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REVIEW

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Integration of EVs into the smart grid: a systematic literature review

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Abstract

Integration of electric vehicles (EVs) into the smart grid has attracted considerable interest from researchers, governments, and private companies alike. Such integration may bring problems if not conducted well, but EVs can be also used by utilities and other industry stakeholders to enable the smart grid. This paper presents a systematic literature review of the topic and offer a research framework to guide future research and enrich the body of knowledge. The systematic literature review presented in this paper does not contain all the material available on this subject. It does, however, include most of the key publications readily available in a power-utility or technical-reference library together with some of the earlier papers in the field (the anchor papers). For this review, we selected appropriate digital sources (digital libraries and indexing systems; IEEE Xplore and Web of Science), determined the search terms, and conducted a broad automated search. This article also details the components of the research theme—EV integration into the smart grid—as well as its accompanying use cases. The analysis of the relevant papers indicated four types of key research concerns: power-grid, power-system, and smart-grid reliability and the impacts of changes on them. These results can help guide future research to further smart-grid development. Future research can also expand the reach of this research to address its limitations in scope and depth.

Keywords: Electric vehicles, Distributed storage, Literature review, Vehicle to grid

Introduction and research background

Integration of electric vehicles (EVs) into the smart grid can be leveraged by utilities and other industry stakeholders to bring several benefits and to enable the smart grid. Mwasilu et al. (2014) emphasized the importance of vehicle to grid (V2G), an example of services on the grid that will allow the shift of the static power system to the efficient virtual power grid. San Diego Gas and Electric (2015) reported that deploying networks of EV charging stations can stabilize and bring advantages to the grid in locations with excess power; EV charging can absorb mid-day solar overgeneration and alleviate wind curtailment at night. Sultan et al. (2017) highlighted how charging EVs when nondispatchable assets, such as solar and wind generators, are producing more energy can help flatten out the demand curve and reduce the extent to which supply suddenly escalates. All these characteristics reduce system costs, benefit ratepayers, and improve the profitability of generators (San Diego Gas and Electric 2015).

On the international stage, the EV industry has been prominently used as a tool by countries to meet their carbon-footprint-reduction goals. EVs also have spurred a potential new avenue of electricity sales while at the same time impacting maintenance costs by adding to peak loads and changing historical grid-load patterns. The integration of EVs with electrical grids is giving rise to the concept of smart grids. This integration can come from potential bidirectional charging (V2G), grid storage research, and innovative energy generation (Denholm et al. 2015).

EVs can potentially serve a dual purpose, an alternate form of grid storage offloaded to the public. It can allow the vehicle owners to be compensated for providing electric service when the vehicle is not in use, helping to reduce the cost of ownership. Also, the quality of life for large urban centers can increase due to the potential opportunity to move emissions from large population centers. This relocation of energy production can improve air quality and public health in metropolitan cities, while remaining emission production further decreases as remaining energy needs are met by renewable resources (Denholm et al. 2015).

However, it is important to note that the integration of many EVs into the electric power system is a major challenge which requires a thorough evaluation and examination in terms of economic impacts, operation, and control benefits at ideal circumstances (Mwasilu et al. 2014). Large-scale integration of EVs into the smart grid may bring a series of problems if EVs are not integrated carefully into the smart grid. According to Green et al. (2011), several works analyzed the impact of EVs on the power-distribution system. Examples of the anticipated adverse impacts are power transformers overheating and the need for new investments in distribution facilities (Mwasilu et al. 2014).

A major challenge is the impact of simultaneously charging many EV batteries on the power network, this could change the overall load profile of the grid significantly. The issue is that the charging behaviors of EVs are only regulated by the customer so it's not within the control of the grid operators and the electric utilities. The risk of grid overload can lead to a degradation of the grid performance, bad power quality and/or voltage deviations, even a blackout of the whole power system if EV charging is not managed properly. However, time-of-use rates can guide an EV charging, and V2G benefits can be easily ramped up and down in response to the load on the system, improving voltage regulation and droop control.

The high cost of integration due to inadequate charging infrastructure and competition from other energy-storage technologies are additional challenges to EV integration. Pumped hydroelectric storage is considered, for example, to be much cheaper than the V2G option. According to Hernández-Moro et al. (2012) and Mullan et al. (2012), pumped hydro has greater efficiency (up to 99%) and can store energy for long periods as compared to the EV battery (Hernández-Moro et al. 2012).

On the other hand, EVs have advantages when operated in the V2G mode to feed power to the utility grid. The primary advantages stem from the EV battery's ability to provide power when needed. EV technology can provide grid support by delivering ancillary services such as peak power shaving, spinning reserve, and voltage and frequency regulation (Ehsani et al. 2012).

Peak shaving means reducing the highest demand levels at the power plant. From a utility perspective, EVs can be viewed as both dynamic loads which may not be easy to predict, but also potential backup for the electric grid through the V2G technology (Mwasilu et al. 2014). So, EVs can respond to changes in demand, they provide a spinning reserve and can dramatically reduce the need to use expensive peaking plants, savings that utilities can pass on to their customers in the form of lower energy costs.

Another point is that mismatches between power supply and demand can lead to oscillations in the supplied voltage, phase angle, and frequency. These oscillations degrade power quality, possibly damaging utility customers' sensitive electronic equipment. EVs can both provide and absorb power and energy so to help dampen both intra- and inter-area power oscillations. Mwasilu et al. (2014) claim that EVs have the potential to assist in voltage and frequency regulation, thus enhancing electric-grid reliability and power quality.

A modern grid that is well equipped to handle the additional EV loads and reap the benefits from the intersection of the EVs and the electric power network could contribute to an enhanced grid with real environmental benefits for all customers.

Thus, more research is needed, and it is critical especially with the increasing penetration of EV charging into the electric power system. Unease about global warming, energy security, and the current health of the environment has caused more interest in EVs. The existing power grid suffers from unpredictable and intermittent supply of the electricity from wind and photovoltaic (PV) solar sources, so EV charging and V2G services are a promising solution to balance the generation from renewable energy sources (International Electrotechnical Commission 2012).

The intent of this paper is to present a systematic literature review of EV integration into the smart grid and develop a research framework to guide future research and enrich the body of knowledge. A systematic literature review is a particularly influential tool in research; it allows a scholar to gather and recap all the information about a specific field (Spanos and Angelis 2016).

This paper is organized as follows. In the "Introduction and research background", we introduce and present the topic's research background. In the "Methodology", we delineated our research methodology. The "Results" describes the results of the review and offers a bibliography of anchor papers. The "Discussion" discusses the results. Finally, "Conclusion" concludes.

Methodology

This paper's systematic literature review follows the three stages defined by Kitchenham (2004) and Kitchenham et al. (2009): planning, conducting, and reporting. In the first stage, we create the research protocol. The second stage is the actions of reviewing literature based on the protocol, and the last stage manifests the article's results section.

Research protocol

The research protocol established in the planning stage guided the systematic literature review. The first step is to identify the need for a systematic review. Although several studies try to investigate EV integration into the smart grid, no comprehensive review has so far summarized all these studies and offered a deeper insight. Therefore, the need for a systematic literature review providing solid foundations and equipping researchers with pertinent information is clear.

To develop the review protocol, we define the research questions, select the search strategy, establish the study's inclusion and exclusion criteria, select quality-assessment criteria, and identify the data to be extracted from the studies. Three research questions guide our review.

1. What are the themes within research on EV integration into the smart grid?
2. What are the results of the studies?
3. What research methods are used?

To conduct the systematic literature review, we adopted a broad automated search, a method that includes the selection of the most appropriate digital sources (digital libraries and indexing systems) and the determination of the search terms (Spanos and Angelis 2016). We selected two digital libraries, IEEE Xplore and Web of Science, as they are the most relevant digital sources in electricity-infrastructure research. Our searches relied on the titles of the papers to avoid retrieving irrelevant papers. The search strings we used were.

IEEE Xplore Boolean Phrase:	("Document Title":electric vehicle) AND ("Document Title":smart grid)
and refined by	Content Type: Conferences, Journals, and Early Access Articles
Web of Science Boolean Phrase:	TOPIC: (electric vehicle AND smart grid)
Refined by:	DOCUMENT TYPES = (ARTICLE). Timespan = All years. Indexes = SCI-EXPANDED, SSCI, A&HCI, ESCI

Inclusion and exclusion criteria

According to Spanos and Angelis (2016), a systematic literature review's inclusion and exclusion criteria must be distinct and clearly stated. We used three selection criteria and one exclusion criterion in our systematic review.

Inclusion:	1.Full-article publication (not just an abstract)
	2.English-language publication
	3.Study relevance
Exclusion:	1.Duplicate publications (to avoid double-counting of studies)

Quality assessments

Once each paper has passed the relevancy test, we peruse the papers based on the quality-assessment criteria. These rigorous criteria ensure all studies included in the systematic literature review achieve an adequate level of quality. After consulting with domain experts and independent researchers, we decided to include each article for the final analysis if it satisfies three criteria:

1. The data description is available, and its existence can be verified.

2. Research methodology is clearly described.
3. Results presentation is clear and impactful.

Once the articles had passed the inclusion and quality-assessment criteria, we recorded the data features of the papers for the final analysis: (1) title, (2) authors, (3) publication year, (4) authors' affiliations, (5) journal title, (6) number of papers citing the article, (7) abstract, (8) research questions, (9) research methodology, and (10) results.

Results

Summary

For this survey, we analyzed results from 724 papers relevant to integration of EVs into the smart grid, 260 papers from the IEEE Xplore and 464 papers from the Web of Science. The analysis process considered the research results, as stated by the authors, and was mainly conducted throughout the abstract, conclusion, and results sections if required. Tables 1 and 2 present counts of document identifiers and publication years. Table 3 presents summary statistics.

The analysis of the relevant papers indicated four types of key research concerns.

- Assessing power-grid reliability considering EV integration.
- Improving power-system reliability considering EV integration.
- Planning for smart-grid reliability in preparation for EV integration.
- Evaluating the impacts of adding EVs and charging stations on grid reliability.

The research methodologies of the included papers can be classified into two categories, analytical and simulation. Analytical techniques "represent the system by mathematical models and evaluate the reliability indices from these models using mathematical solutions" (Faulin et al. 2010). Simulation views problems as a series of real experiments, such as Monte Carlo simulation which is used for the prediction

Table 1 IEEE documents

Document type	Count	Publication year	Count
IEEE Conferences	206	2010	7
IEEE Early Access Articles	2	2011	23
IEEE Journals	49	2012	27
SGEPRI Journals	1	2013	21
VDE Conferences	2	2014	29
Grand total	260	2015	31
		2016	28
		2017	21
		2018	24
		2019	20
		2020	26
		2021	3
		Grand total	260

Table 2 Web of science documents

Document type	Count	Publication year	Count
ACTA Physica Sinica	1	2010	5
Applied science and technology	22	2011	8
Applied sciences—Basel	5	2012	27
Communication networks	10	2013	18
Computing	12	2014	41
Electricity and electronics	53	2015	49
Energies	96	2016	53
Engineering technologies	27	2017	61
IEEE	164	2018	54
IET	10	2019	67
International journals	10	2020	63
Security	5	2021	18
Sustainability	29	Grand total	464
Technical journals	14		
Transportation	6		
Grand total	464		

Table 3 Summary statistics

Database criteria	IEEE Xplore	Web of Science	Total count
Number of papers found as a result of the search	260	464	724
Irrelevant papers	13	93	106
Duplicate papers	1	22	23
Not an English-language publication	0	1	1
Final number of relevant papers	246	348	594

Table 4 Analytical versus simulation

Research Method	IEEE Xplore	Web of Science	Total count
Analytical	127	193	320
Simulation	119	155	274

of probability for various outcomes when dealing with random variables. Table 4 presents the statistics for the different research methods. Finally, 58 papers used the Monte Carlo simulation method.

Based on the results of the systematic literature review, we have constructed a smart-grid–EV-integration framework highlighting research components of EV integration into the smart grid, with goals, themes, use cases, and research tools.

Research contribution: framework

In this section, we propose the smart-grid–EV-integration framework with three main research domains (Fig. 1), solutions for charging, microgrids and distributed generation, and managing power demand. This framework recognizes these three EV-integration domains as cardinal research-movement drivers for studying the benefits

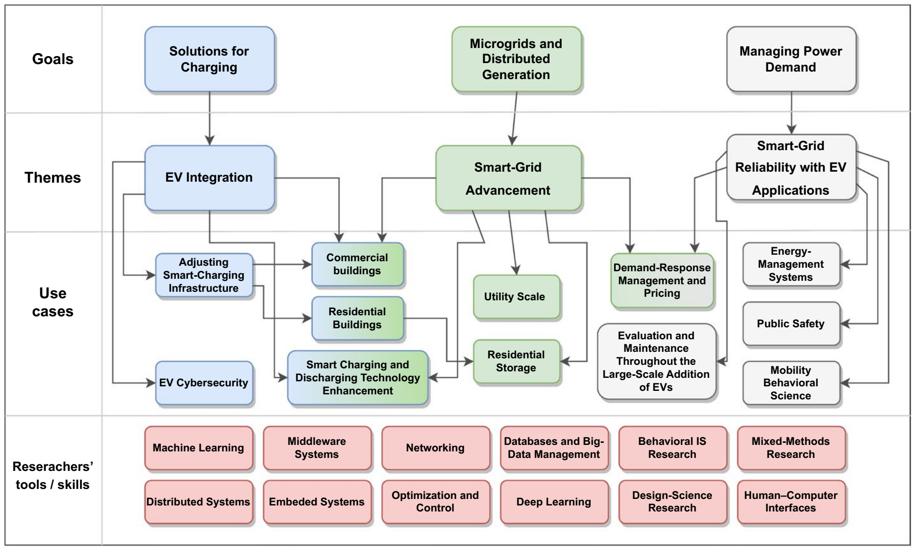

Fig. 1 Smart-Grid–EV integration framework

and challenges of integrating EVs into a smart grid. We also propose technological and socioeconomic solutions. Next, based on our literature analysis, we present common themes within the domains. The first theme, integrating EVs, drives the enhancement of EV technologies. The second theme, advancement of the smart grid, drives the advancement of distributed generation. The third theme, smart-grid reliability with EV applications, drives power-demand management and smart-grid reliability in the context of EV integration.

The use cases in the research framework are classified based on under which research theme(s) they fall (see Fig. 1). Smart-charging infrastructure use cases deal with the reformation of current structures to achieve both physically and technically suitable charging solutions. "Apart from the technological innovation of EV, effective charging infrastructure plays a fundamental role in supporting the wider adoption of EV" (Chen et al. 2020). An important area of infrastructure adjustments is, for instance, planning for EV smart charging stations, involving both geographical research and charging-management system implementation.

According to Zhou et al. (2021), commercial buildings with EV charging stations and PV panels are common prosumers in the smart grid. Thus, "the energy management of commercial buildings has significant potential for electricity cost saving, load levelling, and distributed generation consumption." Site-integrated EV charging solutions for workplaces and other business or commercial areas are interesting use cases, where growth in EV smart-grid penetration calls for improved charging load management. Algorithms, charging and discharging impacts on smart-grid peak loads, and cost benefits are worthy of investigation.

Residential-building use cases explore the impacts of EV integration on a household, very often in combination with implementation of photovoltaic or wind-energy appliances. Charging solutions can have economic benefits. Residential storage, on the other hand, like EVs, can be both flexible and time shiftable and can significantly increase residential-demand elasticity (Rassaei et al. 2015). The use cases explore how to manage smart-home energy in a residential smart grid and how energy stored in the EV can be used for distributed generation either for the household or for a larger residential area. This area also involves associated-risks investigation, including increased power losses, overloads, and voltage fluctuations, and how they influence the smart grid.

EV Cybersecurity use cases investigate EV integration into the smart grid from the perspectives of energy safety, usage, user information, and transactions. According to Sanghvi et al. (2021), EV integration can potentially leave the grid "vulnerable to cyberattacks from both legacy and new equipment and protocols, including extreme fast-charging infrastructure." Since EV participation in the smart grid will unavoidably partially depend on accessing power and communication networks and systems, such a system might become a target of such attacks. Thus, cybersecurity and energy security are crucial areas of research around smart-grid–EV integration.

Technological enhancement of smart charging and discharging evaluates problems caused by advancements in charging technologies to identify strategies, benefits, and risks and evaluate and propose how EV charging and discharging can help improve a smart grid's flexibility and effectiveness in response to energy fluctuations in the distribution area. According to Aghajan-Eshkevari et al. (2022), "it is essential to manage the charging and discharging of EVs [that] can be also considered sources of dispersed energy storage and used to increase the network's operation efficiency with reasonable charge and discharge management." Use cases may also include improvement of fast-charging technologies, battery technologies, wireless charging, and roadway electrification.

Utility-scale energy storage solutions help maintain a balance between energy generation and consumption in the smart grid. As the EV market grows, more degraded batteries can be further used for other purposes. "In particular, the repurposing of EV [lithium-ion batteries] in stationary applications is expected to provide cost-effective solutions for utility-scale energy storage applications" (Steckel et al. 2021). Use cases in this category involve addressing questions of battery recycling sustainability, degradation, participation of EVs in the load balancing through the dispatch of batteries, and other areas.

Demand-response management and pricing use cases focus on both technical and socioeconomic areas of energy supply and demand for smart-grid operators, charging-station operators, and EV users and their demand response during the peak time. While smart-grid–EV integration has a significant impact on energy demand, they also represent an energy resource. "Therefore, in smart grid, the consumer demand is expected to be controlled so as to coordinate with the electricity generation, which is the main objective of demand response management" (Yu et al. 2016). Power demand response can positively impact peak shaving and load balancing, and open new possibilities for energy market and energy trading through energy-aggregator demand-response programs (Ren et al. 2021).

Evaluation and maintenance throughout the addition of EVs can involve mathematical modeling for both technological and economic evaluation of EV deployment's impacts on the smart grid, predictive maintenance solutions for distribution transformers under the increased EV load, energy-dispatch strategies, involved systems' life cycles, charging behavior, and other methods to maintain a balanced smart grid with growing numbers of EVs.

Energy-management systems are crucial to the smart grid's ecosystem. Integrated EVs can contribute to the important task of effectively maintaining the power supply–demand balance and decrease the peak load. Energy-management systems also handle sharing or exchanges among different energy sources, including EVs, to establish reliable and effective supply. Use cases in this category involve many topics like energy-quality management systems, optimization systems, energy-consumption control systems, and scheduling systems. Energy-management systems are also closely linked to demand management and response (Meliani et al. 2021).

Public safety in EV adoption must be considered. As countries around the globe strive to meet energy objectives while decreasing their climate impact, it is crucial to identify and regulate new EV-related technologies to protect the public from potential undesirable effects. A growing number of EVs increases risks from, for instance, disposed or damaged batteries. Therefore, proper risk-mitigation techniques—professional training, recycling policies, and standardization—must ensure public safety and environmental protection (Brown et al. 2010).

Mobility behavioral science explores the questions associated with human behavior's impact on transportation and energy and is crucial for understanding of how future EV and smart-grid technologies should be implemented. According to Rames et al. (2021), "exploring multidimensional aspects of differences in technology adoption, travel, and vehicle ownership across settlement types can help inform energy-efficient and affordable mobility system goals." Thus, research in this area involves modeling EV owners' usage and driving behavior for effective power planning and operations, drivers' motivation to participate in peak shaving, and implementation of localization technologies to adjust charging behavior and manage demand.

We aim to help resolve problems in the EV-integration field using such tools as machine learning, deep learning, networking, distributed systems, middleware systems, embedded systems, optimization and control, databases and big data management, human–computer interfaces, behavioral information systems research, design-science research, and mixed-methods research. When applied to the EV-integration field, these tools have the potential to significantly increase knowledge in the field and solve some of the problems it faces.

Smart-grid–EV-integration research framework founded on the previous literature

In addition to our smart-grid–EV-integration perspective, Fig. 2 illustrates our smart-grid–EV-integration research framework founded on the previous literature and our view of the domain. The framework focuses on two main areas: EV integration and the smart grid. The first research focus involves systems connecting EVs, transportation infrastructure, power grid, buildings, and renewable energy sources (Meintz 2022). Adjusting infrastructure, charging solutions, and associated costs are all possible goals in the EV-integration research focus.

The smart grid (the second research focus) refers to the electric grid, a network of transmission lines, substations, transformers, and more that deliver electricity to a set

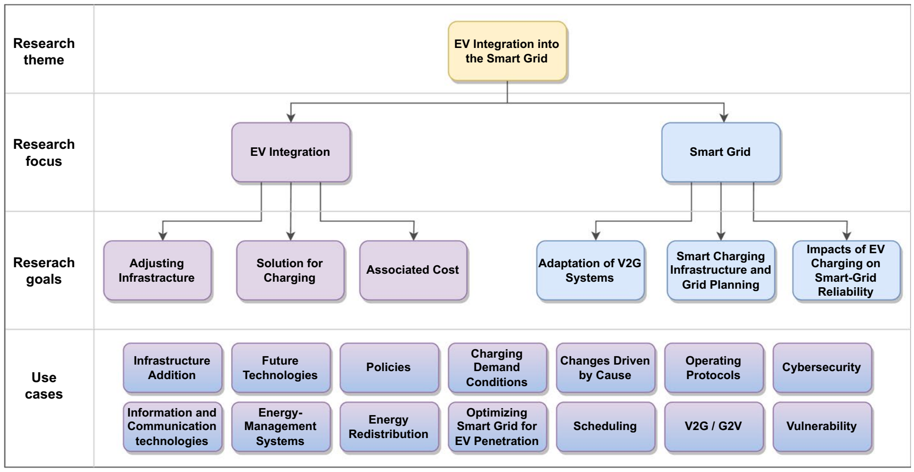

Fig. 2 Smart-grid–EV-integration research framework

location, integrated with digital technology allowing for sensing and two-way communication between the utility and its consumers (Department of Energy, Office of Electricity 2022). Adaptation of V2G systems in the smart grid, smart charging infrastructure, grid planning, and impacts of EV charging on the smart grid's reliability are the possible goals within the smart-grid research focus.

In the context of a smart-grid–EV-integration research framework, scenarios and use cases can be classified into infrastructure addition, future technologies, policies, charging-demand conditions, changes driven by causes, operating protocols, cybersecurity, information and communication technologies, energy-management systems, energy redistribution, optimizing the smart grid for EV penetration, scheduling, V2G, and vulnerability.

Anchor papers on the integration of EVs into the smart grid

One way to ensure the grasp of the main core of a subject is to examine the references cited in the current articles and highlight repeatedly cited papers. In this literature review, papers cited more than one standard deviation above the average are considered anchor papers.

From the articles that passed the filter criteria, we identified anchor papers, highly cited and influential papers. To identify anchor papers, we used the same search string without an exclusion criterion (no year-range restriction) to pull all journal and magazine publications matching the search criteria from the database. We sorted the extracted articles (700 total) in descending order based on the number of articles citing each focal article, calculated the standard deviation for the articles' number of citations, and identified the outliers (articles whose number of citations exceeded one standard deviation greater than the mean). The search string that we used for IEEE Xplore is ("Document Title":electric vehicle) AND ("Document Title":smart grid) and refined by Content Type: Conferences, Journals, and Early Access Articles. Meanwhile, for Web of Science, we used the search TOPIC: (electric vehicle AND smart grid) refined by DOCUMENT TYPES = (ARTICLE) Timespan = All years. Indexes = SCI-EXPANDED, SSCI, A&HCI, ESCI.

Based on this analysis, we found 61 anchor papers and passed them through a relevancy test to see if they are related to grid-reliability research. As each paper passed the relevancy test, we peruse it to apply quality-assessment criteria. After excluding the irrelevant papers and those not meeting the quality criteria, we identified 45 anchor papers (Table 5).

Table 6 presents a bibliography and analysis of anchor papers on the subject of the integration of EVs into the smart grid. Based on this analysis, Table 7 presents the distribution and percentages of anchor articles by research theme or question previously identified as follows. Optimizing grid usage to EV needs and the impacts on EV applications of smart-grid implementation or V2G communication have received the most attention. Environmental changes due to EV or grid applications show the lowest percentages of anchor articles.

Table 8 presents the research methods used by the authors of the anchor papers. Though simulation is the dominant research method considering the entire literature, articles using analytical approaches seem to get more attention based on articles citing them.

Discussion

Bearing in mind the research themes and the methods illustrated in the anchor papers, we posit that simulation has been a popular topic in research and that there is need for more research in the area of environmental changes due to EV or grid applications, how to adjust the reliability and adequacy of charging stations and impacts on EV and grid applications.

Analytics using machine learning and big-data management would help the research community plan and improve EV integration into the smart grid. In future research, we intend to highlight the novel use of analytics to predict research themes such as environmental changes due to EV or grid applications, how to adjust the reliability and adequacy of charging stations and impacts on EV applications of grid applications. The goal is to offer an enhanced viewpoint for this research topic, while considering the impact of changes, EVs' integration, and the potential benefits to the smart grid.

Table 5 Anchor paper statistics

Database criteria	Total count
Count of journal and magazine papers found as a result of the search	700
Standard deviation for the articles' count of citations	54
Mean number of citations per article	26
Articles whose citation count exceeded one standard deviation above the mean (26 + 54)	61
Irrelevant papers	14
Papers not included due to inadequate quality	2
Final number of relevant anchor papers	45

Table 6 Anchor paper bibliography and analysis

Citation	Research question	Research method	Research result	Citation count
Deilami et al. (2011)	Uncontrolled and random EV charging can cause increased power losses, overloads and voltage fluctuations, which are all detrimental to the reliability and security of newly developing smart grids	Simulation	A novel real-time smart load management control strategy is proposed to coordinate the charging of multiple EVs in a smart grid	670
Tan et al. (2014)	Can costs be reduced by integrating plug-in electric vehicles and renewable distributed generators?	Simulation	In a market in which users can sell back the energy generated by their distributed generators or the energy stored in their plug-in electric vehicles, numerical examples show that the demand curve is flattened by the new pricing model of demand-response management for the future smart grid that integrates plug-in electric vehicles and renewable distributed generators, even though the model includes uncertainties, thus reducing the utility company's costs	154
Veldman and Verzijlbergh (2015)	In this paper, we assess the financial impact of various EV charging strategies on distribution grids	Simulation	Using a strategy that minimizes network peak loads (from a network operator's perspective) with a strategy to minimize charging costs (from the commercial party's perspective), a large difference in network impacts between the price-based and network-based charging strategies was only observed with a high wind penetration. Therefore, we additionally study the effect of wind energy on electricity prices and, consequently, on the resulting EV load and network impacts	144
Mukherjee and Gupta (2015)	What work has been done recently in the area of scheduling algorithms for charging EVs in smart grid?	Literature review	The works are first classified into two broad classes of unidirectional versus bidirectional charging. Then each class is further sorted based on whether the scheduling is centralized or distributed and whether any mobility aspects are considered	130

Table 6 (continued)

Citation	Research question	Research method	Research result	Citation count
Kennel et al. (2013)	Can hierarchical model predictive control (HiMPC) improve energy management system for smart grids with electric vehicles?	Simulation	The aggregator in particular provides predictions to the HiMPC on the availability of electric vehicles for LFC based on the current mobility demand and the statistical mobility behavior of the vehicle users. The main component is the HiMPC, which allows covering different time scales, regarding constraints (e.g. power ratings) and predictions (e.g. on renewable generation), as well as rejecting disturbances (e.g. due to fluctuating renewable generation) based on a systematic model- and optimization-based design	129
Rigas et al. (2015)	How can EVs and the systems that manage EV collectives be made smarter?	Literature review	Artificial intelligence techniques can render EVs and the systems that manage EV collectives smarter. A survey of the literature identifies the commonalities and key differences in the approaches	111
Kim et al. (2013)	Can novel electricity load scheduling algorithms improve a power system with an aggregator and multiple customers with EVs?	Model	Collaborative and noncollaborative approaches are proposed. In the collaborative approach, an optimal distributed load-scheduling algorithm maximizes the power system's social welfare. In the noncollaborative approach, the energy scheduling problem is modeled as a noncooperative game among self-interested customers, where each customer determines its own load scheduling and energy trading to maximize its own profit. A tiered billing scheme that can control the electricity rates for customers according to their different energy consumption levels to resolve the unfairness between heavy and light customers in the noncollaborative approach. Both approaches also consider uncertainty in load demands, with which customers' actual energy consumption varying from the schedule	103

Table 6 (continued)

Citation	Research question	Research method	Research result	Citation count
Sojoudi and Low (2011)	Scheduling the charging of PHEV batteries	Physical simulation	A solution to this highly nonconvex problem optimizes the network performance by minimizing the generation and charging costs while satisfying the network, physical, and inelastic-load constraints. A global optimum to the joint OPF-charging optimization can be found efficiently in polynomial time by solving its convex dual problem whenever its duality gap is zero	91
Rassaei et al. (2015)	Assigning real-world randomness to EVs' availability in households and their charging requirements, how can EVs' demand response (DR) help minimize the peak power demand and, in general, shape the system's aggregated demand profile?	Simulation	A general demand-shaping problem applicable for limit-order bids to a day-ahead (DA) energy market. We propose an algorithm for distributed DR of the EVs to shape the daily demand profile or to minimize the peak demand. Additionally, we put these problems in a game framework	87
Xing et al. (2016)	Can utilities gain load-shifting service by optimally scheduling the charging and discharging of EVs in a decentralized fashion?	Algorithm load-shifting service proposal	We propose a solvable approximation of the MDP problem by exploiting the shape feature of the base demand curve during the night, and develop a decentralized algorithm based on iterative water-filling. Our algorithm is decentralized in the sense that the EVs compute locally and communicate with an aggregator	84
Rostami et al. (2015)	Can grid reliability and energy cost be improved by managing PHEV charging?	Simulation	A novel optimal stochastic reconfiguration methodology to moderate the charging effect of PHEVs by changing grid topology using remote-controlled switches. Uncertainties associated with network demand, energy price, and PHEV charging behavior in different charging frameworks are handled with Monte Carlo simulation and the proposed stochastic problem is solved with krill herd optimization algorithm	84

Table 6 (continued)

Citation	Research question	Research method	Research result	Citation count
Kong and Karagiannidis (2016)	What is the state of the art of existing PHEV battery-charging schemes?	Analysis	For uncontrolled charging, existing studies focus on evaluating the impact of adding variable charging load on the smart grid. Various indirectly controlled charging schemes have been proposed to control energy prices and indirectly influence charging operations. Smart charging schemes can directly control a rich set of charging parameters to achieve various performance objectives, such as minimizing power loss, maximizing operator's profit, ensuring fairness, and so on. Finally, bidirectional charging allows a PHEV to discharge energy into the smart grid, such that the vehicle can act as a mobile energy source to further stabilize a grid partially supplied by intermittent renewable-energy sources	80
Martinez et al. (2017)	This paper presents a comprehensive analysis of EMS evolution toward blended mode and optimal control, providing a thorough survey of the latest progress in optimization-based algorithms	Analysis, survey	This is performed in the context of connected vehicles and highlights certain contributions that intelligent transportation systems, traffic information, and cloud computing can provide to enhance PHEV energy management. Nevertheless, it has been evidenced that the EMS cannot be fully optimized without detailed information about the future route	256
Hu et al. (2017)	How do three important control tasks interact in PHEVs: charging, on-road power management, and battery-degradation mitigation?	Analysis	A new convex-programming (CP)-based cost-optimal control framework to minimize the daily PHEV operational expense seamlessly integrates the three tasks' costs with a very close precision to DP while running approximately 200 times faster. Sensitivity analysis suggests that the PHEV evolves toward a pure electric vehicle, with increased gasoline price and reduced battery price. The optimization does not allow V2G activities, because V2G-induced battery aging cost outweighs the added V2G revenue	108

Table 6 (continued)

Citation	Research question	Research method	Research result	Citation count
Yao et al. (2017)	How can EV charging and DR programs be coordinated in parking stations?	Convex relaxation, simulation	Extensive simulation results show that the proposed work is able to satisfy EV charging demand while accommodating both types of DR programs in the parking station. The proposed work is also able to simultaneously maximize the number of EVs for charging and minimize expenses	86
Ahmadi et al. (2017)	What are the potential technological, economic and environmental opportunities for improving energy systems and material efficiency from lithium-ion battery recovery from end-of-life electric vehicles?	Analysis	Results indicate that the manufacturing phase of the Li-ion battery will still dominate environmental impacts across the extended life cycle of the pack (first use in a vehicle, then reuse in a stationary application). For most impact categories, the cascaded use system appears significantly beneficial compared to the conventional system. Consuming clean energy sources for both use and reuse supports global and local environmental stress reductions. Greenhouse gas advantages of vehicle electrification can be doubled by extending the life of the EV batteries and enabling better use of off-peak low-cost clean electricity or intermittent renewable capacity	90
Shafie-khah et al. (2016)	What is a EV parking lot's the optimal behavior in the energy and reserve markets?	Analysis	The results indicated that a parking lot, because of its charging-station nature, is similar to a large demand in the system. Consequently, participation in different DRPs significantly affects its operational behavior. Therefore, the pattern of EV charging and discharging, trading energy with the grid, and participation in the reserve market are meaningfully influenced by the DRP type	88

Table 6 (continued)

Citation	Research question	Research method	Research result	Citation count
Yu et al. (2016)	Can an exploration of EV mobility impact DRM in V2G systems in a smart grid?	Simulation with real-world data	Based on simulation with real world data, the districts' DRM dynamics are coupled with each other through EV fleets. A complex network-synchronization method analyzes the dynamic behavior in V2G mobile-energy networks. Numerical results show that mobility of a symmetrical EV fleet is synchronously stable and power demand is balance among different districts	81
van der Kam and van Sark (2015)	How can self-consumption of photovoltaic power by smart charging EVs and V2G technology be increased?	Model simulations	Self-consumption increases from 49 to 62–87% and demand peaks decrease by 27–67%. These results clearly demonstrate the benefits of smart charging EVs with PV power. Furthermore, our results give insight into the effect of different charging strategies and microgrid compositions	123
Deng et al. (2015)	How do four major aspects (programs, issues, approaches, and future extensions of demand response) of incentive-based programs affect utilities' demand response	Survey, analysis	Reviewing DLC, interruptible/curtailable load, demand bidding and buyback, emergency demand reduction, ToU pricing, CPP, RTP, and IBR, the demand-response issues include mathematic models and problems. Commonly used utility and cost functions model the demand-response activities. Based on the models, most of the existing works aim at utility maximization, cost minimization, price prediction, renewable energy, and energy-storage problems	376
Jian et al. (2015)	Can a novel event-triggered scheduling scheme for V2G operation based on the scenario of stochastic EV connection to smart grid address power-load fluctuation?	Analysis	Statistical analysis results demonstrate that the proposed V2G scheduling scheme can dramatically smooth out fluctuations in power-load profiles	91
Erdinc et al. (2015)	Can a collaborative evaluation of dynamic pricing and a bi-directional use possibility for EV and energy storage system improve peak-power-limiting-based DR strategies?	Simulation	The proposed strategy provided a more efficient operation by means of up to 65% relectricity-cost reduction. Adding more smart technologies to a HEM system offers a more economically efficient use of electricity	216

Table 6 (continued)

Citation	Research question	Research method	Research result	Citation count
Mou et al. (2015)	Can DSM for PHEV charging at low-voltage transformers flatten their load curve while satisfying each consumer's requirement for timely PHEV charged?	Simulations, algorithm	Simulation results show that the proposed algorithm can efficiently fulfill the task of flattening the power demand curve and avoid transformer overloading	80
Kisacikoglu et al. (2015)	Can a single-phase on-board bidirectional EV charger provide reactive power support to the utility grid in addition to charging the vehicle battery?	Simulation	The proposed unified system controller receives charging active power and reactive power inputs from the utility grid and adjusts the line current and battery current without exceeding THD limits. It provides a fast dynamic response, along with a good steady-state performance	143
Sbordone et al. (2015)	How do different types of EV charging stations, in reference to the present international European standards, and storage technologies integrate in a smart grid?	Prototyping	The results of the experimental tests show that the system has a good performance in the implementation of peak-shaving functions, making the prototype a nearly zero-impact system	83
Lopez et al. (2015)	Can an optimization-based model perform load shifting in the context of smart grids?	Simulations	The deviations in the final-load mean curve can be decreased more than 70% with a significant reduction of the difference between the hourly maximum and minimum demand values	101
Verzijlbergh et al. (2014)	Do we need congestion management in the distribution grid?	Mathematical formulation of the EV optimization problem	The constraint that limited network capacity puts on EV charging has a low associated cost, but shifting demand peaks through an optimal congestion-management mechanism only marginally increases EV-charging costs. Ex-ante fixed tariffs, based on historic network load profiles, do not solve congestion efficiently and may not be effective at all. They influence the economic signal of the wholesale electricity price, leading to unnecessarily high EV-charging costs because that network capacity is only a constraint during a limited number of hours per year, while these tariffs force continuous changes in EV charging	92

Table 6 (continued)

Citation	Research question	Research method	Research result	Citation count
Heymans et al. (2014)	Can we use a MATLAB simulation to analyze the feasibility of and cost savings from repurposing an EV battery unit for peak shifting?	MATLAB simulation	Using repurposed EV batteries for energy storage and peak shaving can save costs to residential users while shifting power from peak to off-peak times, thus reducing strains on the electric grid. However, the approach has marginal economic feasibility without government intervention and moderate economic feasibility with intervention. Thus, governments should subidize this green technology. Such subsidies can be justified through reduced strains on the electricity grid and support of smart-grid objectives for cleaner power generation and energy security	123
Su et al. (2014)	Can a stochastic problem aid microgrid energy scheduling?	Simulation	The proposed problem formulation minimizes the expected operational cost of the microgrid and power losses while accommodating the intermittent nature of renewable-energy resources. Case studies on a modified IEEE 37-bus test feeder demonstrate the effectiveness and accuracy of the proposed stochastic microgrid energy-scheduling model	346
Zhang and Chen (2014)	What is a strategy for energy management and optimized operation of EVs considering the impact of EVs' deep electric-grid penetration?	Simulation	Regional management of EVs based on the microgrid not only averts the adverse effects of uncoordinated charging, but also reduce the difference between the load peak and valley. Besides peak loading, the system economics are improved by encouraging EVs, BSS, and ILs to provide regulation service and reserve capacity, facilitating the integration of DERs and further promoting the renewable sources and reliability of the power supply	98

Table 6 (continued)

Citation	Research question	Research method	Research result	Citation count
Donadee and Ilie (2014)	Can stochastic dynamic programming optimize charging and frequency-regulation capacity bids of an EV in a smart electric grid?	Stochastic dynamic programming	This paper presents an MDP with three sources of uncertainty for EV charging and an approximate SDP algorithm to optimize an EV's charging and frequency-regulation bids over a continuous space of decisions. The methods developed minimize an approximation of expected future costs and lowers average EV charging costs than deterministic MPC. Although the relative improvement in mean charging cost is large, the absolute improvement very small	90
Vachirasricirikul and Ngamroo (2014)	Is coordinated V2G control and conventional frequency controller for robust LFC in the smart grid with large wind farms feasible?	Simulation	The V2G power output can be controlled effectively considering the proposed optimized battery SOC deviation control. The PSO based on the fixed-structure mixed-control technique helps concurrently tune the LFC's PI control parameters. Simulation results demonstrate the robustness and coordinated-control effects of the proposed V2G control and LFC PI controllers against the changed system parameters and various operating conditions	111
Wang et al. (2013)	Can a multiobjective EV-charging planning method ensure charging service while reducing distribution-system power losses and voltage deviations?	Analysis, simulation	Optimal EV charging-station sizing and locating can be achieved to minimize the power losses and voltage deviations as well as EV travel distances	168
Jin et al. (2013)	How can EV charging be efficiently scheduled from an electricity-market perspective with joint consideration for the aggregator energy trading in the day-ahead and real-time markets?	Simulation	"It has been shown by extensive simulation results based on real electricity price and load data that compared to a baseline method without charging regulation, the aggregator's revenue can be improved by 80.1% using optimal charging scheduling and can be further improved by 7.8% with the aid of ES on average. The proposed heuristic algorithm yields close-to-optimal solutions. Moreover, we investigated how several key parameters (including the number of EVs, the number of ES units, the penalty factor, and the prediction accuracy) affect the performance of the proposed approach."	139

Table 6 (continued)

Citation	Research question	Research method	Research result	Citation count
Tushar et al. (2012)	Can the grid-to-vehicle energy exchange between a smart grid and EVGs be optimized using a noncooperative Stackelberg game?	Distributed algorithm, simulation	The proposed approach yields improved performance in terms of the average utility per EVG, compared to a particle-swarm optimization and an equal-distribution scheme	197
He et al. (2012)	Is a globally and locally optimal scheduling scheme for EV charging and discharging feasible?	Simulation	The independently developed distributed locally optimal scheduling scheme is not only scalable to a large EV population, but also resilient to dynamic EV arrivals. Such a scheme can achieve performance close to the globally optimal scheduling scheme	410
Su and Chow (2012b)	Can a suite of computational intelligence-based algorithms (distribution-estimation algorithm, particle-swarm optimization) for optimally manage a large number of PHEVs/EVs charging at a municipal parking station?	MATLAB simulation	The proposed energy-management program can handle the energy management at a large-scale PHEV/EV parking deck. By grouping the vehicle fleet, the proposed energy-management program has the potential to solve a larger energy-management problem with little additional cost	98
Su and Chow (2012a)	Can an algorithm for optimally managing a large number of PHEVs (e.g., 3,000) charging at a municipal parking station help solve the problem of a large number of PHEVs simultaneously connecting to the grid?	MATLAB simulation	The estimation of distribution algorithm (EDA) effectively solved energy management at a municipal PHEV/EV parking deck. Since an EDA explicitly extract global statistical information from promising solutions, it is immune to the potential local minimum and the nonlinear nature of the problem. The algorithm converged to a better solution than some of the more traditional methods	179
Wu et al. (2012)	Can a game-theoretic model help understand EV–aggregator interactions in a V2G market where EVs help frequency regulation on the grid?	Simulation	The proposed pricing model and design mechanism work well and can benefit both EVs (additional income) and the grid (frequency regulation)	249

Table 6 (continued)

Citation	Research question	Research method	Research result	Citation count
Pang et al. (2012)	What are the potential benefits of EVs and PHEVs as dynamically configurable dispersed energy storage acting in a vehicle-to-building operating mode? What are the implementation issues of DSM and OM in the smart distribution grid?	Case studies	"The use of BEVs/PHEVs battery as dispersed energy storage should meet requirements for the charging/discharging infrastructure leading to the practical data necessary for V2B operation. For demand side management, the peak load shifting strategy using BEVs/PHEVs can reduce on-peak load demand and energy consumption, which in turn will reduce the electricity purchase cost for the customer and vehicle owner. For outage management, the outage restoration for buildings using BEVs/PHEVs to generate power during faults in the main grid is envisioned by solving a optimization problem of merit-order scheduling of BEV/PHEVs under operating constraints."	127
Ota et al. (2012)	How can an autonomous distributed V2G control scheme help energy storage smooth their natural intermittency and ensure grid-wide frequency stability?	Simulation	The proposed V2G control is effective for a distributed spinning reserve without system-wide information exchange and without interfering in the conventional thermal power generation. The proposed smart charging control satisfies the scheduled charging by the vehicle user. The combined control scheme of the V2G and smart charging contribute to a move toward low carbon energy systems through the large-scale integration of intermittent renewable energy sources	241
Singh et al. (2012)	How can a city be modeled to demonstrate V2G capabilities such as meeting peak demand and voltage-sag reduction?	Simulation	"Simulation results reveal that charging and discharging of EVs can be easily controlled using an FLC. Power leveling and peak saving can be achieved by charging of EVs during off-peak hours and discharging the EVs energy during peak hours."	114

Table 6 (continued)

Citation	Research question	Research method	Research result	Citation count
Su et al. (2012)	What is the state of electrification of transportation in an industrial environment?	Literature review	Without sophisticated energy management at the charging infrastructure, large numbers of PHEVs and EVs have the potential to threaten the stability of the existing industrial system. Discussing the conceptual and practical knowledge of V2G allows for EVs to feed power back directly to the grid. In addition, V2G can allow easier integration of renewable resources and support grid stability through ancillary services. The successful rollout of EVs also relies on advanced communication technologies and industrial-informatics systems. This paper presents an overview of the appropriate information exchange architectures and framework to facilitate the effective integration of PHEVs and EVs	423
Boulanger et al. (2011)	Which areas must be addressed to achieve widespread adoption of vehicle electrification?	Systems approach	Policies that reduce the EV and PHEV total cost of ownership, compared to conventional internal-combustion-engine vehicles, will lead to faster market penetration. Greater access to charging infrastructure will also accelerate public adoption. Smart-grid technology will optimize the vehicle integration with the grid, allowing intelligent and efficient use of energy	248
Peterson et al. (2010)	What are potential economic implications of using vehicle batteries to store grid electricity generated at off-peak hours for off-vehicle use during peak hours?	Simulation, analysis	It appears unlikely that these profits alone will provide sufficient incentive to the vehicle owner to use the battery pack for electricity storage and later off-vehicle use	305

Table 7 Research themes

Research theme or question	Anchor-paper count	Percent (%)
How to adjust the reliability and adequacy of charging stations	5	11
How to increase the efficiency of plants or distribution for EV end use	5	11
How to optimize/analyze grid usage to EV needs	11	24
What are the impacts within EV applications concerning grid applications?	6	13
What are the impacts on EV applications of smart-grid implementation or vehicle to grid communication?	10	22
How to adjust the associated cost of EV use or implementation	7	16
What are the environmental changes due to EV or grid applications?	1	2

Table 8 Research methods

Research method	Anchor-paper count	Percent (%)
Modeling and simulation	27	60
Quantitative/analytical approach	17	38
Literature review and discussion	1	2

To enable more robust research on smart-grid–EV integration, we both plan our own research and invite other authors to submit original papers on topics including, but not limited to,

- EV battery charging optimization
- Mobility behavioral science
- Location analytics for EV integration
- Demand management and pricing for EVs in the electricity network
- Internet of things and sensors for EV integration
- Recent advancement in analytics for EV integration and microgrids
- Innovative charging strategies for EVs

As described in the previous section, this systematic literature review provides a solid foundation to equip researchers with pertinent information.

Conclusion

The intent of this paper is to present a systematic literature review of smart-grid–EV integration and offer a research framework to guide future research and enrich the body of knowledge. Because the systematic literature review presented in this paper focuses on two digital libraries and searches only article titles, it does not contain all the material available on this subject. It does, however, include most of the key publications readily available in a power-utility or technical-reference library together with some of the earlier papers in the field (the anchor papers).

To conduct a systematic literature review, we completed a broad automated search, a method that includes the selection of appropriate digital sources (digital libraries and indexing systems) and the determination of the search terms. We selected the digital libraries IEEE Xplore and Web of Science for the systematic review. This article also details the components of our research theme and its accompanying use cases.

This review is limited to the IEEE Xplore and Web of Science digital libraries to facilitate an automated search of the literature. This limitation is reasonable because these sources are most likely to be available in a power-utility or technical-reference library. However, a broader search may find other research not analyzed here. Additionally, the search was restricted to article titles to reveal those research projects most closely related to the topics of interest. A broader search of abstracts and full text would certainly find more articles, but would likely involve considerably more false positives.

Analytics using machine learning and big-data management could help the research community plan and improve smart-gid–EV integration. Based on the four types of key research concerns (power-grid, power-system, and smart-grid reliability and the impacts of changes on them), we intend to highlight the novel use of analytics to predict research themes in future research. The goal is to offer an enhanced viewpoint for smart-grid–EV integration while considering the impact and the potential benefits to the smart grid of such changes and EVs' integration.

Abbreviations

EV	Electric vehicle
PV	Photovoltaic
V2G	Vehicle to grid

Author contributions

VS and AA initiated the research project, conducted the broad automated search, selected the digital sources, determined the search terms, administered and led the analysis, reviewed the findings, and proofread/edited the final paper. HC and JK completed the literature review. All authors read and approved the final manuscript.

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Availability of data and materials

Additional supporting data is available from the first author.

Declarations

Ethical approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare that they have no competing interests.

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