthermore, a statistical analysis reported in Bhattarai et al. [14] shows that the majority of vehicles (around 60%) are driven by their owners from the home to the workplace between 6:00 and 9:00 a.m. At the same time, the majority also drive back home from 2:00 to 5:00 p.m. The final result of the statistical analysis shows that 94% of EVs are available for charging (similarly discharging as well when technically supported) throughout the day. The high level of availability of EVs is also confirmed by other papers. For example, [15] mentions that the probability that an EV is parked anywhere during daylight time is over 90%, while the probability that it is parked at home most of the day is over 50%. Compared to vehicles with ICEs, EVs significantly reduce CO_2 emissions and other harmful gases [16–18]. Furthermore, they reduce noise levels and allow for better urban air quality [17]. Despite this, [12,17,19] demonstrate that EVs charged from conventional power plants such as coal-based plants produce more CO_2 and harmful gases compared to normal ICE vehicles. Hence, for EVs penetration to benefit the environment and reduce harmful gas emissions, it should be accompanied by the integration of RES, hydropower plants, and nuclear plants. An EV can have a unidirectional charger in which it absorbs energy from the PG without injecting energy [20] or a bidirectional charger through which it may absorb or inject energy from/to the PG [21]. Research demonstrates that the coordinated smart charging/discharging of EVs is much more efficient than uncoordinated charging [17,22], especially when advanced converters are used. The used optimization techniques reduce the power losses on the PG and reduce the operation cost of the whole system. In addition, aggregators such as Parking Lots (PLs), Charging Stations (CSs), and Power System Operators (PSOs), as well as individual EVs are benefiting from this coordination [20,21,23–30]. Coordinated charging/discharging minimizes the detrimental impact of EV on the PG [21,31,32], even with high penetration level [33]. By contrast, the uncoordinated charging may negatively affect the PG even with a small penetration level [34].

1.3. Contribution

Many review papers were done on the impact of the EVs integration on the PG [21,35,36]. Others focused on the charger power levels [36], the infrastructure for EVs [36], the unidirectional and bidirectional chargers [36], the optimal scheduling methods [35], and the power flow [21]. Many papers mentioned the charging strategies, but they are not detailed and lack important definitions and information [21,36]. There is a lack of relevant information in these review papers because (1) a complete list of different charging and discharging strategies of EVs does not exist; (2) the advantages and barriers of each strategy are not described completely, and (3) there are hundreds of different methods of charging and discharging, and most of them are not related to each other in a systematic and comprehensive review. In fact, even the latest review paper we are aware of was written by Solanke et al. [37]. The authors provided an excellent comprehensive review of the optimization objectives of charging strategies and challenges facing V2G implementation. However, [37] covers only five charging/discharging methods (compared to 14 as identified by our work). Filling a gap in the literature, this review paper contributes to categorize different charging and discharging strategies according to many criteria and presents the advantages and barriers of each strategy. The main contributions of this review are as follows:

1. Clearly and systematically classifies different charging and discharging strategies
2. Presents (in detail) the advantages and barriers as well as positive and negative impacts on power grids of the identified strategies
3. Defines new strategies that (up to the date of this review) were not mentioned in the literature
4. Rates the strategies based on detailed coverage of multiple aspects of interest
5. Comprehensively identifies the optimization constraints of charging/discharging strategies as covered in the literature
6. Provides recommendations on the suitability of each strategy for specific applications

2. Categorizing All Charging Strategies

After an extensive literature review on different charging and discharging strategies, we concluded that a detailed classification of charging strategies does not exist in the literature (to our best knowledge). Therefore, this paper categorizes all different charging methods into 14 main strategies according to many criteria, as described in the following subsections. For the sake of completion, we propose new strategies, which might be potential research topics in the future. The strategies are divided into two main groups: (A) Uncoordinated Strategies (Table 1) and (B) Coordinated Strategies (Tables 2 and 3). The mentioned strategies are compared in Tables 4–8 considering techno-economic aspects.

2.1. Uncoordinated Strategies

Uncoordinated Strategies (USTs) are defined as the "charging" or "charging and discharging" processes (also called modes) of a single or a fleet of EVs which occurs in an uncoordinated manner, without scheduling, without using optimization techniques, without coordinating between different EVs on the same transformer, and without following pricing mechanisms (as in Table 1). This group contains three different methods of charging and discharging and six main strategies, as depicted in Figure 1. The first method of charging is "Direct", which means that when the EV is plugged in, the charging starts immediately and stops when the EV is charged to the desired State-of-Charge (SOC) level or disconnected. The second method of charging is "Delayed", which means that when the EV is plugged in, the charging may be delayed to off-peak time. Such a delay reduces the total load congestion during on-peak periods. The third method of charging is "Random". This method is similar to the "Direct" method, except for the difference that the plug-in time distribution of EVs on a bus is random.

Table 1. Definitions of Uncoordinated Charging Strategies of Electric Vehicles (EVs).

Strategy			Definition and References that Discuss/Propose the Strategy
Item	**Name and Abbreviation**		
1.	Uncoordinated Direct Charging	U-Di-C	The charging mode of a single or a fleet of EVs that automatically charge when they are connected to a PG until they are charged to the desired SOC or disconnected [9,17,20,26,38–40].
2.	Uncoordinated Direct Charging and Discharging	U-Di-CD	SAS1. In addition, the discharging mode could be used to supply electricity to the load or the PG during the on-peak time. The discharging occurs in an uncoordinated manner (as defined in Section 2.1) and subject to the owner's desire. The discharging power rate is not optimized or controlled. Therefore, it is not recommended to use it because it might discharge at an unwanted power rate. Therefore, it creates unnecessary demand reduction. This strategy has not been studied yet to the best of our knowledge.
3.	Uncoordinated Delayed Charging and Discharging	U-De-C	The charging mode of a single or a fleet of EVs in which the charging is delayed to a certain period (usually to the off-peak time) in order to reduce the power congestion during the on-peak time. Since it uses uncoordinated charging (as defined in Section 2.1), the delay of charging may create another peak load during the off-peak time (a phenomenon known as "rebound peak" [41]). Therefore, it could have a negative impact on the PG. This strategy was studied by [42,43].
4.	Uncoordinated Delayed Charging	U-De-CD	SAS3. In addition, the characteristic of the discharging mode is similar to strategy 2 (U-Di-CD). This strategy has not been studied yet to the best of the authors' knowledge.
5.	Uncoordinated Random Charging	U-R-C	The charging mode of a fleet of EVs distributed randomly during a certain period. This type of charging is similar to strategy 3 (U-De-C), but the difference is that in the latter, the EVs are not distributed randomly during a certain period of time. Some papers studied this strategy, such as [33,44,45]. Paper [38] studied a similar type of charging called "random schedule", in which the distribution of charging EVs is done randomly during a certain period
6.	Uncoordinated Random Charging and Discharging	U-R-CD	SAS5. The characteristic of the discharging mode is similar to strategies 2 and 4 (U-Di-CD, U-De-CD). This strategy has not been studied yet to the best of the authors' knowledge.

SAS#: Same as Strategy Number #.

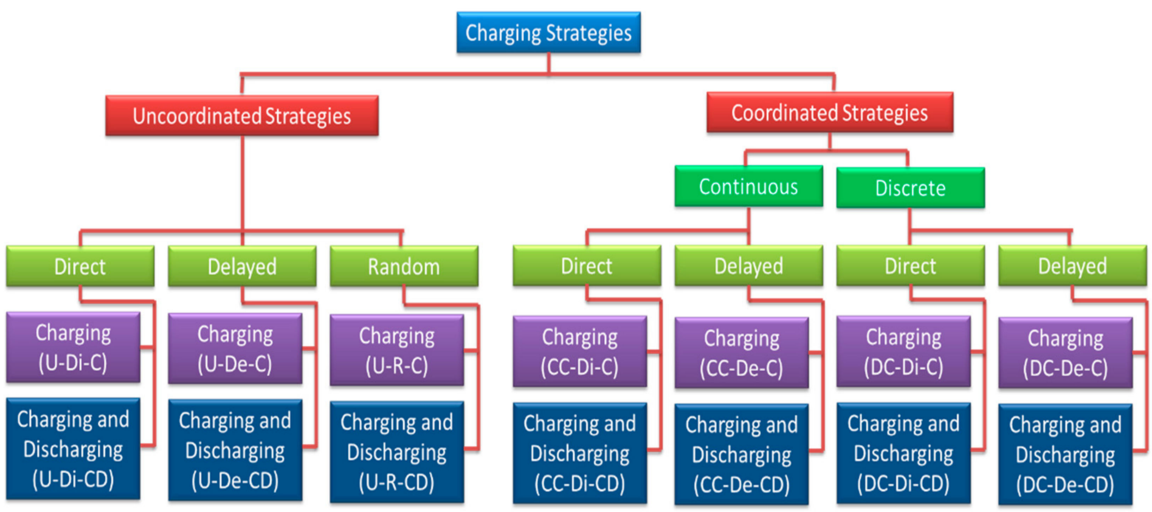
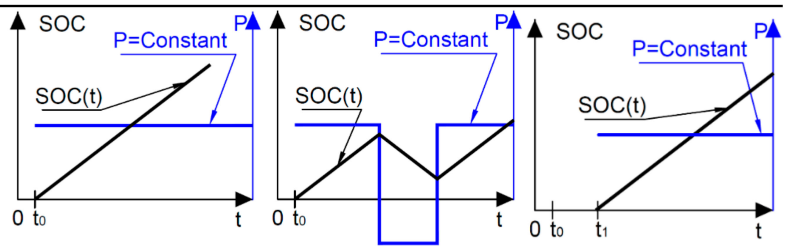
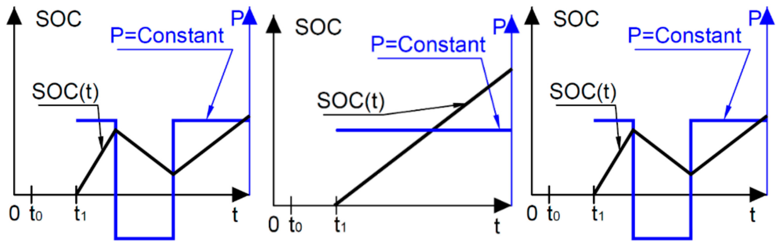


Figure 1. Coordinated and Uncoordinated Strategies.

A graphical illustration of all uncoordinated strategies is shown in Figure 2.



	(a)	(b)	(c)
Strategy	U-Di-C	U-Di-CD	U-De-C
Plug-in time	t_0	t_0	t_0
Start charging time	t_0	t_0	$t_1 > t_0$
Power profile	Constant or Variable	Constant or Variable	Constant or Variable



	(d)	(e)	(f)
Strategy	U-De-CD	U-R-C	U-R-CD
Plug-in time	t_0	t_0	t_0
Start charging time	$t_1 > t_0$	$t_1 > t_0$	$t_1 > t_0$
Power profile	Constant or Variable	Constant or Variable	Constant or Variable

Figure 2. Illustration SOC and Discharge Power for Uncoordinated Strategies.

2.2. Coordinated Strategies

Coordinated Strategies (CSTs) are defined as the "charging" or "charging and discharging" modes of a single or a fleet of EVs which occur in a coordinated manner, with scheduling, with using optimization techniques, with or without coordination between different EVs on the same transformer, and with following the pricing mechanisms [46–53]. This group contains two major branches: "Continuous" and "Discrete" Charging Strategies as in Tables 2 and 3, respectively. Each major branch contains two different methods of charging and discharging, which are "Direct" and "Delayed" similar to the UST mentioned in Section 2.1. In total, it contains eight different strategies, as depicted in Figure 1. The Continuous Charging Strategies are defined as the "Charging" or "Charging and Discharging" of EVs in a continuous manner during a certain period (e.g., ≥1 h) without dividing the charging time into separate intervals. The "Continuous" is used at home, PL, and a CS. The Discrete Charging Strategies are defined as the "Charging" or "Charging and Discharging" of EVs in a discrete manner during a certain period (e.g., ≥1 h). The total time of charging is divided into several intervals (e.g., 5 min each interval). The charging may occur during certain intervals, while other intervals could be used for other EVs. It is used only in PLs and not for a single EV.

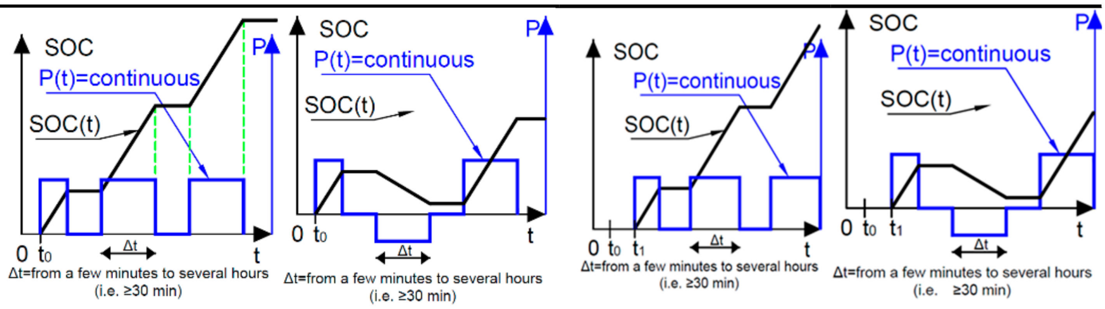
The CST is widely studied in recent years. They are regarded as the best strategies that could be implemented to EVs. The charging and discharging modes are controlled, coordinated, and optimized in such a way that the negative impacts of the EVs' penetration become positive impacts on the PG. Most of these studies have concentrated on the Grid-to-Vehicle (G2V) concept, in which the charging mode is only considered. Others have concentrated on both concepts V2G and G2V in which a bidirectional power flow is implemented (i.e., it is possible to charge the EV during G2V mode or discharge it during V2G mode). The main goal of these strategies is to reduce the power losses in the PG, reduce the total operation cost, reduce the peak load, etc. There are also other concepts such as Vehicle-to-Vehicle (V2V) [54], Vehicle-to-Home (V2H), or Home-to-Vehicle (H2V) [54], etc. All these concepts have similar goals to the ones of Vehicle-to-Grid (V2G) and G2V modes.

Table 2. Definitions of Continuous Coordinated Charging Strategies of EV.

Strategy			Definition and References that Discuss/Propose the Strategy
Item	**Name and Abbreviation**		
7.	Continuous Coordinated Direct Charging	CC-Di-C	The charging mode of a single or fleet of EVs, which automatically charge when they are connected to the PG until they are charged to the desired SOC or disconnected. It uses an optimization technique that charges EVs continuously during a certain period of time without being interrupted. Furthermore, the charging mode is coordinated in a way to avoid charging during the on-peak time and fill valleys during the off-peak time [26,38,44,46]. This strategy also includes fuzzy coordinated Direct Charging in which it uses the Fuzzy reasoning [39] as well as real-time coordination [44].
8.	Continuous Coordinated Direct Charging and Discharging	CC-Di-CD	SAS7. Additionally, the discharging mode could be used to supply electricity to the load or the PG during the on-peak time. The discharging occurs in a coordinated manner (as defined in Section 2.2) during the on-peak time and when the electricity price is very high [47,48]. The discharging power rate is optimized and controlled. Therefore, it is highly recommended to use this strategy because of its many advantages, such as reducing the peak load, minimizing the total operating cost, etc. This strategy includes the fuzzy coordinated direct charging and discharging (it has not been studied yet, and it is highly recommended).
9.	Continuous Coordinated Delayed Charging	CC-De-C	The charging mode of a single or fleet of EVs in which the charging is delayed to the off-peak time [20,40,49–51]. It uses an optimization technique to charge EVs continuously during a certain period without being interrupted. There are reasons to use this strategy such as (1) it reduces the congestion on the network; (2) it charges when the electricity price is low [49]; and (3) it fills valleys [49,51].
10.	Continuous Coordinated Delayed Charging and Discharging	CC-De-CD	SAS9. Furthermore, the characteristic of the discharging mode is similar to strategy 8 (CC-Di-CD). Ref. [40] used this strategy in which the discharging occurs when the load overpasses the limit on the transformer.

SAS#: Same as Strategy Number #.

A graphical illustration of all uncoordinated strategies is shown in Figure 3.



	(a)	(b)	(c)	(d)
Strategy	CC-Di-C	CC-Di-CD	CC-De-C	CC-De-CD
Plug-in time	t_0	t_0	t_0	t_0
Start charging time	t_0	t_0	$t_1 > t_0$	$t_1 > t_0$
Power profile	Constant or Variable	Constant or Variable	Constant or Variable	Constant or Variable

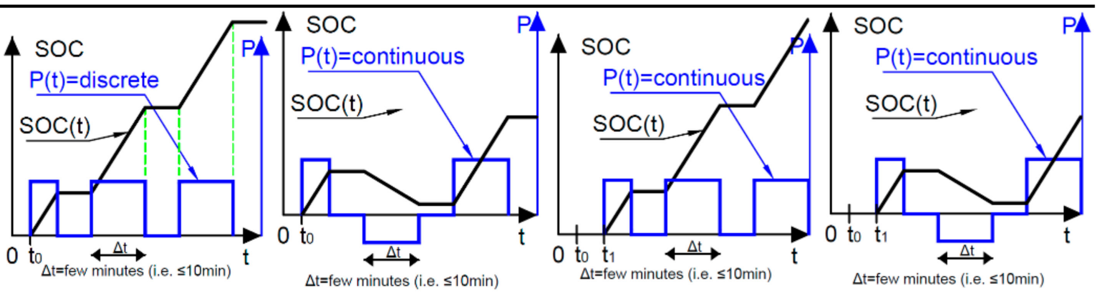
Figure 3. Illustration SOC and Discharge Power for Continuous Coordinated Strategies.

Table 3. Definitions of Discrete Coordinated Charging Strategies of EV.

Strategy			Definition and References that Discuss/Propose the Strategy
Item	Name and Abbreviation		
11.	Discrete Coordinated Direct Charging	DC-Di-C	The charging mode of a fleet of EVs in which they automatically charge when they are connected to the PG until they are charged to the desired SOC or disconnected. It uses optimization techniques, and it charges EVs within discrete intervals for a period, as defined in Section 2.2. The width of the interval depends on the engineer who designs the optimization algorithm. It could range from several seconds to several minutes. The intervals could be equally or unequally distributed. For each interval, the charging occurs for a limited number of EVs. The same charged EVs could not be charged in the next interval. The charging partition of EVs depends on many factors such as their numbers, their initial and the desired final SOC, their priority of charging, and their arrival and departure time. The purpose of this method is to extend the charging mode to a more extended period to reduce the impact of EVs' high penetration on the grid [52,53].
12.	Discrete Coordinated Direct Charging and Discharging	DC-Di-CD	SAS11. In addition, the characteristic of the discharging mode is similar to strategy 8 (CC-Di-CD), but the difference is that the charging time is decomposed of different intervals instead of one interval. Therefore, the peak demand is reduced and prolonged to a wider period. This strategy has not been studied yet to the best of the authors' knowledge. It is highly recommended to use this strategy for its many advantages.
13.	Discrete Coordinated Delayed Charging	DC-De-C	SAS9. However, the difference is that discrete charging is used instead of continuous charging. The charging process is delayed to a longer period in order to reduce the detrimental impact on the PG. This strategy has not yet been used to the best of the authors' knowledge.
14.	Discrete Coordinated Delayed Charging and Discharging	DC-De-CD	SAS13 and SAS10. However, the difference is that discrete charging is used instead of continuous charging. This strategy has not yet been used to the best of the authors' knowledge.

SAS#: Same as Strategy Number #.

A graphical illustration of all uncoordinated strategies is shown in Figure 4.



	(a)	(b)	(c)	(d)
Strategy	CC-Di-C	CC-Di-CD	CC-De-C	CC-De-CD
Plug-in time	t_0	t_0	t_0	t_0
Start charging time	t_0	t_0	$t_1 > t_0$	$t_1 > t_0$
Power profile	Constant or Variable	Constant or Variable	Constant or Variable	Constant or Variable

Figure 4. Illustration SOC and Discharge Power for Discrete Coordinated Strategies.

3. Comparative Study and Analysis

Tables 4–8 compare between different charging strategies. They show their potential uses, expenses, integration issues, advantages, barriers, etc. Each point in the tables is explained in detail as below. The order of points is the same as in Tables 4–8. The criteria for comparison are defined as follows.

3.1. Complexity Comparison

This comparison is shown in Table 4, which includes the following aspects:

1. *Complexity of charging*. To implement some strategies (especially coordinated ones), we may need advanced equipment to control the charging rate and duration [55–57]. Thus, software, programming, optimization, data transmission, and reading the electricity market price are all design requirements that add complexity to the system, whether at the grid side or the EV side. For instance, in the table, VS stands for a very simple charging strategy, in which a single bidirectional charger is used without using any optimization methods or control strategies. The EV is just charged when it is plugged into the electricity with a specific power rate. S1, S3, and S5 are considered as simple charging strategies for the previously mentioned reasons. The charging strategy becomes complex when a bidirectional charger is used, in which the power flow is in both directions. Therefore, S stands for a Simple charging strategy in which a bidirectional charger is used (such as strategies S2, S4, and S6). This strategy is more complicated than the previous one; however, it is always considered simple since optimization techniques and methods are not used. Therefore, we are not able to control the charging and discharging of the batteries as we would like, and the power rate is almost considered constant. The third level of complexity is when optimization algorithms are used beside the unidirectional chargers to control the charging of the batteries as the case of strategies S7, S9, S11, and S13. These strategies have almost the same complexity as the use a single bidirectional controller and optimization algorithms, which make the system more complicated than the previous strategies. Finally, VC represents the most complex strategy, in which a bidirectional converter and advanced optimization algorithms and control strategies are used to control the charging and discharging of the batteries. This is the case of the strategies S8, S10, S12, and S14 in which the charging rate is not fixed as the previous ones, but it varies depending on the output results of the optimization algorithms. Therefore, controlling the batteries becomes very complex, which require high control and communication speed.
2. *Complexity of power electronic interfaces*. To achieve the charging/discharging process, the EV must use a power electronics interface linking it to the grid. Such an interface is simple when only the charging mode is used. It requires a diode bridge, unidirectional converter, and unidirectional power flow [21,36]. It is complex when both charging and discharging modes are used. It requires semiconductor devices (such as MOSFETs, IGBTs, or GTOs), bidirectional chargers, and control mechanisms for bidirectional power flow [21,36,58].
3. *Requirement of control and digital communication*. Some strategies (again, especially the coordinated ones) need advanced communication means between EVs, chargers, aggregators (PL/CS), and the PG [9,10,21,43,58–63]. Some institutions provide specifications and requirements on this topic, such as IEEE, Society of Automotive Engineering (SAE) [64,65], as well as National Electric Infrastructure Working Council [66,67]. Strategies S1 to S6 do not need any communication, as they are uncoordinated charging and discharging strategies. It means that the EVs start charging when they are plugged to the electricity. Therefore, there is no need for any communication with external agents. On the other hand, strategies S7, S9, S11, and S13 need communication since they are coordinated charging strategies. Hence, communication is considered complex compared to the previous one. Finally, strategies S8, S10, S12, and S14 are considered as very complex strategies since bidirectional converters are

used and since the communication does not deal only with the charging process but also with the discharging process that makes the optimization and control much more complicated compared to the previous strategies. Hence, more advanced, and complex optimization algorithms are needed to control the bidirectional power flow from the batteries to the grid.

4. *Necessity of collecting and storing data*. The data collection and storage are mandatory for a smart grid, or at least for a grid with smart loads such as EVs. They allow the aggregator to optimize the charging and discharging of its EVs, minimizing the total charging cost, control the active and reactive power flow from the EVs to the grid, and vice versa, etc. Similar to the previous point, the complexity of the communication also includes the complexity of the data and information needed. Strategies S1 to S6 do not require any data from the system operator and the electricity retailer since they are uncoordinated charging. However, for coordinated charging strategies such as S7, S9, S11, and S13, some data are needed such as the electricity price, and the power profile. These data are necessary to obtain an optimal solution to charge the EVs in a way to satisfy the objective function of the EV and parking lot owners, the system operator, etc. Finally, a bidirectional converter needs much more data since the optimization algorithm does not calculate only the charging profile but both charging and discharging power profiles. Therefore, more data are needed besides the mentioned ones. In this case, the algorithm should know the preferences of the EV owner, what is the final state of charge, at which rate he wants to charge and discharge his battery, how much energy he allows to discharge from his battery, etc. All these data increase the complexity of strategies S8, S10, S12, and S14.

Table 4. Complexity Comparison for Different EV Charging and Discharging Strategies.

Description	Charging Strategy														References
	S1:U-Di-C	**S2: U-Di-CD**	**S3: U-De-C**	**S4: U-De-CD**	**S5: U-R-C**	**S6: U-R-CD**	**S7: CC-Di-C**	**S8: CC-Di-CD**	**S9: CC-De-C**	**S10: CC-De-CD**	**S11: DC-Di-C**	**S12: DC-Di-CD**	**S13: DC-De-C**	**S14: DC-De-CD**	
1. Complexity of charging	VS	S	VS	S	VS	S	C	VC	C	VC	C	VC	C	VC	[9,21,36,52,53,55]
2. Complexity of power electronic topology	S	C	S	C	S	C	S	C	S	C	S	C	S	C	
3. Require control and digital communication	N	N	N	N	N	N	Y	VC	Y	VC	Y	VC	Y	VC	
4. Require complex data collection and storage from EVs, aggregator, power network, and other parties	N	N	N	N	N	N	Y	VC	Y	VC	Y	VC	Y	VC	[9]

Y: Yes. N: No. VS: Very Simple. S: Simple. C: Complex. VC: Very Complex.

3.2. Economic and Power Losses Comparison

This comparison is shown in Table 5, which includes the following aspects:

5. *Operation cost reduction*. It shows the impact of different charging strategies on the operation cost of the mentioned elements. For strategies S1 to S6, the charging and discharging of EVs did not reduce the operation cost. This is due to the fact that uncoordinated charging may result in peak load demand, especially if there are lots of EVs charging at the same time. Therefore, additional generators will be turned on just to supply the peak demand during a very short period, which will increase the operating cost and increase the financial losses of the system operator. On the other hand, coordinated charging strategies such as S7, S9, S11, and S13 are able to shift the peak demand to another period when the consumption is lower. Therefore, it somehow limits the operation cost, and there is no need to turn on a generator. On the contrary, the charging and discharging strategies such as S8, S10, S12, and S14 can minimize the operation cost as they are able to provide ancillary services by injecting power to the grid when needed and store energy when there is an excess

in the power generation. The best strategy among all the others is S12, since it has more flexibility to charge and discharge during a very short period (less than 10 min), which is very beneficial for the system operator, and it can be used to regulate the frequency and the voltage on the grid whenever needed.

6. *Power loss reduction*. The power losses in this paper are on the lines and transformers. The power loss is equal to the resistance of the line multiplied by the square of the current ($P = RI^2$). It means that when the current increases on the lines, the power losses increase, too. Uncoordinated charging strategies (S1 to S6) are not capable of minimizing the power demand on the grid. On the contrary, they increase it, since most of the EVs can charge at the same time, which will put more stress on the network and increase the power losses. On the other hand, coordinated charging strategies (S7, S9, S11, and S13) can reduce the power losses by shifting their charging to off-peak times. Coordinated charging and discharging strategies (S8, S10, S12, and S14) are able not just to avoid high power losses but to minimize them. Optimization algorithms and advanced control strategies can detect the high peak demand on the network and order the EVs to discharge during these periods, which may minimize the power and energy losses [21,39,42,44,47].
7. *Revenues from ancillary services*. Usually, uncoordinated charging and discharging strategies (S1 to S6) do not participate in the ancillary services. In contrast, the coordinated charging strategies have very limited participation since they can only shift their charging and cannot inject power to the grid. On the other hand, coordinated charging and discharging strategies (S8, S10, S12, and S14) use a bidirectional converter, which allows the EV to absorb and inject power to the grid, regulate the voltage and the frequency, and inject active and reactive power when needed [11–13,21,25,47].
8. *The necessity of additional investments or expensive equipment*. The cost of chargers, power electronics circuits, and infrastructure are high [13,21,33,36,56,68] when using bidirectional power flow capability. It includes on/off-board smart meters [11,58], on/off-board chargers, data infrastructure, sensors [58], etc. The infrastructure might need upgrades because of (1) potential high demand by EVs fleets, (2) EV being a smart load, and (3) the use of power electronic interfaces that support bidirectional power flow; at the same time, a CST may reduce the installation of other equipment on the PG, reducing additional investments on the infrastructure [69]. It is obvious when an uncoordinated charging strategy is used using the unidirectional charger (such as S1, S3, and S5), there is no need to invest in an advanced infrastructure, as it will not serve the grid, since it is uncoordinated [70–78]. By adding a bidirectional charger, the investment increases, which is the case of S2, S4, and S6. The investment increases when the charging strategy becomes more complex [79–88] such as using bidirectional chargers [89–94], and advanced communication protocols [95–100], optimization algorithms [101–136] and development boards [137–142], which is the case of strategies S8, S10, S12, and S14.

Table 5. Economic and Power Losses Comparison for Different EV Charging Strategies.

Description	Charging Strategy														References
	S1:U-Di-C	S2: U-Di-CD	S3: U-De-C	S4: U-De-CD	S5: U-R-C	S6: U-R-CD	S7: CC-Di-C	S8: CC-Di-CD	S9: CC-De-C	S10: CC-De-CD	S11: DC-Di-C	S12: DC-Di-CD	S13: DC-De-C	S14: DC-De-CD	
5. Operation cost reduction															
1. Power plants	N	N	N	N	N	N	L	Y	L	L	L	Y	L	L	[12,142]
2. Power grid	N	N	N	N	N	N	L	Y	L	L	L	Y	L	L	[56,57,143]
3. EV charging electricity cost	N	N	N	N	N	N	Y	Y	Y	Y	Y	Y	Y	Y	[36,144–149]
4.Reduce dependency on small/micro expensive power units	N	N	N	N	N	N	N	Y	N	L	N	Y	N	L	[12]
5. Turn off some generators during on-peak time by providing energy to the grid using V2G	N	N	N	N	N	N	N	Y	N	L	N	Y	N	L	[12,47]
6. Power and energy losses are reduced on the PG	N	N	N	N	N	N	Y	Y	Y	Y	Y	Y	Y	Y	[95–99]
7. Generate revenue from ancillary services	N	N	N	N	N	N	N	Y	N	L	N	Y	N	L	[51,78]
8. Infrastructure and equipment expenses/investments															
1. Cost of chargers, power electronics, and infrastructure are high	N	Y	N	Y	N	Y	N	Y	N	Y	N	Y	N	Y	[21,39,44]
2. Infrastructure needs upgrade to support the strategy	N	Y	N	Y	N	Y	N	Y	N	Y	N	Y	N	Y	[21,39,44]
3. Avoid additional investment on the infrastructure	N	N	N	N	N	N	Y	Y	Y	Y	Y	Y	Y	Y	[21,39,44]

Y: Yes N: No L: Limited.

3.3. Ancillary Services and Peak Demand Aspects

This comparison is shown in Table 6, which includes the following

9. *Ancillary services provided*. Depending on the type of CST, it may provide different types of ancillary services, which are very important to stabilize the PG. For example, for frequency regulation, there are three types of control, which are defined by the Union for the Coordination of Transmission of Electricity [88]. Other types of ancillary services include voltage regulation, supporting the integration of RESs, etc. Note that ancillary services might be provided only by CST. EVs using UST are treated as normal loads. In general, uncoordinated charging strategies (S1 to S6) do not provide ancillary services, while the coordinated ones (S7 to S14) do provide them. More specifically, coordinated charging and discharging strategies such as S8, S10, S12, and S14 can provide better ancillary services than just the coordinated charging, as mentioned in the previous table. More precisely, strategies S10 and S12 are considered as the best ones, since they are able to provide all kinds of ancillary services such as voltage and frequency regulations, reduce harmonic distortions, and many others, which is not the case of other strategies.
10. *Network congestion relief*. It means that sometimes, the network can have a lot of electric burdens, and congestion can be created, which puts the distribution systems in danger. UST (S1 to S6) are the worst, since they increase in the network congestion, while CST (S7 to S14) reduce network congestion and improve the load factor. More particularly, when discharging EV is considered (S8, S10, S12, and S14), the strategies participate in the reduction of the network congestion because they can inject energy into the grid when there is high demand.
11. *Optimize charging time and power demand*. Optimization techniques help the aggregator and PG to optimize the charging time of EVs, the power demand, and flow. Strategies S1 to S6 do not use optimization, since they are uncoordinated charging strategies. Strategies S7 to S14 use optimization and advanced algorithms; therefore, optimal solutions are necessary to improve the functionality of the power grid and minimize the technical and economic losses.
12. *Peaks and valleys improvements*. CST might shave the peak demand on a distribution transformer, shift the hourly generation portfolio, balance the demand and supply by valley filling [19,21,89] (sometimes referred to as 'load-leveling' [90]), and minimize the load variance [81]. USTs are not the best strategies, since they are not capable

of shifting their load and filling the valleys automatically because they do not use advanced optimization algorithms to control their power profiles. In the CSTs, S8 and S12 are the best, since they are capable of shifting their energy demand to off-peak time and participating in shaving the peak demand by injecting energy into the grid.

13. *Duration of response time*. The response time of ancillary services should be very short compared to other conventional power generators (e.g., nuclear or hydropower plants or wind farms). Therefore, EVs may potentially replace other regulation service units [51,78]. Some strategies (S7, S9, S11, and S13) have a limited response time because they use only a unidirectional power flow from the grid to the EVs, or they use delayed charging strategies. However, S8 and S12 always show superior performance compared to other strategies since they have short response times and can instantly or within a few minutes to respond to the requirements of the system operator.

Table 6. Ancillary Services and Peak Demand Aspects Comparison for Different EV Charging Strategies.

Description	Charging Strategy														References
	S1:U-Di-C	S2: U-Di-CD	S3: U-De-C	S4: U-De-CD	S5: U-R-C	S6: U-R-CD	S7: CC-Di-C	S8: CC-Di-CD	S9: CC-De-C	S10: CC-De-CD	S11: DC-Di-C	S12: DC-Di-CD	S13: DC-De-C	S14: DC-De-CD	
9. Ancillary serviced provided															[60,62,69,150]
1. Improve grid stability	N	N	N	N	N	N	L	Y	L	L	L	Y	L	L	[36,151–161]
2. Frequency regulation	N	N	N	N	N	N	L	Y	L	L	L	Y	L	L	[13,21,25,29,51,69,71–75]
3. Voltage regulation	N	N	N	N	N	N	L	Y	L	L	L	Y	L	L	[77,161–166]
4. Harmonic regulation	N	N	N	N	N	N	L	Y	L	L	L	Y	L	L	[161]
5. Support the integration of RES	N	N	N	N	N	N	N	Y	N	Y	N	Y	N	Y	[21,47,56,57,60,69]
6. Spinning reserve participation	N	N	N	N	N	N	L	Y	L	L	L	Y	L	L	[13,21,47,75,78]
7. Energy storage (i.e., injects energy into the grid)	N	N	N	N	N	N	N	Y	N	L	N	Y	N	L	[36,47,79]
8. Improve power quality	N	N	N	N	N	N	N	Y	N	L	N	Y	N	L	[36,39,44,47]
9. Improve grid efficiency and reliability	N	N	N	N	N	N	L	Y	L	L	L	Y	L	L	[21,80]
10. Active and reactive power regulation	N	N	N	N	N	N	L	Y	L	L	L	Y	L	L	[33,39,44,47]
11. Improve generation dispatch	N	N	N	N	N	N	L	Y	L	L	L	Y	L	L	[21]
12. Replace large-scale energy storage systems	N	N	N	N	N	N	N	Y	N	L	N	Y	N	L	[21]
13. Black start a part of the distribution grid	N	N	N	N	N	N	N	Y	N	L	N	Y	N	L	[21]
10. Reduce network congestion and load factor	N	N	N	N	N	N	Y	Y	Y	Y	Y	Y	Y	Y	[21,31,42,81]
11. Optimize charging time and power demand	N	N	N	N	N	N	Y	Y	Y	Y	Y	Y	Y	Y	[22]
12. Peaks and valleys in daily demands															
1. Peak shaving	N	N	N	N	N	N	N	Y	N	L	N	Y	N	L	[21,33,36,48]
2. Shifting hourly generation portfolio	N	N	N	N	N	N	N	Y	N	L	N	Y	N	L	[39,44,47]
3. Balance load valleys by valley filling and minimize load variance	N	N	N	N	N	N	Y	Y	Y	Y	Y	Y	Y	Y	[39]
13. Response time is shorter than conventional generators	N	N	N	N	N	N	L	Y	L	L	L	Y	L	L	[21]

Y: Yes. N: No. L: Limited.

3.4. Operating Aspects

This comparison is shown in Table 7, which includes the following.

14. *EVs interacting with the grid*. When USTs are used, the number of charging EVs is not limited. Thus, it might negatively affect the PG (e.g., a large fleet of EVs might be connected at 8:30 AM when people drive from their homes to the workplace, overloading the distribution transformer of the area). When a CST is used, the number of charging EVs could be limited in order to maintain the stability of the PG. This might be done by adjusting the penetration level (e.g., the total number of EVs being charged at a specific instant) to a certain limit without violating the constraints on the PG [91]. Therefore, it is possible to charge a larger number of EVs using CSTs compared to the USTs, which might satisfy the EV owners.

15. *Priority of charging/discharging*. The priority of charging and discharging is considered in some papers of the mentioned categories with "Y". USTs show chaos, since the charging of EVs is not organized even in an EV parking lot; each EV starts to charge when it is plugged to the electricity, disregarding what is happening on the network. However, CSTs show more organization while charging the existing EVs. This is due to the fact that optimization algorithms are used, and users' preferences are also considered, which will improve the performance of the system and increase the satisfaction of both EV owner and the system operator or parking lot owner.
16. *Charging management and timing*. It shows whether charging occurs instantly or it is delayed depending on the constraints of EVs and the PG [21,43,45,51,79]. Table 7 shows whether the management of charging and discharging becomes difficult and complex for a large number of EVs when discrete charging methods are used. The period of charging and discharging is extended, thus reducing the management reliability and dissatisfying many clients [55].

Table 7. Operating Aspects Comparison for Different EV Charging and Discharging Strategies.

Description	Charging Strategy														References
	S1:U-Di-C	S2: U-Di-CD	S3: U-De-C	S4: U-De-CD	S5: U-R-C	S6: U-R-CD	S7: CC-Di-C	S8: CC-Di-CD	S9: CC-De-C	S10: CC-De-CD	S11: DC-Di-C	S12: DC-Di-CD	S13: DC-De-C	S14: DC-De-CD	
14. EVs interacting with the grid															
1. A large number of EVs participate in the charging mode	Y	Y	Y	Y	Y	Y	L	L	L	L	L	L	L	L	[164]
2. Increase EVs penetration level while respecting constraints of the PG	N	N	N	N	N	N	Y	Y	Y	Y	Y	Y	Y	Y	[161]
15. Priority of charging/discharging is considered	N	N	N	N	N	N	Y	Y	Y	Y	Y	Y	Y	Y	[162]
16. Charging management and timing															
1. Charging occurs instantly	Y	Y	N	N	Y	Y	Y	Y	N	N	Y	Y	N	N	[20,21]
2. Delayed charging depending on constraints of EVs and PG	N	N	Y	Y	N	N	M	N	Y	Y	M	N	Y	Y	[20,21]
3. Complex management of charging and discharging	N	N	N	N	N	N	N	N	N	N	Y	Y	Y	Y	[20,21]
4. Arrival and departure time of each EV is considered	N	N	N	N	N	N	Y	Y	Y	Y	Y	Y	Y	Y	[161–166]

Y: Yes. N: No. L: Limited. M: Might be.

3.5. Detrimental Impact on EV, PG, or Environment

This comparison is shown in Table 8, which includes the following.

17. *Potential battery degradation*. Lithium-ion batteries might experience a reduction in their lifetime due to being excessively charged and discharged. An excessive discharge of stored energy in a battery may cause cycling wear as well as a reduction in its lifetime and total capacity. However, some new technologies are being developed, which are less impacted by the discharging and high charging rate [92]. Another solution is to provide trading inquiries before discharging, as suggested in [93]. The owner may decide the minimum SOC (which would then become a constraint in the optimization/algorithm used by the aggregators). This might not only be important to avoid the degradation of the battery but also to ensure that the EV has enough energy left when they use their EV again. Usually, USTs face less degradation, since the charging power profile is almost constant all the time and does not reach a high rate (for example, the charging rate at 4 kW). Meanwhile, CSTs face higher degradation since the charging rate may increase (e.g., 7 kW) at specific periods, which may increase the stress on the batteries. Sometimes, the aggregator or the system operator may increase the charging rate of the EV at a specific period when there is not much demand on the network in order to avoid EVs charging during the on-peak time. Therefore, these strategies are mostly used and convenient for the system operator, which will help them minimize the congestion and losses on the

network. By including discharging strategies, the stress on the batteries increases, and their lifetime is reduced. Hence, it is up to the EV owner to decide whether he wants to participate in the ancillary services or not and which power rate to accept to charge or discharge his battery. For example, an EV owner may agree to charge his EV at 6 kW and does not allow a charging rate higher than this value, even when there is a need on the network. At the same time, he can restrict the discharging to 2 kW even when the aggregator needs a rate of 6 kW. This factor could be an agreement between the EV owner and the aggregator, and incentive programs could be applied to incite the EV owner to participate in the ancillary services and get paid for that.

18. *Overloading impact on distribution transformers*. Due to high power demand from the base load only ("1"), from the base load and EVs ("2"), or from both ("3"), the lifetime of distribution transformers might be reduced [23,94]; overheat, shutdown, insulation breakdown, increase in losses, and reduction in efficiency are all potential consequences [21,36,42,44,45,87,95–97]. It may also overpass its operating limits [20,21,33,42,98]. The same applies to cables and distribution infrastructure. The impact of EVs depends on their number; a small number may have a small impact, and a large number may have a large impact. However, it depends on the charging strategies as well. In general, the existing transformers are designed to support only the base load without EVs. It means that a high penetration level of EVs can deteriorate the transformer. Hence, it is very important to use advanced control strategies such as S7 to S14 and, more specifically, S8 and S12 in which they are capable of reducing the stress on the transformer, therefore increasing its lifetime. USTs can be applied when the number of connected EVs is very limited (e.g., maximum 2 EVs on the transformer), while CSTs can even connect many EVs on the same transformer without affecting its lifetime. However, the charging period is extended to reduce stress.
19. *Impact on the PG*. The detrimental impact on the PG could be caused by a high-power demand from base load only, base load + EVs, or from both. It could negatively impact the PG by reducing its efficiency, high peak demand could be created even during the off-peak time [9,20–22,36,42,44], or the system may lose its stability and experience voltage and frequency violations [21,33,36,45]. A shortage in the PG could be created when the demand on a certain bus exceeds the power supply. It may cause a severe voltage drop [99]. USTs (S1 to S6) make the PG very vulnerable. However, CSTs can improve the impact of EVs on the PG. More precisely, S8 and S12 show better performance compared to other strategies, since they use bidirectional power flow and advanced optimization and control algorithms, and they can respond immediately to any request from the system operator.
20. *Reduction of harmful gases*. The emission of harmful gases could be reduced by using EVs in the condition that they are not supplied by power plants that consume fossil fuel. Generally, when EVs are supplied by conventional power plants, the emission of harmful gases is much higher than conventional vehicles. Hence, it is thus recommended that EVs should be supplied by RESs, or power plants where fossil fuel is not used (e.g., nuclear power plant, hydropower plant, etc.) [12,23,29,35,51,57]. In general, USTs (S1 to S6) might increase the energy demand during a certain period, which obliges the system operator or the power utility to turn on some fossil-fuel based power plants to respond to the demand. Therefore, the emission of harmful gases is increased. However, the CSTs (S7 to S14) are able to reduce their power demand during certain periods, which might reduce the stress on the network and reduce the possibility of turning on some fossil-fuel based power plants to supply the demand. More precisely, S8 and S12 are the best among all other strategies since they discharge and minimize the possibility of turning on some generators.

Table 8. Impact on the Grid, EVs, and Environment for Different EV Charging Strategies.

Description	S1:U-Di-C	S2: U-Di-CD	S3: U-De-C	S4: U-De-CD	S5: U-R-C	S6: U-R-CD	S7: CC-Di-C	S8: CC-Di-CD	S9: CC-De-C	S10: CC-De-CD	S11: DC-Di-C	S12: DC-Di-CD	S13: DC-De-C	S14: DC-De-CD	References
	Charging Strategy														
17. Battery might experience															
1. Degradation due to regulation service	N	Y	N	Y	N	Y	N	M	N	M	N	M	N	M	[21,51,82–84]
2. Cycling wear	L	Y	L	Y	L	Y	N	M	N	M	N	M	N	M	[79,82,85]
3. Lifetime & storage capacity reduction	L	Y	L	Y	L	Y	N	Y	N	Y	N	Y	N	Y	[21,86]
18. Impact on Distribution transformers due to high power demand from Base Load "1", Base Load + EVs "2", or Both "3"	3	3	3	3	3	3	1	N	1	1	1	N	1	1	[161–166]
19. Negative impact on the PG due to high power demand from Base Load "1"; Base Load + EVs "2", or Both "3"															[161–166]
1. Power grid's efficiency is decreased	3	3	3	3	3	3	1	N	1	1	1	N	1	1	[161–166]
2. High demand during off-peak time	3	3	3	3	3	3	1	N	1	1	1	N	1	1	[161–166]
3. Loss of stability	3	3	3	3	3	3	1	N	1	1	1	N	1	1	[161–163]
4. Uncontrolled load	3	3	3	3	3	3	1	N	1	1	1	N	1	1	[21,33,45]
5. Increase in power and energy losses	3	3	3	3	3	3	1	N	1	1	1	N	1	1	[20,21,33,36,87]
6. Network congestion	3	3	3	3	3	3	1	N	1	1	1	N	1	1	[87]
7. Reduced PG reliability	3	3	3	3	3	3	1	N	1	1	1	N	1	1	[21,33]
8. Shortage in the PG (i.e., demand exceeds supply)	3	3	3	3	3	3	1	N	1	1	1	N	1	1	[21,33]
20. Emission of CO2, NO_x, SO_2, etc, and fossil fuel usage are reduced for															
1. EV	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	[21,32,47]
2. Conventional power plants when EVs are charged from RES	N	N	N	N	N	N	Y	Y	Y	Y	Y	Y	Y	Y	[47,56,57]
3. Peak demand periods	N	N	N	N	N	N	N	Y	N	L	N	Y	N	L	[47,56,57]

Y: Yes. N: No. L: Limited. M: Might be.

It is hard to determine how many EVs will positively or negatively affect the PG and the transformer. The impact of the same number of EVs could be different from one bus to another and from one PG to another. The main factors that play an essential role in the impact of EVs on the PG are as follows: (1) the penetration level of EVs; (2) the used strategy; (3) the charging and discharging power rate; (4) the EVs' arrival and departure time; (5) the initial and final SOC of EVs; (6) the initial base-load power before introducing EVs; (7) the available power capacity of the transformer that could be used by EVs; (8) the initial voltage on the transformer; (9) the voltages on other buses may affect the penetration level of EVs; (10) the type of the network (if it is a smart or conventional grid); (11) the type of regulators on the PG, and (12) the nature of the load: residential, commercial, etc. [22].

Usually, for coordinated charging and discharging, there could be two main limitations if the charging time is not sufficient to charge the EVs to the desired SOC levels. The first limitation is that when the power rates are increased to charge the EVs to the desired SOC levels, the total power on the bus may increase and overpass the required limit. This creates a peak load and may badly affect the transformer, the PG, and voltage stability. The second limitation is that when the power rates are optimized in a way not to overpass the limits on the transformer, the EVs may not be charged to the desired SOC levels. It could create dissatisfaction for the EV owners in which the SOC may not be sufficient to travel long distances [100]. Therefore, there are always limitations, whatever the used strategy. It is important to mention that most of the studies fail to limit the penetration level of EVs. High penetration levels may negatively affect the PG even when coordinated charging is applied [33,44]. This paper recommends that the penetration level should have an upper limit. Therefore, overlooking such an important aspect in the design and implementation of charging strategies could negatively impact PG, even when optimization techniques are used. All these limitations and advantages are presented in Tables 4–8.

4. Operation of Power Systems in the Presence of EVs as Dispatchable Loads

4.1. The Optimization Problem

Optimization algorithms are beneficial to manage the charging and discharging of EVs. Optimization allows the distribution system operator to benefit from the existence of EVs and use it to provide ancillary services, as shown in Figure 5. To use optimization algorithms, it is necessary to define the problem using an objective function and some constraints. The objective function could be minimizing the total operation cost on the network, reducing the total power losses, etc. It could be a single- or multi-objective function [35]. Constraints are also essential to determine the availability of the solutions within the required limits.

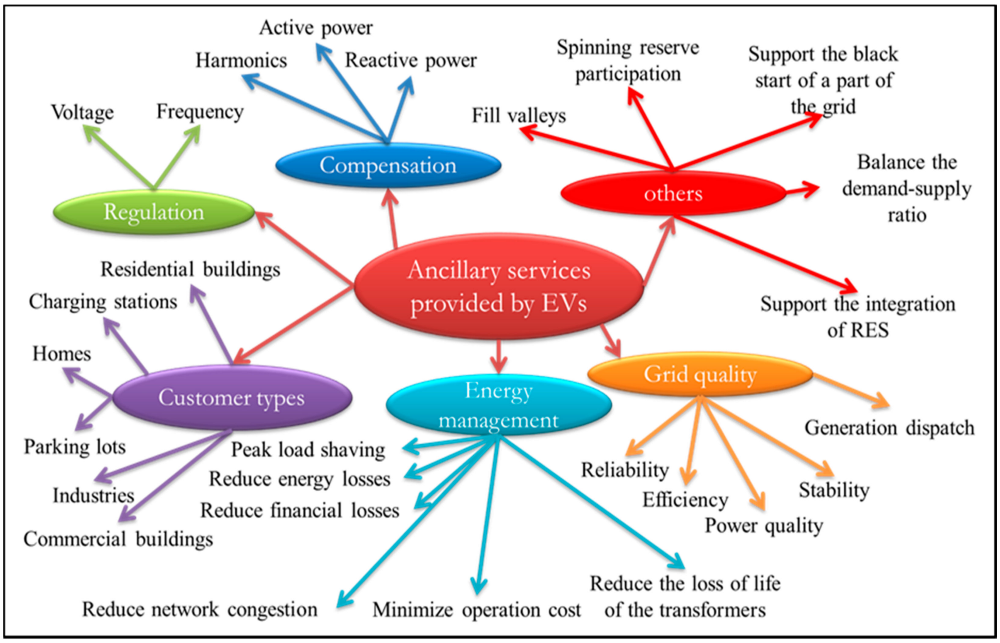


Figure 5. Illustration of the main ancillary services provided by a fleet of EVs.

If the objective function and the constraints are polynomial functions of the first order, the optimization problem is classified as linear programming. By contrast, the optimization problem is classified as nonlinear programming when the objective function or some of the constraints are second or higher-order polynomial functions [35,101]. There are different optimization techniques used to optimize the charging and discharging of EVs in a PL/CS or even at home. These algorithms are categorized into two main categories: (a) conventional mathematical optimization and (b) meta-heuristic algorithms.

The *conventional mathematical optimization* includes (1) linear programming [23–25,51–53,102,103]; (2) quadratic programming [9,20,26,40,52,104]; (3) stochastic/deterministic dynamic programming [20,28,55,105] and relaxed dynamic programming [27,29]; (4) Lagrange relaxation [55]; (5) binary linear programming [53]; (6) mixed integer linear programming [38,52,55,57,89,106]; (7) mixed-integer nonlinear programming [107]; (8) stochastic programming [20,57]; (9) mixed-integer linear stochastic programming [57]; (10) maximum sensitivities selection optimization approach [39,44]; (11) game theory [35,108,109]; and (12) queuing theory [88,110].

The *meta-heuristic algorithms* are also used for optimization problems [35]; they are powerful optimization tools and can be used for both single and multi-objective functions [35]. They are categorized into two categories. The first one is population-based methods in which they use a population of solutions to search for the optimal one. The second one is trajectory-based methods, in which they use solutions to trace a trajectory or path to the optimal solutions; as the iterations continue [35,111], the algorithm keeps updating solutions until finding the optimal one. This category is well known for its fast convergence and fast computational time compared to the traditional methods of optimization.

The *trajectory-based methods* include (1) hill climbing [112], and (2) Simulated Annealing (SA) [113]. The population-based methods include (1) Ant Colony Optimization (ACO) [114]; (2) biogeography-based optimization [115]; (3) covariance matrix adaptation evolution strategy [116]; (4) differential evolutionary [117]; (5) estimation distribution algorithm [118,119]; (6) Genetic Algorithm (GA) [120,121], Integer-Code GA [122], Lagrangian relaxation and GA [123], Non-Dominated Sorting GA II [124], a hybrid combination of ACO and Real Coded Genetic Algorithm (RCGA) called GA-API [125]; (7) Harmony Search (HS) [126], and (8) Particle Swarm (PS) optimization [12,127,128], Binary PS optimization [12,129], Balanced PS optimization [12], Evolutionary PS optimization [130], Integer PS optimization [131], Hybrid PS optimization [132], Interior-Point-Based [133] PS optimization, Quantum-Inspired PS optimization [134], and Teaching-Learning Based optimization (TLBO) [135].

From our literature review, we noted that some authors devise their optimization techniques. For example, Cao et al. [46] propose a new Heuristic Algorithm for charging EVs. Some algorithms, such as differential evolutionary, biogeography-based optimization, and covariance matrix adaptation evolution strategy, are not widely used to optimize the charging and discharging of EVs. Consequently, it is recommended to use them as powerful tools to find the optimal solution because of their fast computational time.

Optimization is beneficial for the PSO, since the integration of distributed generation and RESs is optimized. Therefore, the performance of the network is improved, while the total cost of operation and techno-economic losses are minimized, and a negative impact on the power grid is reduced [29,35]. Some optimization software can be used to solve the optimization problem such as MATLAB, LINGO, AMPL [136], and some solvers such as CPLEX [89,137], Xpress, BARON, LGO, CONOPT, KNITRO, MINOS, SNOPT, and GAMS [138,139].

Table 9 presents the most used optimization algorithms to control not just the charging and discharging processes of the EVs, but also the electrical loads, too. The main goal of these advanced algorithms is to solve the optimization problem with the minimum required time while maintaining a good level of accuracy and respecting the constraints.

Table 9. Most common optimization algorithms.

Algorithm	Reference
Mathematical programming	
• Convex programming	[157]
• Linear	[158]
• Nonlinear	[125]
• Mixed-integer linear	[115]
• Mixed-integer nonlinear	[117]
• Quadratic	[113]
• Mixed-integer quadratic	[158]
• Stochastic	[159]
• Dynamic	[160]
Meta-heuristic	
• Genetic Algorithm	[157]
• Particle Swarm Optimization	[12]
• Ant Colony Optimization	[114]
• Biogeography-based optimization	[115]
• Differential evolution	[117]
• Simulated annealing	[113]
• Tabu search	[158]
Artificial Intelligence	
• Artificial Neural Networks	[159]

4.2. Objective Functions

The objective function and constraints have the following form

$$\min f(X) \tag{1}$$

Subject to:

$$A_{Ineq1} X \leq B_{Ineq1} \tag{2}$$

$$A_{eq} X = B_{eq} \tag{3}$$

$$LB \leq X \leq UB \tag{4}$$

$$C(X) \leq 0 \tag{5}$$

$$C_{eq}(X) = 0 \tag{6}$$

where X is a matrix of elements of the objective function, A_{Ineq1}, A_{Ineq2}, B_{Ineq1}, and B_{Ineq2} are matrices for the inequality equations of the constraints, A_{eq} and B_{eq} are matrices for the equality equations of the constraints; and LB and UB are the lower and upper bounds of the matrix X.

There are lots of objective functions that can be used to maximize the benefit from integrating EVs on the distribution network, in which the most important ones are mentioned in Figure 6a.

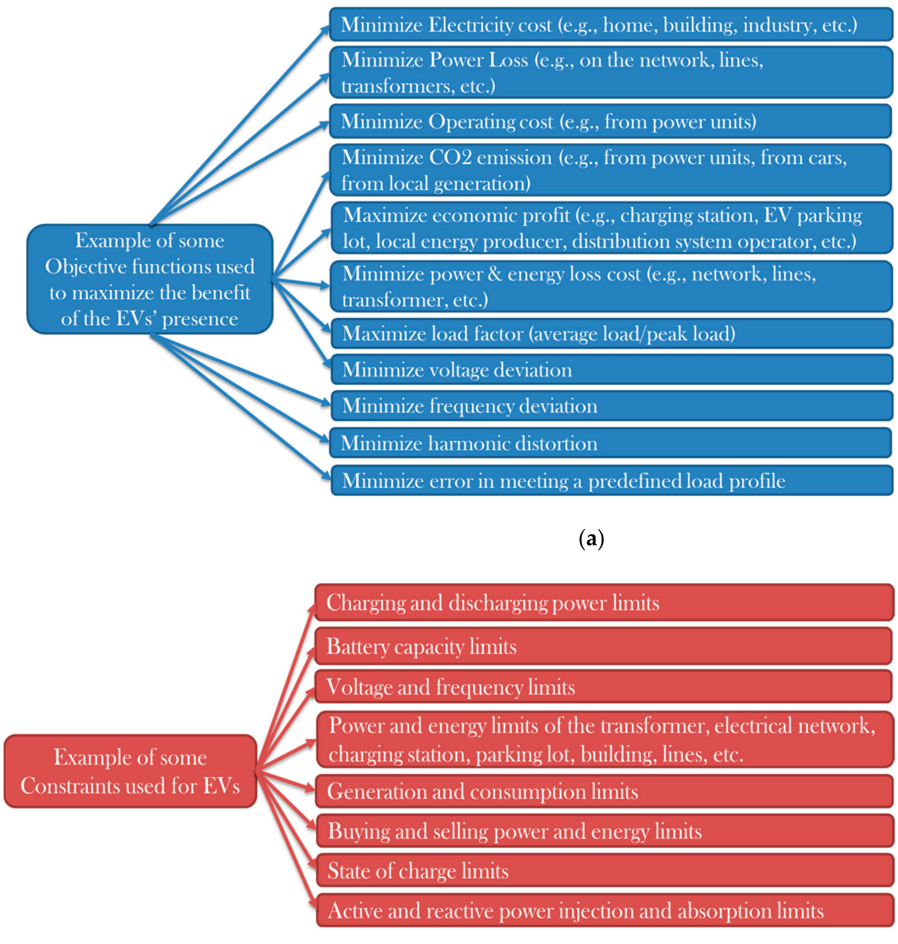


Figure 6. (**a**) Most common objective functions used to maximize the benefit from integrating EVs on the distribution network. (**b**) Sample of main objective functions and constraints used for EVs.

The most widely used objective function for the charging strategies of EVs is to minimize the electricity cost as presented in Equation (3), in which we present a general objective function. The first part is the cost function of buying and selling the energy.

The second part is not mandatory for all objective functions; however, the decision-maker can choose some of the mentioned parameters that present the additional cost where the power and/or energy exceed certain limits.

$$\min\left[\left(\sum_{t\in T}\left(\pi_t^{buy}P_t^{buy}-\pi_t^{Sell}P_t^{Sell}\right)\Delta t\right)+\left(\begin{array}{c}+E_T^L\pi_E^L+P_t^L\pi_P^L\\+E_T^{An}\pi_E^{An}+P_t^{An}\pi_P^{An}\\+E_T^{IP}\pi_E^{IP}+P_t^{IP}\pi_P^{IP}\\\cdots\end{array}\right)\right] \tag{7}$$

where

π_t^{buy} and π_t^{Sell}	time-based electricity tariff (e.g., Time-of-Use (Pricing) (ToU), Real-Time Pricing (RTP)), [$/kWh]
P_t^{buy} and P_t^{Sell}	bought and sold power from/to the grid, [kW]
π_E^L and π_P^L	limit-based electricity tariff of the energy [$/kWh] and power [$/kW]
E_T^L and P_t^L	energy and power limit that should be respected in order to avoid the additional tariff
π_E^{An} and π_P^{An}	ancillary service-based electricity price for the energy [$/kWh] and power [$/kW]
E_T^{An} and P_t^{An}	energy and power needed to provide ancillary services
π_E^{IP} and π_P^{IP}	incentive-based electricity tariff for the energy [$/kWh] and power [$/kW]
E_T^{IP} and $P_{\forall t}^{IP}$	incentive-based energy and power limits

4.3. Optimization Constraints

When optimizing an objective function for a charging/discharging strategy of EVs, several constraints must be accounted. From our extensive review of the literature, we classify them into five levels (1) country level; (2) power network level; (3) bus level; (4) fleet of EVs level such as parking lots, charging station, etc., and (5) PV owner level. Leemput et al. [140] decomposed the objectives into three main categories:

1. Technical objectives, which include the minimization of energy losses, increased robustness, minimization of voltage deviation, support the integration of RES, balancing power supply and demand, and reducing peak power demand
2. Economic objectives such as minimizing the cost of charging or deferral of transmission system upgrades
3. Coupled techno-economic objectives that combine the two previous aspects influencing the total energy price to be paid by a client.

For the *country level*, the main constraint is the limitation in the investments in electricity sector. The main objectives are as follows: (1) reduce the CO_2 and harmful gases emissions [12,17,21,23,47,51,56,57,141,142]; (2) reduce the total operation cost [21,47,51,140]; (3) reduce the system average interruption duration and frequency indices [23,143]; (4) reduce the utilization of fossil fuel from fossil plants [17,21,47,51,140], and from EVs; (5) maximize the satisfaction of the clients [140]; (6) increase the penetration of renewable energy [137,141]; (7) increase the penetration level of EVs [20,22,51,63,88,144,145]; and (8) maximize social benefit [140,146].

For the *power network level* (also called the utility level or power system operator level), the main constraints are as follows: (1) maintain the stability of the network; (2) maintain the voltage and frequency within the required limits [21,33,40,146]; (3) maintain the current and voltage on the transmission lines within the required limits [40,146]; and (4) maintain harmonics within the required limits. The main objectives are (1) reduce harmonics; (2) reduce power loss [20,21,33]; (3) minimize grid operation costs [12,21,106,140]; and (4) maximize the load factor [20,21,31,81], minimize system demand [33,48], reduce peak load [48], as well as minimize load variance [81]. For renewable energy sources, the main constraints are minimum and maximum generation capacity limits [47]. The main objectives are (1) mitigate the variability of the renewable energy sources on the network [47]; (2) reduce the consumption of fossil fuel from non-renewable energy sources [47,57,141], and (3) reduce the operation costs of renewable energy sources including startup and shutdown costs [47,57]. For the transmission line level, the main constraints are respected for the capacity of the transmission lines [47] and the power transfer limit [146]. The main constraint is reduced transmission losses [33,47]. For the power plants level (called the Power Supply Enterprises level by [147]), the main constraints are (1) minimum and maximum generation capacity [47] and (2) minimum and maximum reactive power that can be generated by a generator [47,146]. The main objectives are as follows: (1) minimize the operation costs, including the startup and shutdown costs of generators and other units [47], and (2) turn off expensive generators (e.g., diesel) when the demand is not high [47].

For the *bus level* (also called distribution system operators [9] level), the main constraints are as follwos: (1) respect the limits of the transformer or substation such as temperature limits, rated load, etc., [23]; (2) maintain voltage, frequency, and power factor within the required limits [33,40,146], and (3) maintain the stability on the bus and maintain the total demand power below a peak demand level [33]. The main objectives are as follows: (1) reduce the instability on the bus; (2) regulate the power flow (active and reactive power) [47]; (3) reduce harmonics; (4) reduce power loss and energy loss [20,33,47,140]; (5) reduce the voltage unbalance between phases [87]; (6) minimize voltage deviation [140]; (7) reduce the heat in the transformer in order to reduce its life loss [23]; and (8) minimize system demand [33].

For the *aggregator level* (such as PL/CS, which sometimes are called the Charging Service Providers [9]), the main constraints are as follows: (1) respecting all constraints imposed by the EV individual level and the bus level; (2) following the pricing schedule [26]; (3) the arrival and departure time of all EVs [53]; (4) the charging/discharging rate of EVs (also called power rate) is limited between a maximum and minimum value [40,47]; (5) the initial and final SOC of all EVs; (6) respecting the voltage and frequency constraints on the bus [29,31,40]; (7) batteries capacity limits [40,47]; (8) maintaining the line currents and voltages of the infrastructure within the required limits [40]; (9) the maximum energy of the EV fleet that can be supported; (10) power limits imposed at the bus level; (11) the storage capacity limits of all EVs [47] and the maximum and minimum charging/discharging rate of all EVs [47]; (12) the number of EVs that can be supported in the PL/CS; (13) efficiency of the charging/discharging modes [47]; and (14) on/off-board charger constraints such as unidirectional/bidirectional power flow and maximum power rate [21]. The main objectives are as follows: (1) maximizing the profit from both charging and discharging modes [40,57]; (2) maximizing the number of clients in a day; (3) controlling the power flow (active and reactive power) [47]; (4) preventing the introduction of harmonics into the grid and participate in reducing harmonics on the bus; and (5) reducing the voltage unbalance between phases [87].

For the *EV owner level*, the main constraints are as follows: (1) whether or not they wish to follow the pricing schedule [26]; (2) arrival and departure time [53]; (3) initial and final SOC; (4) battery capacity limits [40]; (5) maximum and minimum energy limits of the battery [47]; (6) minimum and maximum charging rate limits imposed by the EV owner [47]; (7) the starting location and destination after leaving the PL [47]; (8) respect the on/off-board charger capacity [21]; and (9) charging and discharging efficiency [12]. The main objectives are (1) minimize the operation and charging costs [40,46–48,57,140]; (2) minimize the benefit from the discharging mode (if applicable) [35,47,48]; (3) obtain the desired final SOC [48,148]; (4) satisfy the EV owner [148]; (5) reduce the impact on the battery lifetime, for the charging mode [148] as well as for the discharging mode [48]; and (6) minimize the utilization of fossil fuel or gasoline used by PHEVs [17].

Optimization requires one or more objective functions and constraints, in which the solution will be available in a feasible region. A sample of the constraints is presented in Figure 6b, which are mostly used for electric vehicles. Table 10 presents a sample of the most used elements for the optimization model besides the EV at home and their mathematical equations. The elements are the home constraints, EVs, Battery Storage System (BSS), Photovoltaic (PV), and Wind Turbine (WT). Other elements can be added; however, the main goal of the table is just to give an idea about how to form the constraints for the elements to be considered in the optimization model. A BSS is mostly used at home, which has a PV system to store the energy from the sun and use it later. A BSS can also be used in connection with an EV charging station/Parking Lot as a buffer to manage the power absorbed from the grid. Another way to use BSS is on the distribution network, on the DC side of a PV plant. The battery is discharged when some EVs need to charge.

Here, P_t^{buy} and P_t^{sell} represent the buying and selling power at instant "t". P_t^{Min} and P_t^{Max} represent the minimum and maximum power limits of the buying and selling power at instant "t". E^{Min} and E^{Max} stand for the minimum and maximum buying and selling energy during a period T. $P_t^{Sell,Min}$ and $P_t^{Sell,Max}$ are the minimum and maximum selling power at instant "t". $E^{Sell,Min}$ and $E^{Sell,Max}$ represent the minimum and maximum selling energy during a period T. $P_t^{V,Ch}$ and $P_t^{V,Dch}$ represent the charging and discharging power of the EV at instant "t". $P_{Max,t}^{V,Ch}$ and $P_{Max,t}^{V,Dch}$ are the maximum charging and discharging power at instant "t". SOC_{min}^V and SOC_{max}^V stand for the minimum and maximum state of charge of the EV. $\eta^{V,Ch}$ and $\eta^{V,Dch}$ are the charging and discharging efficiency of the EV. B_{cap}^V is the battery capacity of the EV. SOC^{Min}, SOC^{Max}, and SOC_i are the minimum, maximum, and initial state of charge of the EV's battery. SOC_{tf}^V and SOC_d^V are the final and desired final state of charge of the EV's battery. P_t^{V2G} and P_t^{V2H} are the discharging power from the EV to the grid and to home, respectively. The same constraints used for the EV are also used for the BSS. P_t^{PV2H} and P_t^{PV2G} represent the supplied power from the PV to home and to the grid, respectively.

Table 10. Most used optimized elements and their equations.

Optimized Element	Constraints	Equation
Total load of a unit (e.g., home, building, etc.)	Power limits	$P_t^{Min} \le P_t^{buy} - P_t^{sell} \le P_t^{Max}$
	Absorption of reactive power limits	$Q_t^{Abs,\ Min} \le Q_t^{Absorb} \le Q_t^{Abs,\ Max}$
	Injection of reactive power limits	$Q_t^{Inj,Min} \le Q_t^{Inject} \le Q_t^{Inj,Max}$
	Energy limits	$E^{Min} \le \sum_{t\in T} \left(P_t^{buy} - P_t^{sell}\right)\Delta t \le E^{Max}$
	Selling power limit	$P_t^{Sell,Min} \le P_t^{sell} \le P_t^{Sell,Max}$
	Selling energy limit	$E^{Sell,Min} \le \sum_{t\in T} P_t^{sell}\Delta t \le E^{Sell,Max}$
EV	Charging power limit	$0 \le P_t^{V,Ch} \le P_{Max,t}^{V,Ch}$
	Discharging power limit	$0 \le P_t^{V,Dch} \le P_{Max,t}^{V,Dch}$
	State of charge limit	$SOC_{min}^V \le SOC_t^V \le SOC_{max}^V \Leftrightarrow \Sigma_{t\in T}\left(\eta^{V,Ch} P_t^{V,Ch} - \frac{P_t^{V,Dch}}{\eta^{V,Dch}}\right)\begin{cases} \le \frac{B_{cap}^V\left(SOC^{Max} - SOC_i\right)}{\Delta t} \\ \ge \frac{B_{cap}^V\left(SOC^{Min} - SOC_i\right)}{\Delta t}\end{cases}$
	Final state of charge	$SOC_{tf}^V = SOC_d^V \Leftrightarrow \Sigma_{t\in T}\left(\eta^{V,Ch} P_t^{V,Ch} - \frac{P_t^{V,Dch}}{\eta^{V,Dch}}\right) = \frac{B_{cap}^V\left(SOC_d^V - SOC_i\right)}{\Delta t}$
	Discharging to home and grid	$P_t^{V,Dch}\cdot\eta^{V,Dch} = P_t^{V2G} + P_t^{V2H}$
BSS	Charging power limit	$0 \le P_t^{B,Ch} \le P_{Max,t}^{B,Ch}$
	Discharging power limit	$0 \le P_t^{B,Dch} \le P_{Max,t}^{B,Dch}$
	State of charge limit	$SOC_{min}^B \le SOC_t^B \le SOC_{max}^B \Leftrightarrow \Sigma_{t\in T}\left(\eta^{B,Ch} P_t^{B,Ch} - \frac{P_t^{B,Dch}}{\eta^{B,Dch}}\right)\begin{cases} \le \frac{B_{cap}^B\left(SOC^{Max} - SOC_i\right)}{\Delta t} \\ \ge \frac{B_{cap}^B\left(SOC^{Min} - SOC_i\right)}{\Delta t}\end{cases}$
	Final state of charge (optional)	$SOC_{tf}^B = SOC_d^B \Leftrightarrow \Sigma_{t\in T}\left(\eta^{B,Ch} P_t^{B,Ch} - \frac{P_t^{B,Dch}}{\eta^{B,Dch}}\right) = \frac{B_{cap}^B\left(SOC_d^B - SOC_i\right)}{\Delta t}$
	Discharging to home and grid	$P_t^{B,Dch}\cdot\eta^{B,Dch} = P_t^{B2G} + P_t^{B2H}$
PV	Discharging to home and grid	$P_t^{PV} = P_t^{PV2H} + P_t^{PV2G}$
Wind Turbine	Discharging to home and grid	$P_t^{WT} = P_t^{WT2H} + P_t^{WT2G}$

5. Future Work and Recommendations

Table 11 shows the recommendations on all strategies. In this subsection, some ideas are proposed to improve the performance of the mentioned strategies.

1. For S1 to S6, it is proposed to limit the charging power rate (e.g., 3kW) in order to reduce the adverse impact on the PG. The control of the charging rate should be done by the EV owner.
2. For S3 and S4, it is recommended to create a mobile application that informs the user when to plug in his EV.
3. S7, S9, S11, and S13 are recommended when the base load does not overpass the limits imposed by the transformer bus or PSO. They are not capable of reducing the peak load. Therefore, it is suggested to create a mobile application that can be used by the EV owners. It consists of informing them when they have to disconnect their EVs or how much charging power they should draw, depending on the information is supplied by the PSO. Of course, such a type of participation requires incentivizing offers such as a fixed or percent reduction on electricity costs.
4. S8, S10, S12, and S14 are highly recommended to be used in almost any case. They allow the discharging during the on-peak time in order to reduce the peak load and respect the limits imposed by the transformer and PSO. The problem of these strategies is their high cost and complexity. In return, they help to stabilize the PG, generate revenues from providing ancillary services, etc. (refer to Tables 5 and 6). In addition, the installation of capacitor banks and other elements on the network could be prevented or reduced.
5. The most recommended strategy is S8, which has the highest performance rate compared to all strategies. It is quite similar to S12, but the difference is that S12 may not be used at home or for a single EV because it uses a discrete method.

Table 11. Final Recommendations from Our Review.

Description	Charging Strategy													
	S1:U-Di-C	**S2: U-Di-CD**	**S3: U-De-C**	**S4: U-De-CD**	**S5: U-R-C**	**S6: U-R-CD**	**S7: CC-Di-C**	**S8: CC-Di-CD**	**S9: CC-De-C**	**S10: CC-De-CD**	**S11: DC-Di-C**	**S12: DC-Di-CD**	**S13: DC-De-C**	**S14: DC-De-CD**
Recommended for a														
1. Home	M	M	M	M	M	M	Y	Y	Y	Y	-	-	-	-
2. Parking lot	N	N	N	N	N	N	Y	Y	Y	Y	Y	Y	Y	Y
Recommended for a														
1. Small number of EVs on the same bus	M	M	M	M	M	M	Y	Y	Y	Y	Y	Y	Y	Y
2. Medium number of EVs on the same bus	N	N	N	N	N	N	Y	Y	Y	Y	Y	Y	Y	Y
3. Large number of EVs on the same bus	N	N	N	N	N	N	Y	Y	Y	Y	Y	Y	Y	Y
Overall rating (rating from 10 with 10 being the best)	1	2	2	3	3	4	9	10	7	8	8	9	7	8

Y: Yes. N: No. L: Limited. M: Might Be. -: not applicable.

In this paper, we suggest that future work should include the annual growth rate of power demand on the CS bus and the annual growth rate of EVs.

6. Conclusions

This paper defines and discusses different charging strategies of EVs. It contributes through classifying different charging and discharging strategies in the literature; it presents the pros and cons of each strategy and its impact on the grid; it defines new strategies that were not mentioned in the literature; it rates the strategies based on detailed coverage of multiple aspects of interest; it identifies the optimization constraints of charging/discharging strategies as covered in the literature; and finally, it provides recommendations on the suitability of each strategy for specific applications.

Mainly, there are 14 different charging strategies, in which two of them are classified as the best of all. Tables are formed in order to facilitate the comparison between all strategies. Moreover, some recommendations are presented for each strategy in order to help the researchers find solutions to the related issues. Finally, the paper presents a typical objective function used to optimize charging strategies; then, it comprehensively covers various technical and economic constraints used in the optimization process. The limitations of this study are stated as follows: it does not go deeply into detail for the sake of simplicity, and it is intended for the people who are not very familiar with different charging strategies. For instance, when the complexity of the strategies is compared, the comparison shows only which ones are very simple, simple, complex, and very complex. Therefore, a detailed technical comparison is not made in this paper. Hence, further studies can advance more in technical and economic comparison. This can be applied to all the mentioned criteria in the tables. In addition, future work can compare different optimization algorithms and techniques used to charge and discharge the EVs. Only two charging strategies are considered the best in this paper, which are S8 and S12; however, further investigations are needed to see which one of them is better to use for specific applications such as in parking lot, charging stations, residential and commercial buildings, etc. Moreover, different optimization algorithms should be investigated because they affect the output result of each strategy.

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Abbreviations

BEV	Battery Electric Vehicle
CS	Charging Station
CST	Coordinated Strategies
EPRI	Electric Power Research Institute
EV	Electric Vehicles
G2V	Grid-to-Vehicle
H2V	Home-to-Vehicle
ICE	Internal Combustion Engine
IEA	International Energy Agency
PG	Power Grid
PHEV	Plug-in Hybrid Electric Vehicle
PL	Parking Lot
PSO	Power System Operator
RES	Renewable Energy Source
RTP	Real-Time Pricing
SAE	Society of Automotive Engineering
SOC	State-Of-Charge
ToU	Time-of-Use (Pricing)
UST	Uncoordinated Strategy
V2G	Vehicle-to-Grid
V2H	Vehicle-to-Home
V2V	Vehicle-to-Vehicle

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