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Review Article

A comprehensive review on coordinated charging of electric vehicles in distribution networks

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ABSTRACT

The active participation of electric vehicles (EVs) in both the transportation sector and energy systems is essential to curb the ever-increasing greenhouse gas emissions. EV sales grow yearly in most countries, which calls for efficient charging infrastructure. The large-scale penetration of EV fleets in power distribution networks exhibits an increasingly visible effect on legacy power systems. Coordinated charging of EVs in existing power systems provides an alternate way to considerable investments in power infrastructure upgradation. Therefore, this paper discusses state-of-the-art coordinated charging methods, energy management systems, and ancillary services for EV charging infrastructure. A brief survey of the current policies promoting EVs and charging infrastructure adopted worldwide is also presented. This paper critically reviews charging station architectures, scheduling techniques, tariff structures, aggregator requirements, and infrastructure designs regarding communication and control systems. Moreover, various advanced technologies enabling the active participation of EVs in coordinated charging are also explored in this paper. Finally, the paper summarises the findings in existing literature. It also identifies the related research challenges, making the research fraternity capable of exploring unidentified solutions for the coordinated charging of EVs in distribution networks.

1. Introduction

1.1. Motivation

The CO_2 equivalent emissions from the transport sector have grown at an annual average rate of 1.7 % from 1990 to 2022. The reliance on petroleum products for combustion in the transport sector may lead to economic and environmental concerns. The worldwide petroleum reserves have decreased, which has prompted governments, organizations, and researchers to switch to electric vehicles (EVs). A range of collaborative initiatives, such as the Accelerating to Zero coalition, Electric Vehicle Initiative, Production Linked Incentives, and Zero-Emission Medium- and Heavy-Duty Vehicles, has been adopted to reduce global emissions in the transport sector. These initiatives will help achieve the vision of Net Zero Emissions by 2050 through an annual reduction of CO_2 emissions from the transport sector by more than 3 % per year by 2030 [1]. The exceptionally high prices of petroleum products, government policies, and fiscal incentives will help to bolster EV sales by motivating prospective buyers. The global sales of EVs exceeded 10 million in 2022 with an international investment of USD 425 billion, estimated to reach 59.25 million in 2030, representing a 35 % year-on-year increase in new purchases [2]. A comparative analysis of internal combustion engine vehicles (ICEVs) and EVs is presented in Table I, regarding share in global sales, CO_2 equivalent life-cycle emissions, and rare earth mineral content.

Adopting large-scale EVs with solid sales growth will depend on the significant factor of developing charging infrastructure with continuous government support and private sector investments. A charging infrastructure with publicly accessible slow and fast chargers is a crucial enabler for EV adoption. The power ratings of slow chargers are less than or equal to 22 kW, whereas fast chargers have power ratings of more than 22 kW and up to 350 kW. A total of 2.7 million public chargers are available worldwide, of which 600 k slow public chargers and 330 k fast public chargers were installed in 2022 [2]. Integrating charging stations (CS) with the power grid brings technical and economic challenges for distribution network operators and researchers.

EVs act as an electric burden on the utility grid during charging. An unregulated and frequent charging technique might have undesirable consequences, such as increased power losses, voltage variations, line saturations, and transformers. This scenario may deteriorate if

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Table I
Comparative analysis of ICEVs vs. EVs [1].

Comparative parameter	ICEVs	EVs
Share in global sales by 2030 (%)	35	65
Amount of oil displaced by 2030 (barrels/day)	–	5 million
CO_2 equivalents avoided by 2030 (Mt)	–	700
Lifecycle GHG emissions (ton CO_2 eq./ vehicle lifetime)	41.9	11.9
Rare earth mineral content per vehicle (kg)	35	210
Well-to-wheel GHG emission (gram CO_2 eq./km)	202	83

Mt = metric tons; kg = kilogram; km = kilometer; eq. = equivalent; CO_2 = Carbon dioxide

unanticipated EV arrivals and their erratic charging requirements occur. Furthermore, erratic charging operations might cause power quality concerns on the user side. As a result, EVs and grid operators must coordinate their charging schedules efficiently [3]. According to the International Renewable Energy Agency, user incentives and smart charging are the two most important strategies for maximizing EVs' flexibility, which is essential for the imminent grid integration of EVs and RESs [4]. Due to the negative consequences of uncoordinated EV charging on power networks, smart charging may thus be essential in reducing undesirable effects on the grid. Coordinated charging can increase power grid operating performance and lower charging costs by considering a dynamic pricing policy [5]. Coordinate charging benefits user directly by lowering their charging costs as well as indirectly by minimizing distribution system losses [6], distribution networks (DNs) investment costs [7], peak shaving [8], transformer loss of life, and valley filling [9]. Renewable energy sources (RESs) are also employed to charge EVs and reduce the burden on the grid system [10]. Due to the variable generation characteristics of RESs, it becomes incredibly challenging to coordinate the charging of EVs with other grid loads and RESs [11]. Vehicle-to-grid (V2G) technology may also sell power back to the grid to sustain the grid's expanding demand. Several studies have been identified to maximize the V2G integration of RESs into the DNs and to certify an effective energy management strategy [12]. The coordinated charging of EVs through an intelligent charging mechanism results in the satisfaction of EV users and grid characteristics while choosing the numeral EVs and associated charging/discharging sites in each period [13].

In keeping with this, numerous recent research projects have examined the coordinated charging of EVs with DNs and RESs in the smart grid environment [14–16]. In [17], a comprehensive study on the effects of EV charging infrastructure on power system design and operation at both distribution and transmission levels is provided. Various fitness functions and optimization strategies have been suggested for the appropriate location of EVCS in DNs to improve power grid performance and solve budgetary restrictions and environmental challenges [18]. A review of coordinated and uncoordinated charging of EVs considering technical and ecological factors is highlighted in [19]. State of the art on charging standards, control techniques, and energy management strategies for EV charging have been discussed [20]. A deep investigation of the various types of EVs, their charging modes, charging methods, communication infrastructure, the interaction of EVs with smart grid, and the market policy of EVs has been reviewed in [21,22]. Renewable-based EV charging using advanced enable technologies such as network, shift, and on-site renewable charging has been reviewed in detail [23]. In [24], the author has presented various pros and cons of EVs charging with a power grid. The participation of aggregators in EV charging, EVCS integrated energy systems, challenges, and benefits of implementing innovative green CS considering the economic perspectives have been detailed [25]. A detailed discussion on energy management systems (EMS) in EV technology has been discussed in [26], which aims to reduce fuel consumption and include EMS classification and EV load management. A study on government incentives and social welfare with investments in EV charging infrastructure from an EV manufacturer's perspective is presented in [27]. A comprehensive explanation of advanced optimisation methods for the location and sizing of EVCS, as well as strategies for charging and control mechanisms, is presented in [28]. Machine learning (ML) approaches for EV infrastructure planning, such as charging demand prediction, charging station placement, and charging schedule, are surveyed in [29,30]. Different problems associated with the high penetration of EV charging connected to the power grid and an analysis of the various EV charging schedule techniques already in use are covered in [31]. V2X (X can be building, home, grid) is analyzed concerning control modes, power flow, types of charging systems, charging/discharging strategies, and the aggregator role has been convened [32]. A research study on the most recent advancements in coordinated EV charging, including the various methodologies and the participation of multiple stakeholders and aggregator levels [33].

Coordinated charging of EVs includes vast research areas such as EMS, control approaches, communication infrastructure, load management, dynamic pricing, etc. Table II compares coordinated approaches, which signifies that most review papers do not cover all coordinated charging strategies. It is evident that the existing literature only presented a piecemeal assessment of the methods and effects of EV charging on the power system infrastructure while lacking a comprehensive overview of the emerging technologies enabling coordinated EV charging and their applications in ancillary services. These research gaps have motivated us to systematically evaluate coordinated transportation electrification for DNs with state-of-the-art methods, supporting policies, and enabling technologies. Therefore, to close these research gaps, this paper critically reviews EV charging infrastructure, scheduling procedures, policies, standards, services, and enabling technologies.

1.2. Review methodology

This article explores various scientific journals, conference proceedings, news articles, magazines, and books to gain in-depth insights into the coordinated charging of large-scale EVs in power distribution networks. The primary data acquisition sources include IEEE Xplore, ScienceDirect, MDPI, Wiley Online Library, Springer Link, and Scopus. A combination of meticulously framed keywords, such as “Electric vehicle charging station infrastructure”, “Coordinated charging”, “Charge scheduling techniques”, “Optimization techniques”, “Loss minimization”, and “Profit maximization” [34–37]. A set of specific search filters is adopted to extract the most cited, widely applicable, and novel research papers published within the last 15 years for in-depth review. After applying search filters, the suitable research papers obtained from various interpretive sources are quantified and visualized, as shown in Fig. 1. The methodology used throughout the review process is illustrated in Fig. 2.

1.3. Key contributions

This paper provides a detailed study of the coordinated EV charging in the power distribution infrastructure while exploring various government policies and enabling technologies. The significant reforms in international and national policies that promote the public adoption of EVs in mainstream transportation are discussed briefly. Furthermore, conductive and inductive charging methods for EVs are presented with related grid integration and safety standards. Different architectures of EV charging stations with and without RESs are also discussed. A system-wide overview of various optimization- and rule-based energy management systems is summarized with advances in communication, control, dynamic pricing schemes, and aggregators. The state-of-the-art methods in EV charge scheduling are surveyed in detail for cost minimization, load variance minimization, and voltage and frequency regulation objectives. In addition, the potential advantages of coordinating the charging of EVs within the power distribution infrastructure are discussed from the transmission system operator, distribution system operator, and RESs operator points of view. Beyond this, the paper

Table II
Summary of research area related to coordinated charging.

Ref.	Year	Research area					
		EVs policy	EV charging infrastructure	EMS	EV charging scheduling	EVs services	Advanced enabling technologies
[10]	2014	×	✓	×	✓	✓	×
[12]	2018	✓	✓	×	✓	✓	×
[22]	2020	×	✓	✓	✓	✓	×
[24]	2020	×	✓	×	×	✓	×
[31]	2021	×	✓	×	✓	✓	×
[26]	2021	×	✓	✓	×	✓	×
[27]	2021	✓	✓	×	×	×	×
[20]	2022	×	✓	✓	✓	✓	×
[21]	2022	✓	✓	✓	✓	✓	×
[11]	2022	×	✓	×	✓	✓	×
[7]	2022	✓	✓	×	✓	×	×
[25]	2022	×	✓	✓	✓	✓	×
[19]	2023	×	✓	×	✓	✓	×
[23]	2023	×	✓	×	×	✓	×
[3]	2023	✓	✓	×	×	×	×
[17]	2023	✓	✓	×	✓	✓	×
[18]	2023	✓	✓	×	✓	✓	×
[28]	2023	✓	✓	×	✓	×	×
[33]	2023	×	×	×	✓	✓	×
This paper		✓	✓	✓	✓	✓	✓
✓ -Yes	× -No						

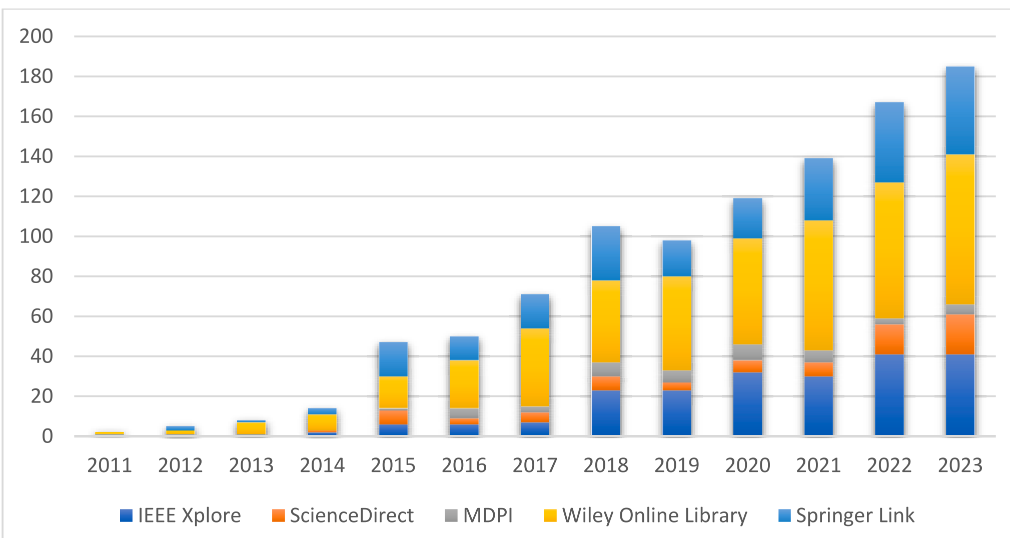

Fig. 1. Published research paper within the last 15 years.

explores the existing emerging technologies and the new-age techniques used for coordinated EV charging, focusing on the interests of multiple stakeholders in a smart city environment. Thus, the literature review presented in this paper addresses multiple research challenges for technical, economic, and environmental interests, providing a critical discourse on coordinated charging of EVs in the power distribution infrastructure.

The significant contributions of this paper are as follows:

1. Highlight various projects of national and international interests in EV charging management, including electric vehicle charging station infrastructure.

2. An overview of various energy management methods is discussed with enhancement in communication systems, control approaches, and dynamic pricing schemes.

3. Critical review of several strategies for coordinated charging of EVs based on objective functions and scheduling techniques.

4. Various services of coordinated EV charging in power distribution infrastructure are discussed from the multiple stakeholders' perspectives.

5. Address the applications of various enabling technologies for coordinated charging of EVs in a smart city environment.

The paper is organized as follows: Section 2 includes the charging scenario of EVs based on national and international policies and projects. Different types of CS, standards, and strategies of EV charging. Various coordinated charging strategies that provide ancillary services and optimal EV charging scheduling using different optimization techniques and control approaches are briefly discussed in Section 3. Section 4 discusses the enabling technologies that have recently been applied in the charging of EVs. Research challenges and future scope are presented in Section 5. The discussion part is highlighted in Section 6, followed by the conclusion in Section 7.

2. Current status of EV technologies

The global sales of EVs have increased exponentially from 1 % to 10 % from 2016 to 2022, the sales in developed countries will rise to 80 % in the upcoming six years, and by the end of 2030, EVs will lead global car sales [38]. The large-scale adoption of EVs will help achieve the

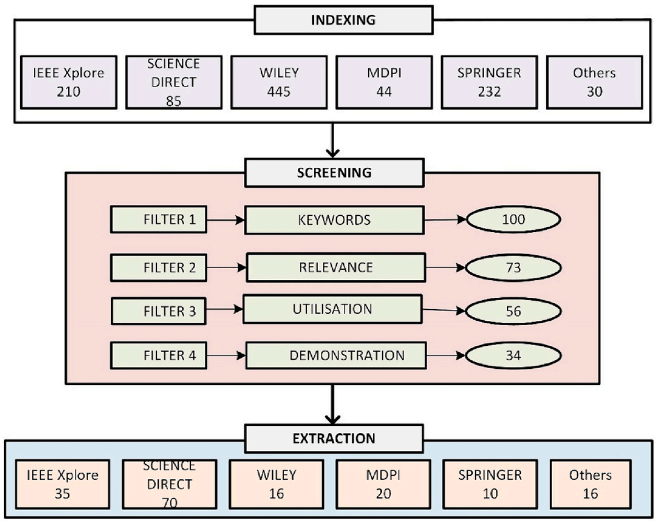

Fig. 2. Overview of review methodology.

vision of net zero emissions by 2050 and limit the global temperature rise to 1.5 °C. However, there are still some challenges for mass adoption of EVs due to high investment costs, range anxiety, poor charging infrastructure, battery disposal, limited life cycle of battery, operational losses, and heavy weight of battery [19]. These limitations could be overcome by introducing practicable policy reforms to encourage more purchases of EVs to drive sustainability and tackle climate change. Therefore, many governments have rolled out various policies related to infrastructure development, fiscal subsidies, and research for transportation electrification.

2.1. International policy

Over 20 countries, including Cabo Verde, Costa Rica, Sri Lanka, and more, have stopped selling automobiles with ICE entirely within the next 10 to 30 years [39]. In addition, more than 120 nations have committed to achieving economy-wide net-zero emissions in the next several decades [40]. Since 2014, the United States (US) has been the largest seller of EVs, followed by China, Norway, Netherlands, and France, but in 2015, China's EV sales increased by 38 % compared to 2014 [41,42]. China's growth has been in the works for years, with the government giving massive subsidies for EVs and other incentives and production-encouraging measures [43]. In 2016, China's consumers bought more EVs than the rest of the world and have not looked back since, and by 2021, it will account for more than half of all global EV sales. Different international countries announce various policies, which are shown in Table III. With the increase in EV markets, the adoption of EV chargers is proliferating. To address infrastructural difficulties, many governments all over the world are establishing incentives for the installation of EV chargers. The Biden industry unveiled a plan to build 500,000 public EV CSs in the US by 2030 [44]. The Chinese government revealed a goal of installing enough EV chargers in China for 2 million vehicles by 2025. In Tokyo, the Japanese government unveiled plans to have 150,000 public charging outlets nationwide by 2030 [45]. Table IV shows the target of adapting EVCS in various countries.

2.2. Indian scenario

Light EVs comprise two-wheelers (scooters, motorcycles) and three-wheelers, and they will have a significant role in India's electrification of transportation during the next ten years (both for passengers and for goods). Electric buses are already gaining popularity, and the government has also aggressively planned to raise electric cars to minimize vehicle pollution in the country's main cities. Electric buses and light-duty commercial vehicles are already on the market in the nation thanks to businesses like Mahindra & Mahindra Ltd., Olectra Greentech Ltd., and Tata Motors [47]. In the future, the market will develop because of the alluring incentives approved by the national government for producing and procuring EVs to promote their use. In 2019, just two EV models were available on the Indian market. As a result, only 0.15 % of BEVs were registered between April 2019 and March 2020. However, the Indian EV industry had eight models at the start of 2021, which gives Indian consumers more options to purchase EVs [48].

Additionally, the cost of EVs will reduce over the projection period, enabling EVs to offer a subordinate Total Cost of Ownership to conventional automobiles. Table V shows the policies adopted by the Indian government to increase the purchasing of EVs. Each state of India campaigns to grow the number of CS due to increased EVs. According to a statement from the power ministry, during the previous four months, government initiatives in Pune, Ahmedabad, Surat, Bengaluru, Delhi, Hyderabad, Kolkata, Chennai, and Mumbai resulted in a 2.5 times increase in CS [49]. The government campaigns to extend the coverage to other cities gradually; according to oil marketing companies, once the EV infrastructure in these megacities has reached saturation, 22,000 EVCSs will be installed nationwide on major routes and in renowned cities. 22,000 EVCSs will be initiated; 10,000 will be done by Indian Oil Corporation Limited, 7000 by Bharat Petroleum Corporation Ltd., and

Table III
Policies for increasing the purchase of EVs in different countries [42].

S. no.	Country	Policies and target	Year	Source
1.	China	By 2025, 20 % of vehicle sales in China must be ZEVs for the country's ZEV sector to compete internationally, according to the New Energy Automobile Sector Plan (2021–2035).	2021	China Society of Automotive Engineers
2.	Europe	With demanding ZEV deployment goals, the EU Sustainable and Smart Mobility Strategy and Action Plan is strengthened to reduce carbon emissions.	2020	EURO pollutants emissions standard.
3.	Japan	It is proposed that fuel efficiency rules, public EV purchases, the extension of the charging network, and significant investments in EV supply chains be reviewed.	2020	Ministry of Economy, Trade, and Industry
4.	California	They adopted the advanced Clean Truck Rule in 2020, which requires zero-emission truck sales as a percentage of total vehicle sales for each truck supplier, and the revolutionary Clean Transit Rule in 2018, which targets to sell all-electric buses by 2029.	2018 & 2020	District of Columbia
5.	New Zealand	Zero-emission public transit may be acquired beginning in 2025 to decarbonize the bus fleet for public transport by 2035.	2021	New Zealand Government
6.	Canada	The Infrastructure Growth Plan was introduced in October 2020, and its objectives include spending CAD 1.1 billion to buy 5000 zero-emission public buses and an additional CAD 2.75 billion over the next five years to electrify transit and school vehicles nationwide.	2020	Government of Canada

Table IV
Targets of installing EVCSs in international countries [46].

S. no.	Country	Targets	Year announced	Source
1	New Zealand	Every 75 km along state highway networks, fast/ rapid direct current CS are available nationally.	2017	Government of New Zealand
2	California	By 2025, 250,000 public CS must be developed	2018	Government of California
3	Egypt	42,000 public CS will be installed across governorates, with 3000 stations being constructed in the scheme's first phase.	2021	Government of Egypt
4	Indonesia	By 2030, there will be 67,000 battery exchange stations and 30,000 CSs.	2021	Government of Indonesia
5	Malaysia	By 2025, the goal is to have 9000 AC and 1000 DC CS	2021	Government of Malaysia
6	Canada	By 2030, the target is to develop 10,000 public CS	2021	Government of British Colombia
7	Australia	EVCS will be installed in more than 400 enterprises, 50,000 homes, and 1000 public fast CSs	2021	Government of Australia
8	Finland	Target to adopt one fast public charger for every 100 BEVs	2021	Government of Finland
9	Germany	By 2025, there will be 50,000 EVCS, of which 20,000 are fast chargers.	2021	Government of Germany

Table V
Policies adopted by the Indian Government to promote the purchasing of EVs [50].

S. no.	Policies	Year	Source
1.	FAMEI initiative encourages the progressive adoption of trustworthy, economical, and effective electric and hybrid vehicles.	2015	National Mission on Electric Mobility
2.	FAMEII gets budgetary support of ₹ 10,000 crores. It aims to provide incentives to various categories of vehicles.	2019	National Mission on Electric Mobility
3.	The Phased Manufacturing Programme was created based on the nation's present manufacturing environment to support electric car development and increase electric mobility.	2020	Ministry of Heavy Industries
4.	The National Mission on Revolutionary Mobility and Storage aims to advance efforts for revolutionary mobility and phased production plans for electric cars, their parts, and batteries.	2019	Niti Aayog

the remaining 5000 by Hindustan Petroleum Corporation Ltd. [2]. Table VI shows policies and measures taken by different states to raise the number of EVCSs in upcoming years.

Table VI
Policies and measures taken by the Indian state for EVCS [51].

S. no.	Measures and targets	Year	State
1.	Aim to have 100,000 slow and rapid CSs and 10 lakh EVs by 2024.	2018	Andhra Pradesh
2.	"Draft EV Policy 2022" aims to develop an extensive network of charging sites by facilitating the availability of power supply and related procedures and utilizing RESs for EV charging.	2022	Chandigarh
3.	By 2024, the Uttar Pradesh EV Policy 2019 seeks to install approximately 2 lakh stations to change between slow and fast charging.	2019	Uttar Pradesh
4.	Private Charging Points will be encouraged to be established in all current residential and non-residential building owners under the EV Policy 2020. According to the government, these CSs will give residents of cooperative housing developments and multi-story apartment buildings access to EV charging.	2020	Delhi
5.	The government intends to offer incentives and concessions under its EV Policy 2019 to promote investment in companies that produce EVs, EV charging infrastructure, and equipment.	2019	Tamil Nadu
6.	To put 2 lakh EVs on the roads in the ensuing four years, the EV Policy 2021 was announced. The State Government will exempt EVCSs from 100 % power duty for the length of this EV policy, and gas stations will be permitted to install CSs.	2021	Gujarat
7.	One of the goals for Maharashtra's EV policy for 2021 is to build a minimum of one giga factory AC battery in the state. Demand incentives offered for public and semi-public are among the policy's other features.	2021	Maharashtra

2.3. EVs charging infrastructure

2.3.1. Methods

Conductive Charging – Conductive charging, a widely adopted method in many countries, involves connecting EVs to a charging port using a cable. This standard cable allows EV users to charge their vehicles at home or public places through a dedicated CS. Conductive charging is of two types: onboard and off-board charging, as shown in Fig. 3. Onboard charging, used for slower charging, occurs entirely within the vehicle. In contrast, off-board charging enables faster charging by relocating the charger outside the EV. Notable EV models like the Nissan Leaf, Chevy Volt, and Tesla Roadster utilize conductive charging.

Inductive Charging- This is also known as Wireless charging (WC), which transfers energy without connecting conducting cables between a source and a load. This method can also be applied to charge the batteries of EVs, offering advantages such as simplicity, reliability, and user-friendliness. Two coils are used in a WC System to charge EVs and transmit power more efficiently. The grid's AC mains are first transformed into high-frequency (HF) AC using a rectifier and inverter. The receiving coil converts the oscillating magnetic flux fields into HF AC, generally positioned beneath the car. The onboard batteries of the EV are charged using a steady DC source created from this high-frequency AC. The system includes battery management, power control, and communication to ensure safe and constant operation. Magnetic planar ferrite plates are used at both sides, i.e., the transmitter and receiver, to minimize detrimental leakage flux and enhance the distribution of magnetic flux, further improving the efficiency and safety of the charging process. Static and dynamic wireless charging systems are the two ways to charge the battery pack of an EV, respectively.

2.3.2. Standards

Various EV charging standards are implemented internationally to focus on the requirements of EV charging infrastructure. The US adopts both IEEE and SAE standards, while Europe and Japan depend on a charging standard known as CHAdeMO. China's Standards Administration (SAC) utilizes GB/T standards, which closely resemble the IEC standard [42]. Table VII shows the different charging standard and their specification. Charging standards vary nationwide; the essential difference between these charging standards is the design of connectors or ports. Tesla created a connection that is compatible with AC and DC fast charging. Tesla has also created an adaptor for other car types, transforming SAE J1772 connections into Tesla connectors. Manufacturers of charging equipment are working to standardize the charging standards

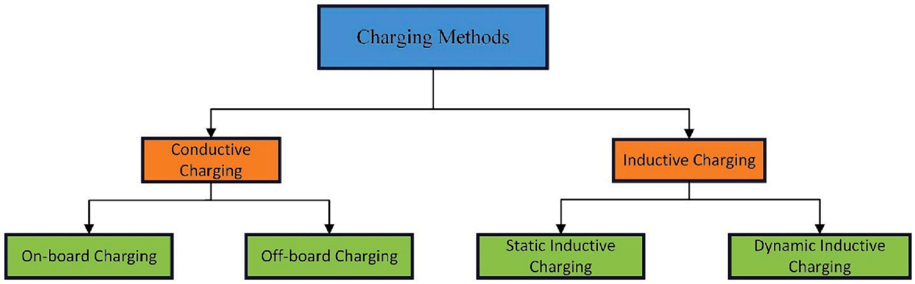

Fig. 3. Charging methods of EVs [52].

Table VII
Summary of EV charging standards [53].

Standards	Charging mode	Charge level	Charger location	Specification
SAEJ1772	AC Charging	Level 1 120 V	on-board charger 1 Φ supply from a household outlet	1.44–1.92 kW (12–20 A)
		Level 2 210–240 V	On-board charger 1 Φ supply from an EVSE	5–19.2 kW (24–80 A)
		Level 3 208–600 V	Off-board 3 Φ charging	30 kW–166 kW (63–160 A)
	DC Charging	Level 1 50–1000 V	Off-board charging	40 kW (80 A)
		Level 2 50–1000 V	Off-board charging	80 kW (200 A)
		Level 3 50–1000 V	Off-board charging	200 kW (400 A)
IEC 61851	AC Charging	Level 1 (120 V)	On-board 1 Φ	3.7–7 kW (16–32 A)
		Level 2 (240 V)	On-board 1 Φ /3 Φ	8–15 kW
		Level 3 (400 V)	On-board/off-board, 1 Φ and 3 Φ supply	3.7–7 kW (1 Φ) 11–43 kW (3 Φ) (16–63 A)
	DC Fast Charging	200–450 V	Off-board	400 kW (80–400 A)
CHAdeMo	DC Charging	500–1000 V	Off-board	62.5–400 kW (125–400 A)
CCS	DC Charging	1000 V	Off-board	360 kW (500 A)
GB/T 20234	AC Charging	250 V	Off-board 1 Φ	8 kW (10–32 A)
		440 V	Off-board 3 Φ	48 kW 16/32/63 A
	DC Charging	700–1000 V	Off-board	250 kW (80–250 A)

and develop a comprehensive EV charging device. The standards are just as crucial for integrating devices into the grid as the ports and connections. All these regulations must be followed to run the entire infrastructure, including the electric grid, CS, equipment, and EVs.

EV-integrated Grid Standards- IEEE1547, UL1741, NFPA, and NEC are standard grid integration codes. The installation of distributed energy resources (DERs) on DNs is highlighted in IEEE1547, which provides requirements pertinent to operation, performance, safety concerns, maintenance, and testing for interconnecting DERs. It covers all DER innovations with a combined capacity at the PCC of 10MVA or below. It is also called "Standards for interconnecting distributed resources with electric power systems" [41]. The standards for the power transfer equipment and protective devices necessary for the grid integration of DERs are included in UL1741. On the customer side of the PCC, NFPA70 specifies wiring procedures and safety. In addition to offering requirements for EV charging infrastructure, NEC is another industry standard that focuses on safety precautions for EVs. Fig. 4. shows different charging standards of EVs, grid, and electric safety and their application.

3. Coordinated charging of EVs

3.1. Architectures

EVCS architecture involves various categories such as charging level, CS, power flow direction, different topologies of grid integration, and charging method. Fig. 5. shows the classification of EVCS.

3.1.1. Charging levels

Due to variations in voltage and frequency around the globe, EVCS can be produced by each nation's specific grid requirements. Most Asian countries have supply voltage and frequency of 230 V and 50 Hz. However, various international countries have a voltage of 120 V with a frequency of 60 Hz per phase. It is generally of four types [54]: (i) Level 1, (ii) Level 2, (iii) DC charging, and (iv) Supercharging.

Level 1 charging (onboard charger) - One of the slowest AC charging methods, as it can deliver only up to 2.3 kW. The voltage and current for this charging are limited to 120 V and 15 A. It is generally used in countries with 60 Hz frequency. It takes 10–13 h to charge and is used in homes or offices. The advantage of this charging level is that it provides low off-peak demand charges.

Level 2 charging is a semi-fast AC charging technique with a supply voltage 240 V per phase with a maximum current of 80 A, and power ranges from 3 to 22 kW. This type of charging is prevalent in India and used for home and public charging. It takes 8 h to charge and is more energy efficient. It is costly and highly impacts peak demand compared to the Level 1 charger.

DC Charging is a fast-charging technique used in public CS, with an extreme power of 400 kW or more. The supply voltage and current range are exceptionally high, i.e., 500 V to 1500 V and 40 A to 400 A. It takes a maximum of 1 h to charge. The main drawbacks are that it is costly, requires extra safety, increases load peaks, and can cause difficulties in the operation of EVs in cold weather.

Supercharger – It is known as a Tesla supercharger since it is manufactured by Tesla. The charger can operate at 120 V, 240 V, 400 V, or high voltages. Output power ranges from 120 kW to 250 kW and charge

Fig. 4. Various EV charging standards and their applications.

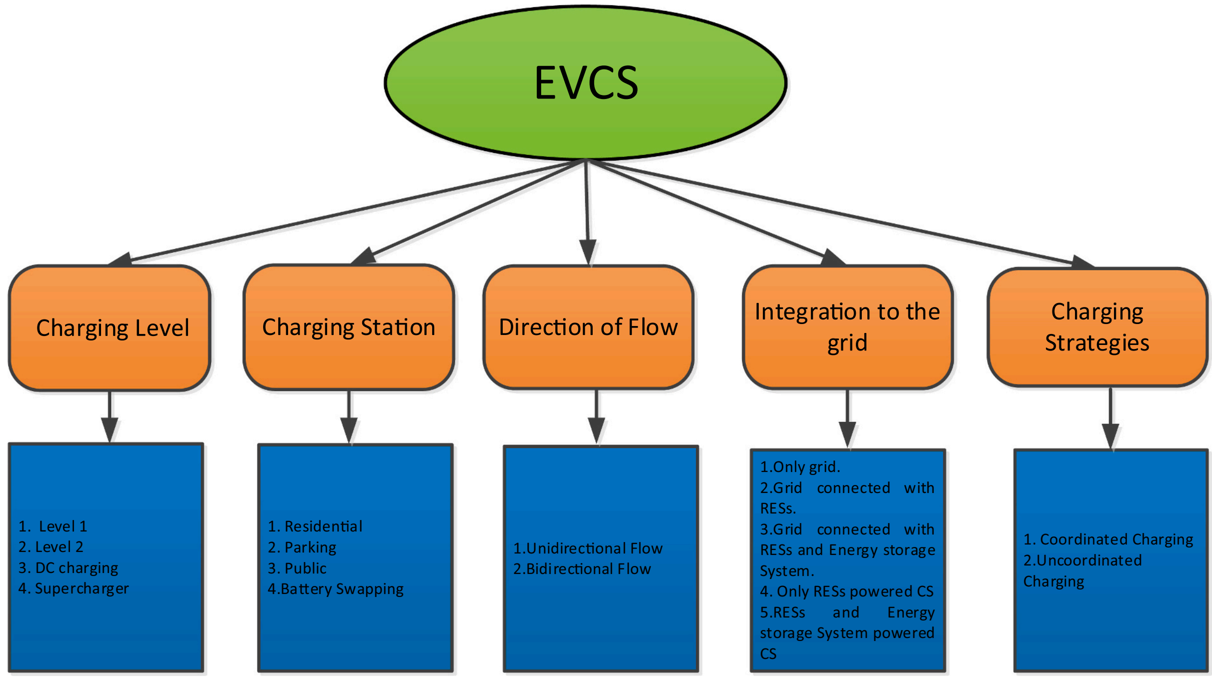

Fig. 5. Classification of EVCSs.

the EVs in 0.33 h. It depends on the battery's capacity and SoC at a specific charge level. It provides high-speed charging, although unique designs are the main drawbacks of Tesla EVs.

3.1.2. Types of CS

Most countries, including India, have a supply voltage of 230 V per phase with a 50 Hz frequency [55]. Different types of CS based on charging level are described as follows:

Residential CSs - It is popular among EV users who live in separate homes and apartment buildings and can access parking and charging spaces. It is also known as domestic charging, providing low voltage to EVs. Despite the modest charging capacity of residential charging systems, widespread research has been carried out on these systems to the advantage of market parties like customers, aggregators, and utilities. The ideal time to charge an EV, in terms of both cost and grid impact, is allegedly at night. The lower base load hours and lower cost per unit of power lessen the load on the grid. Level 1 charging is used to charge vehicles in 10 to 13 h [56].

Parking CSs - These types are generally located in parking areas. Most vehicles are parked in parking areas like workplaces, restaurants, shopping malls, libraries, etc., for 5–6 h; during this period, the load on a grid can be reduced by charging EVs at parking stations. Level 2 charging is generally used at this place for 7–8 h [57].

Public CSs - Public CSs have been established to enable fast charging for vehicles, as opposed to standard charging, which takes longer to charge a battery. Fast charging is done using various charging topologies and fast charger settings. The main components of a CS charger are an AC/DC converter and a DC-DC converter. Both converters are connected through a DC connection capacitor. This type of CS is generally located at airports, shopping complexes, and industrial areas.

Battery Swapping station -The mechanical switching of depleted batteries with fully charged batteries is another method for recharging the batteries that power EVs instead of charging them instantaneously. Although battery swapping stations provide an opportunity for grid support services, they also require a substantial and complex architecture compared with conventional charging infrastructure. Swapping stations may place a significant burden on the grid and require upgrading the power distribution infrastructure. However, these swapping stations combine the advantages of slow and fast charging by gently charging the EV batteries during off-peak hours and quickly refueling the EVs in a relatively short period.

3.1.3. Direction of power flow

Unidirectional power flow - An EV owner will use a unidirectional CS to charge the vehicle or offer grid stabilization services. In this type of charging, the energy can flow in only one direction, i.e., from the grid to the EVs [58].

Bidirectional power flow involves two charging modes, i.e., grid to vehicle (G2V) and V2G. In the peak load period, V2G mode is performed. During the valley period, G2V mode is considered so that the grid can maintain load balance and achieve flexible power control, relieving pressure brought on by load fluctuations and operating more profitably [58].

3.1.4. Configuration of EV charging infrastructure

EV charging infrastructure can be classified into various classes based on their interconnection with the grid, storage systems, and RESs. It is evident that RES-powered EVCSs are cost-effective but may compromise the reliability of the power supply. Various classes of configurations of EV charging infrastructure are given below.

Only grid-connected mode - Only the primary power grid is used to charge the EVs in this mode. However, the main drawback of this configuration is that it increases the burden on the power grid and causes various forms of power like load shedding, etc.

Grid and RESs connected charging - The utility grid and RES cooperate to share energy to provide the electrical energy in this configuration. Introducing RESs lowers the demand for EV charging on the primary power grid.

Grid-connected RESs, CS, and Energy storage system - This arrangement involves EVs charging by the grid and RESs. Still, the intermittent nature of RESs forces the battery source to provide backup for EVs. The prime persistence of this configuration is to reduce the grid burden.

Only RES-powered CSs - The stress on the grid and the environment is reduced when RE powers the EVCSs. When an EV is charged using clean energy, less carbon dioxide is emitted from the RE. E.g., Solar powered EV Charging.

RESs with Energy storage system powered CSs - RESs supply power to EV for charging and battery in this configuration. Developing energy storage devices stabilizes the intermittent nature of RESs.

3.1.5. Types of charging strategies

Uncoordinated Charging – In these charging techniques, a vehicle receives an instant charge after it is plugged in. By implementing the designated start delay, EV owners can charge their vehicles during off-peak hours. The distribution system may experience enormous strain as a result of uncoordinated charging activities, which could lead to [59]:

- Extreme voltage swings and violations,
- Reduced system economy and efficiency,
- Raising the risk of blackouts because of network overload.

Coordinated Charging - By effectively controlling EV charging demand, coordinated charging can enhance a utility's operational efficiency. It can also reduce charging costs by using dynamic pricing regulations. The goals of charge coordination are to increase grid efficiency, lessen power losses and voltage dips, and flatten the daily curve during charging hours without producing undesirable peaks. EV aggregators play a vital role in maintaining the proper coordination between the EV owner and grid operator. It involves various benefits such as peak shaving and valley filling and ensures the reliability of DNs. Depending on the level of research, charging strategies can be categorized as follows: 1) control of charging for a single EV; 2) control of charging for a group of EVs, such as EV aggregator and DNs research; and 3) control of charging for EVs in regional power systems.

3.2. Energy management

A power generation system comprises interconnected subsystems necessary for safe and effective operation to achieve specific objectives. A control system is employed to oversee and synchronize the entire system's operation efficiently. An effective energy management system (EMS) permits the power generation scheme to optimally distribute power among its various components, resulting in extended lifespan, reduced operational costs, enhanced system performance, improved fuel economy, and decreased CO_2 emissions. EMS is categorized into i) optimization-based control approach and ii) rule-based control, as shown in Fig. 6. Optimisation-based EMS includes fundamental and global-based optimization techniques. Rule-based strategy is more practical since it often uses a straightforward problem-solving approach rather than trusting a time-consuming mathematical solution. The intelligent charging strategy must usually respond to the most recent conditions using simple rational concepts, such as stopping charging when the costs and load are high [60]. The rule-based control method is

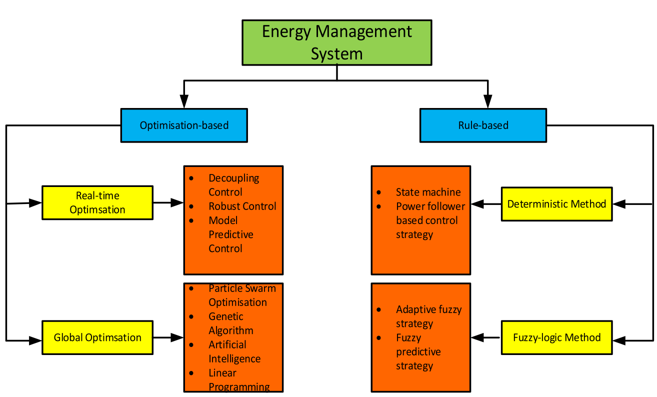

Fig. 6. Overview of energy management system.

categorized into deterministic and fuzzy-based methods. This control strategy can significantly improve calculation accuracy, reduce the computation challenge, and achieve a high-quality optimal [21]. Numerous writers have used metaheuristic algorithms, also known as high supervisory control (rule-based) algorithms, in their investigations.

The control and communication frameworks are crucial for the instantaneous monitoring of EV charging. EV charging increases the total load demand on the grid system; efficient scheduling and coordination of EVCS with the grid, along with the use of control and communication infrastructure, can assist in reducing the demand for charging and decreasing charging costs.

3.2.1. Communications

An efficient communication scheme is necessary among EVs, EVCS, and the power grid to enable efficient management of EV charging. Data transmission between utility companies and consumers is possible using two leading technologies: wired and wireless communication, as shown in Fig. 7. Private networks like Home Area Networks, Neighbourhood Area Networks, Building Area Networks, Industrial Area Networks, and Field Area Networks are utilized to integrate EVs into the grid [61,62]. Wired technologies like Power Line Carrier Communication (PLCC) [63], which transmit data over power lines, are used for long-distance communication. The strength of this protocol lies in its dependability and resistance to interference. Various protocols utilize the PLC concept, including HomePlug turbo, HomePlug 1.0, HD-PLC, UPA, and HomePlug AV [64].

Additionally, wired communication includes Optical and Digital Subscriber Line (DSL) protocols. Optical communication offers substantially higher data rates and a much greater transmission range than PLC [61]. It also displays resilience against electromagnetic interference, making it suitable for data transfer over high-voltage lines. DSL protocol permits digital communication over telephone lines without requiring a separate infrastructure setup. Wireless communication is essential to establish a comprehensive communication structure, particularly for exchanging data between vehicles and CSs. This wireless network efficiently connects electrical components by utilizing LAN strategies arranged in a hierarchical mesh configuration. Notable wireless communication technologies for EV grid connection encompass cellular networks, WIFI, Zigbee, satellite networks, and WiMAX [64]. Wireless communication is pivotal in conveying charging status information to EV users, serving as a primary means to deliver such data.

3.2.2. Control approaches

Uncoordinated charging harms the grid by causing sudden peak load demand, significant voltage fluctuation, increased power loss, network overloading, grid enhancement, and costly charging operations. Coordinated charging improves the operational performance of the utility by smartly coordinating EV load demand and minimizes the charging cost. As depicted in Fig. 8, two approaches are exploited to regulate the power transfer between the CSs and grid in a smart grid environment.: i) centralized control and ii) decentralized control.

i) Centralized Control – In this control arrangement, a central entity oversees the charging of diverse EVs, referred to as an aggregator. The aggregator centrally gathers information from the EVs and offers a universally optimum solution that adheres to grid and user limitations. This form of charging control is termed as direct control charging architecture. Nonetheless, a notable drawback of utilizing this control arrangement is its dependency on numerous prerequisites for load scheduling, leading to reduced flexibility. Centralized methods necessitate EV users to convey comprehensive charging requirements and technical details of EVs to the central controller. It could potentially result in practical challenges such as communication hindrances, restrictions in bandwidth, and the need for substantial enhancements to the infrastructure to accommodate the significant surge of data due to the rapid adoption of EVs [65]. As

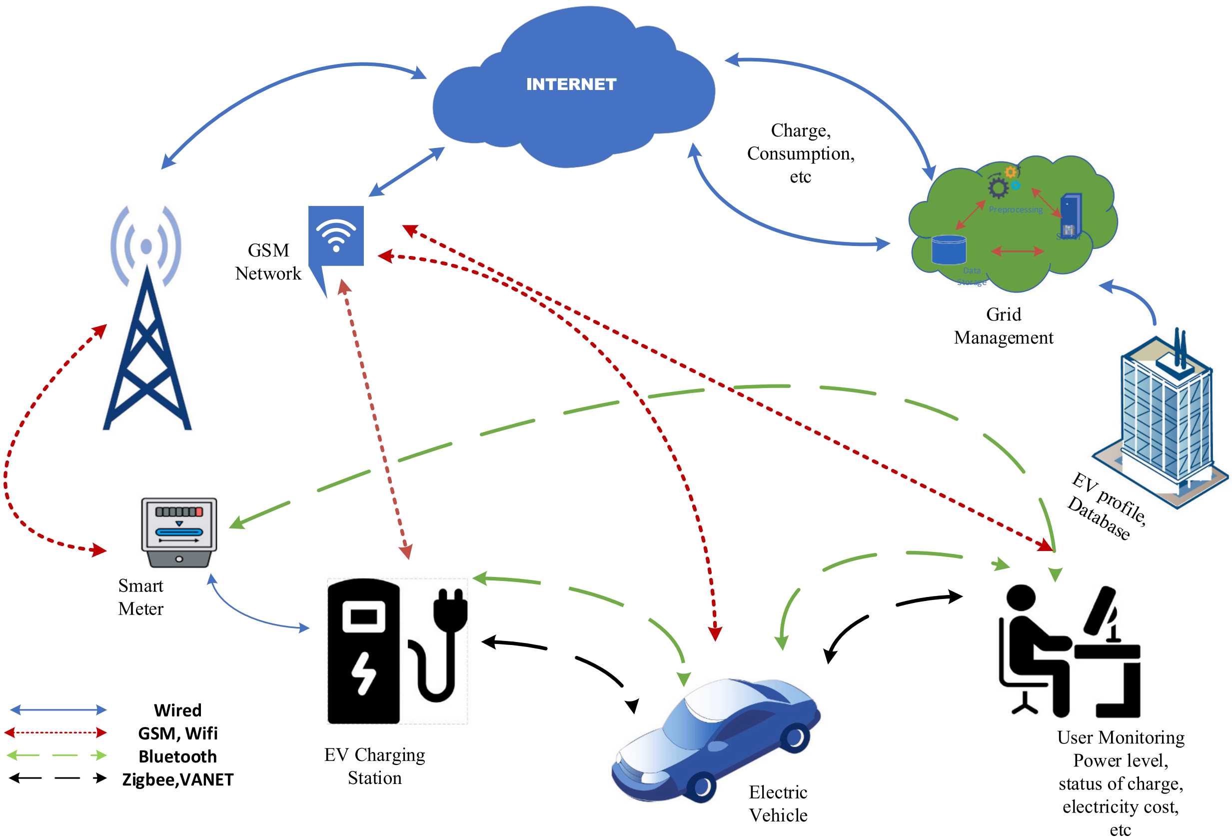

Fig. 7. Communication system of EV charging.

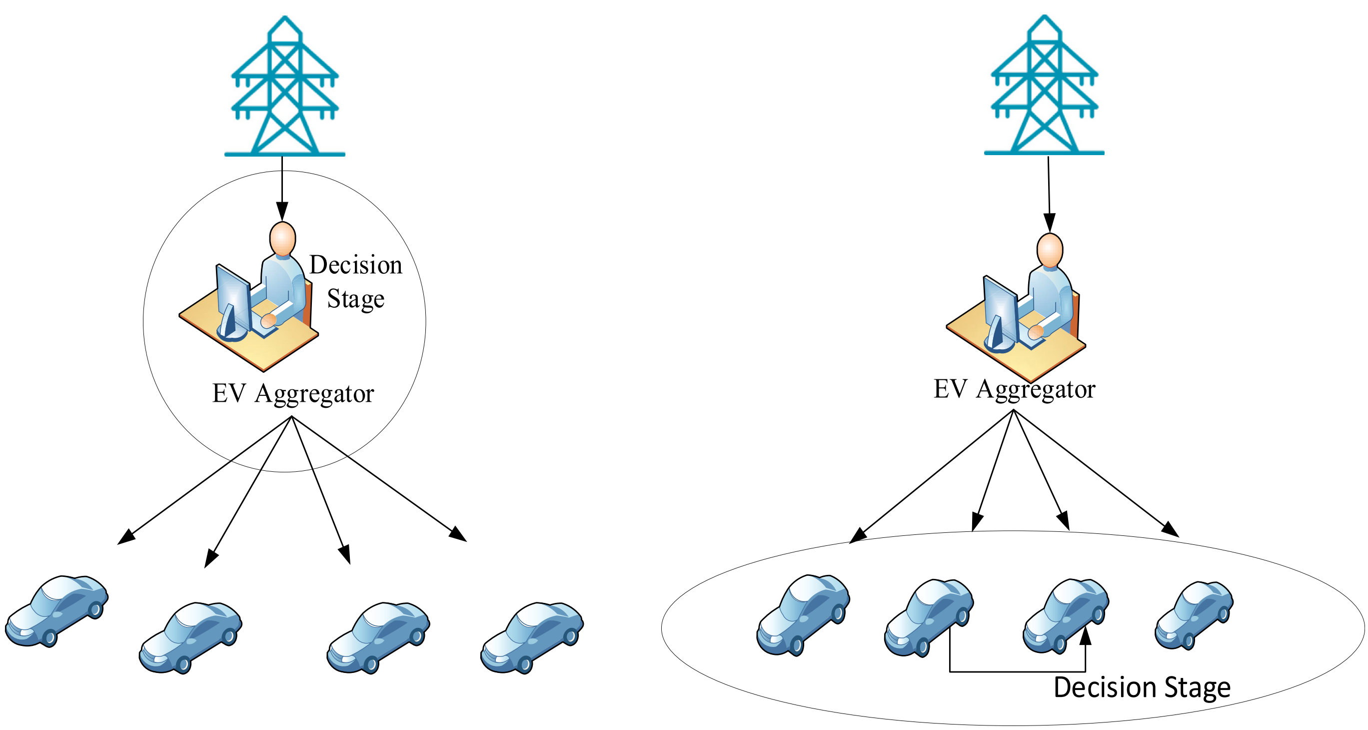

Fig. 8. Centralized and decentralized architecture of EVs.

a result, centralized approaches might experience diminished efficiency and impracticality as the grid-connected EV numbers increase significantly.

ii) Decentralized Control - Within a decentralized charging control framework, the authority to make decisions regarding EV charging is dispersed among individual EV owners. While this approach empowers customers to determine their charging choices, it does not necessarily ensure an ideal solution for the distribution network. This is because aggregators lack direct control over charging activities. Their influence alters customers' charging behaviour by providing enticing incentives through dynamic electricity pricing models. This approach diminishes the need for an extensive communication infrastructure. Notably, decentralized charging strategies exhibit greater robustness against network outages, especially when controllers are engineered to function even in centralized communication breakdown [61].

3.2.3. Load profiles

A load profile must be predicted for a certain degree of EV penetration to evaluate the impact of EV charging on DNs. Without controlling the load demand, the simultaneous charging of several EVs may negatively impact the grid, including harmonics, equipment overload, increased energy loss, voltage drops, and imbalanced load. EVs and electric grids are two fundamental factors that determine the intensity of the impact. The EV variables include the number of EVs, charging levels, plug-in duration, and the batteries' residual SoC. Grid variables include equipment ratings for the power system, phase balance, and the design of the electric power supply.

A V2G concept is introduced to control supply and demand between grid and vehicle. V2G helps to reduce peak demand and increases the reliability of the system. The significant occurrence of network capacity violations resulting from EV penetration exceeding 40 % has been attributed to low voltage network congestion. Additionally, incorporating EVs at various charging levels results in a 38 % load increase in the winter season's night peak load demand [66]. Integrating EVs into the power grid might also delay investments in grid capacity growth and alter the power supply cost. Using EV load management, switching the load from peak hours to off-peak hours may be possible to improve the load factor.

3.2.4. Dynamic tariff structure

Most traditional tariff systems are based on stationary pricing agreements, meaning prices do not change in response to changes in energy demand. In contrast, current tariff plans use dynamic pricing policies, employing that prices move in response to demand. From the consumer's perspective, dynamic pricing provides many advantages, such as giving each customer the option and chance to reduce their power cost by utilizing their preferred pricing scheme or demand-side management techniques. There are several dynamic tariff schemes, such as real-time price (RTP), time of use (ToU), peak time pricing (PTP), and peak time rebate (PTR), which are shown in Fig. 9 [67].

The peak and valley load curves during on-peak hours may diverge more due to the increased penetration of EVs. Power usage during peak hours might rise by up to 5 % due to uncoordinated EV charging. Dynamic pricing rules may reduce peak load issues with unpredictable price changes [68]. The key benefit of dynamic pricing for EV charging is that it enables users to provide more flexibility or to use their flexibility to some extent to control their behaviour to achieve various benefits, such as improving the reliability of the power grid, decreasing the operating costs of CSs, and raising user satisfaction. As a result, dynamic EV charging pricing has recently caught the attention of several academics.

i). RTP - It is described as a rate constantly changing, allowing prices to reflect real-time structure by changing often, at intervals of an hour or less. EVCSs typically offer flat rate charging, which causes CS to experience a traffic rush. Long lines will be reduced if the load on the CS constantly adjusts pricing. RTP will encourage EV owners to choose remote charging, which is less expensive and busy.

ii). ToU- ToU provides customers with various power tariffs for multiple periods throughout the day. Full-peak, mid-peak, and off-peak are typically three periods on which the ToU is based regarding load. Electricity supply capacity exceeds demand

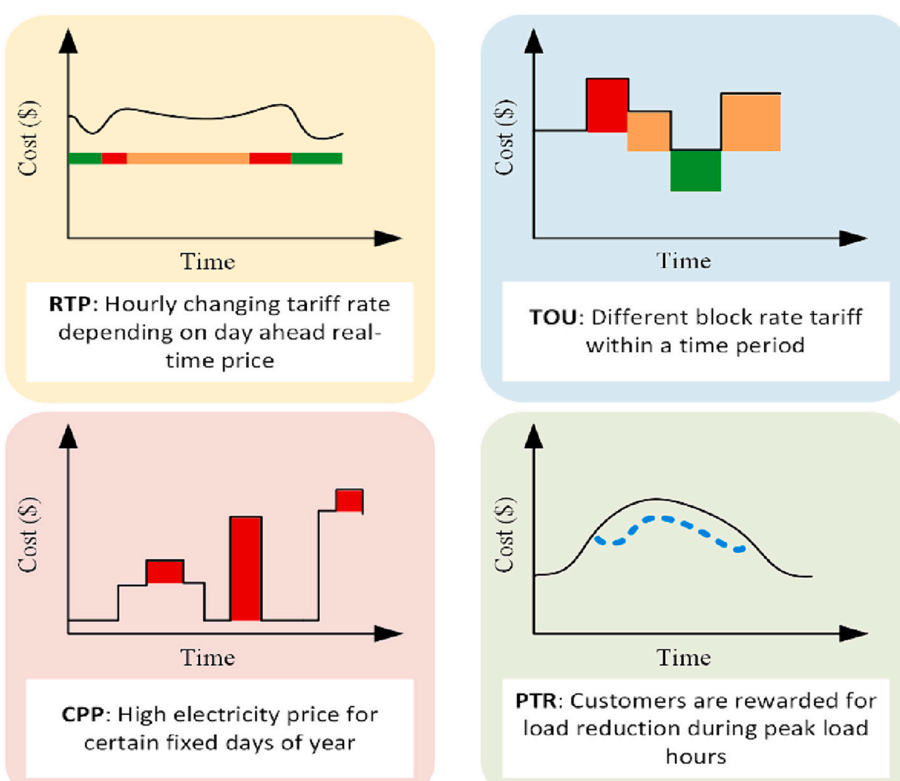

Fig. 9. Different power price plans are represented by tariffs.

during the off-peak time, which lowers the cost of a ToU. Mid-peak pricing is possible because capacity and demand are well matched, and demand for electricity rises dramatically during peak hours. The advantages of this pricing system include EV route optimization, cost reduction, and battery optimization [69]. One of the additional benefits of ToU is the transfer of EV demand from peak to off-peak hours. Concerningly, the demand and capacity equity of the current grid system are negatively impacted by the considerable growth in the large intermittent EV charging load.

iii). PTP- PTP is a price-based DR program that can entice consumers to cut back on or reroute their load during crucial peak periods and lessen the strain on the power grid [70]. PTP encourages the consumers to avoid the critical peak hours better than ToU.

iv). PTR- Customers who use less power during peak hours than a predetermined limit are given refunds under this pricing structure [67]. Utility companies in the first three of these systems cost more in peak times than they pay during non-peak times, but in PTR, customers are rewarded for lowering use during peak hours.

3.2.5. Aggregators

"EV aggregator" refers to a central coordinator overseeing distributed EVs' battery SoC level. EV aggregators participate in the marketplaces for ancillary services, especially during high-demand hours, to maximize their profit. EV aggregators serve as intermediaries between the power grid and EVs. They collect essential information from EV drivers, including charging power requirements and correlation schedules via smart meters and then transmit this dataset to the DNs operators. Additionally, the EV aggregators possess data on electricity prices and CS locations, which is provided to the EV owners. Choosing the most suitable aggregator becomes advantageous for an EV owner when multiple aggregators coexist [71].

Along with benefiting the power infrastructure and end customers, aggregators can also benefit from the business of aggregating energy. The aggregator installs necessary technology, such as communication, measurement, and control systems. To provide auxiliary services for DNs, the aggregator exercises control over various distributed producing resources or flexible loads through participation in the day-ahead and intraday electricity markets following the appropriate energy bidding. The aggregators collaborate with the DSO to forecast power demand behaviour and establish buy/sell prices to prepare for the following day. An EV aggregator must overcome several obstacles, such as the minimum SoC standard for EVs, the dependability of the power supply, the unpredictability of electricity market prices, the availability of reserve and regulation power for EVs, etc., while maintaining the level of satisfaction of EV owners [72]. An EV aggregator pursues two distinct objectives in the broad market and the client-side retail sector [73]. They also compete with other demand-side market participants in the wholesale market to make the best power purchases and secure ancillary services. A general architecture for aggregators is illustrated in Fig. 10.

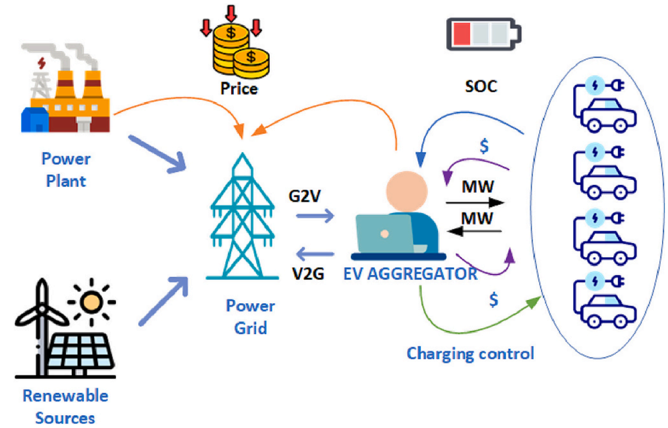

Fig. 10. EV aggregator's participation in EV charging.

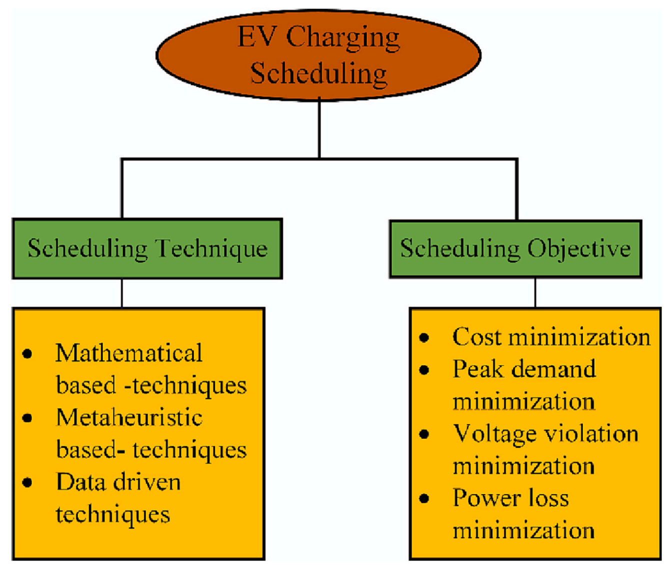

Fig. 11. EV scheduling techniques.

3.3. EV charging scheduling

3.3.1. Scheduling techniques

A charging schedule optimization is required to increase the grid, aggregator, and EV's effectiveness. The scheduling techniques and objectives are explained in Fig. 11. The scheduling challenge for EV charging has numerous objectives, including reducing electricity prices, network power loss, voltage violations, and distribution transformer overloading [74]. Different optimization methods are used to accomplish one or more goals while improving the charging process for EVs. Several techniques are exercised to unravel the objective hindrance associated with EV charging. Table VIII briefly discusses optimization methods used to solve different objective functions in various literatures.

Mathematical based-techniques- Different mathematical techniques, such as quadratic programming (QP), linear programming (LP), mixed integer linear programming (MILP), mixed integer non-linear programming (MINLP), dynamic programming (DP), convex, non-convex, and stochastic programming, are employed to achieve different objectives, such as outage management schemes, incongruity issues between production and consumption of electricity, energy trade between aggregator and CS, annual profit maximization of EV parking lot owner, and so on all are the objective functions which can be solved mathematically [75–77]. The LP technique was applied to maintain the load curve between a parking lot and a neighbouring development with limitations on the power flow [78]. Active and reactive power flows and the current and voltage magnitude were built linearly in a study to employ a MILP. A non-linear programming (NLP) method known as quadratic programming (QP) uses a goal function that can be both linear and quadratic. A QP problem was more accessible than other NLP problems because of the function's convexity and linear limitations. Considering grid and EV battery characteristics, the QP method minimized grid losses for residential distribution [79].

Metaheuristic-based techniques- Simplicity and flexibility are two peculiar factors that have made metaheuristic optimization extremely popular for tackling engineering challenges. This method solves complex computational problems with endurable efficacy. Since it does not depend on the nature of the issue being solved, it can move between many local optima because of their high degree of abstraction. It

Table VIII
Literature survey on various optimization methods.

Ref. no.	Optimisation method	Objective
[78,84–89]	Binary particle swarm and grey wolf optimization, Gorilla troop optimizer, Capuchin search algorithm, Harris hawk's optimization, GA, Chicken swarm optimization, Teaching-learning-based optimization	minimizing power loss, voltage variation
[66,82,90–92] [76,93,94]	PSO, Most valued player algorithm, Opposition-based competitive swarm optimization, convex mathematical modeling, hybrid model on the gravitational search and PSO, LP, Fuzzy logic, QP	To minimize peak load, load variance, and peak-valley difference
[95–101]	Artificial neural network, MILP, Dynamic programming (DP), Monte Carlo simulation, Honey Badger Algorithm (HBA), GA, PSO	Minimizes cost
[77,99,102–106]	MILP, Multi-objective PSO, Mixed integer programming, HBA, Ant colony, advanced and adaptive tabu search, Shuffled Frog Leaping Algorithm	Maximize profit for Parking lot owner.
[107–111]	Fuzzy logic, MILP, Deep reinforcement learning, LP, PSO	Frequency regulation of grid

generally involves nature-inspired and physics-inspired and is based on two concepts: evolution theory and swarm-based intelligence. Common examples of these techniques are particle swarm optimization (PSO), genetic algorithm (GA), harmony search, ant bee colony (ABC) [80], and many more. The GA employs crossings, mutations, and selection equivalents to solve optimization problems. Intelligent charging utilizing GA was to decrease the net-load variation of a region with RES-generating constraints [81]. The PSO approach was used to reduce load fluctuation caused by power flow limitations, boost PV self-consumption, reduce grid impacts, and minimize power losses. In contrast, the SoC and power flow constraints of batteries were used in EVs [82].

Data-driven techniques- With the advent of big data analytics and ML, which have modernized natural language processing, picture, audio, and video identification disciplines, the usual tendency has shifted to data-driven ways to address the EV charging issue. ML algorithms may be qualified and taught to recognize patterns in past data on charging load and user activity. Accurate forecasts can be produced after the training process. When used to improve EV charging scheduling tactics, such predictions can be used separately or in concert with other algorithms. A data-driven approach relies more on complex data and facts than intuition. Making judgments with objectivity is more straightforward when using a data-driven strategy. While optimizing EV charging, trip-based data, population-based data, and cost data are considered [83]. This technology generally uses AI-based technology to predict and analyze the data and perform EV scheduling further. Various data-driven approaches for charging demand for EV prediction and scheduling are discussed in Section 4 in detail.

3.3.2. Scheduling objectives

The primary concern of the grid operator lies in maintaining the operational efficiency of the grid infrastructure, whereas EV customers are mainly concerned about getting the desired SoC on departure. The optimization objective is generally considered for all multiple stakeholders that participate in EV charging, which can be single or multi-objective, such as reducing charging costs, minimizing power loss, maintaining voltage, reducing peak loads, optimizing EV routes, and mitigating line, grid, and transformer overloading [67]. Certain constraints are also required to optimize the objective function. A detailed description of various objective functions is discussed in this section.

- Power loss minimization- Power loss in the DNs occurs due to the high penetration of EVs into the grid, which increases the actual charging demand. Power loss might increase by up to 40 % during off-peak hours, given that 60 % of vehicles linked to the distribution system are EVs [112]. Charging coordination can lower power losses while raising the grid load factor. Power loss in the system may be decreased with the proper placement and number of CSs.
- Voltage regulation- The power quality for customers on the same network may be negatively impacted by the significant deviation of uncoordinated EV charging from the system voltage profile. The utilities seek to offer their customers top-notch service. An ideal charging technique may provide utilities with voltage management to ensure smooth operation; as a result, it is thought of as a crucial goal function in EV charging schedules.
- Cost minimization- Only dynamic tariffs, where the electricity price is time-varying and represents the most recent marginal supply prices, can reduce charging costs. After implementing advanced metering equipment, future smart grids will bill consumers with real-time pricing. Real-time pricing has significantly impacted consumer behaviour and overall network management in DNs. Real-time pricing and charging-cost reduction challenges may be resolved using LP, QP, and convex optimization [113].
- Load minimization- The power grid must lower its peak power demand levels caused by the load of EVs. Peak load reduction requires EV charging to be coordinated with dynamic pricing. Peak load demand of EVs causes peak shaving and valley filling. Hence, load minimization is the crucial objective function to flatten the load curve.
- Frequency Regulation – Charging fewer EVs for a short span does not affect power fluctuations between the grid and EVs. But, charging EVs on a large scale can lead to a change in frequency. Thus, EVs require frequency regulators, which means that the charging load of EVs is of great significance to the frequency regulation of the grid. Various optimization techniques have been employed to maintain frequency, such as the stochastic dynamic method, stochastic optimization, and fuzzy method [107,114,115].

3.4. EV services

Various studies have emphasized the compelling issues of integrating EVs into DNs. High penetration of EVs has negative impacts, such as increases in load demand, energy loss, overload, voltage dips, and deterioration in service quality. EVs are loads for the DNs, but they may also present new opportunities for the grid. It can help the grid by offering a variety of local and international power and energy-based services because of the controllable nature of their loads. Fig. 12. shows the overview of the services provided by EVs in distribution and transmission systems.

3.4.1. Distribution system oriented-services

With the increasing responsibilities of DSOs in the smart grid context, a new paradigm for thinking about auxiliary services for the DSOs has been evolving. It looks to be a collection of adaptable services that may be offered to address the operational issues. In addition to preventing grid malfunctions, distribution system services make the grid work more efficiently by managing load. The prime source of profits for DSOs is active power, which has grown to be a significant problem for distribution networks. However, operational and technical concerns might occur if active and reactive power is not adequately regulated, as well as operational and technical concerns, including overloading, over/undervoltage, and power loss.

Consequently, effective power control is necessary to maximize DSO

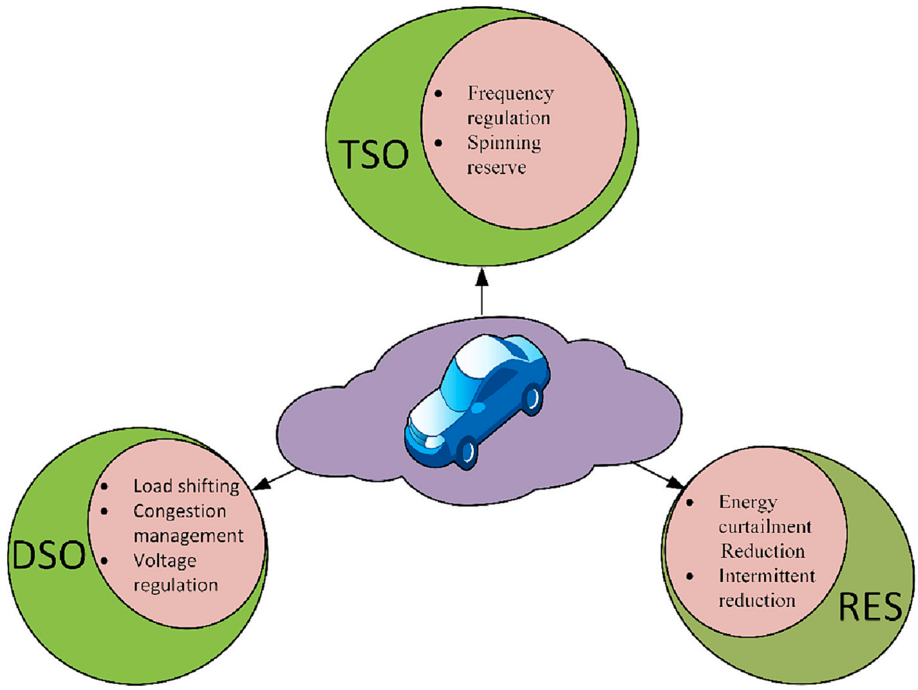

Fig. 12. Overview of EV services.

profits while preserving system fidelity. DSOs provide smart charging by coordinating with EV charging owners to optimize charging times, align with low-demand periods, and minimize grid impact [116]. DSOs also offer dynamic pricing and tariffs to encourage EV owners to charge EVs during lower grid demand periods to promote the efficient use of electricity. In significant EV adoption, distribution-oriented services centre on effectively planning to charge infrastructure, managing loads, regulating voltage, strengthening the grid, implementing intelligent charging, and incorporating EVs as integral grid components. These services guarantee a dependable, steady, and environmentally sustainable transition to increased EV usage in transportation [117].

3.4.2. *Transmission system oriented-services*

The extensive adoption of EVs can have diverse effects on transmission lines, including heightened demand and voltage variations, as well as the requirement for grid enhancements and enhanced operational approaches [118]. Transmission operators must undertake anticipatory planning, optimize the grid, and foster cooperation with energy sector stakeholders to tackle these consequences. Transmission-oriented services generally include frequency regulation, spinning reserve, load balancing, and grid management [119]. High penetration of EVs on the grid causes a frequent change in the load that affects the grid frequency and voltage stability. The transmission system operator (TSO) uses advanced metering to observe the charging pattern of EVs and its effect on grid parameters. TSO also performs load management strategies to prevent overloading on transmission lines during on-peak periods. Transmission lines and substations might encounter congestion caused by many EVs being charged. This congestion can potentially dislocate the continuous flow of electricity and could result in inadequacies in power distribution. To solve these issues, TSO performs various functions such as cross-border coordination, capacity allocation, dispatching, congestion forecasting, and countertrading congestion [120,121]. Due to the increased use of EVs, adding spinning reserve to transmission-oriented services helps TSOs ensure grid stability, prevent excessive loads, and maintain a consistent power supply. This method offers a flexible and adaptive alternative to deal with the difficulties brought on by EV charging requirements' changing and dynamic nature.

3.4.3. *Renewable energy services*

The primary service highlighted in the literature addresses EVs' advantages for facilitating RES integration into the grid. As the penetration of RE sources continuously increases, RES-based CS must be built on a large scale to expurgate extra expenditure and improve the existing DNs [122]. Using RES-based EV charging provides financial benefits in the long run by eliminating the operational costs associated with typical fossil fuel-based energy sources. Additionally, EVs may serve as storage systems to meet demand when there is insufficient RES power supply to mitigate the issue of renewable intermittency. Austin Energy, EVgo, and Charge Forward are some of the schemes adopted by governments of different nations to promote RES-based Charging stations [123]. In [124], a control approach for charging/discharging EVs has been anticipated to reduce the effects of overvoltage, peak load, and PV power curtailments. Considering grid constraints and EV user needs into account, the primary goal is to optimize PV system engagement in auxiliary facilities through the utilization of EV storage. A shift charging strategy is developed in [8] to encourage EV charging when RE generation is high. With this strategy, services only charge consumers 100 % renewable energy without incurring extra costs.

4. Enabling technologies

Conventional charging methods have certain drawbacks, i.e., lack of communication, participation of different agents, load management, and transaction security. However, in the present era, charging technology can become more secure and reliable due to the participation of various platforms. Fig. 13 shows advanced EV charging infrastructure. A literature review on advanced technology employed in the present or future is discussed in Table IX.

4.1. *Artificial intelligence*

Artificial intelligence (AI) can analyze vast volumes of data, recognize trends, and make quick decisions, allowing it to speed up and optimize the EV charging process. AI will play a more significant part in certifying that charging infrastructure satisfies user expectations and the needs of the energy grid as EV usage continues to rise. AI generally

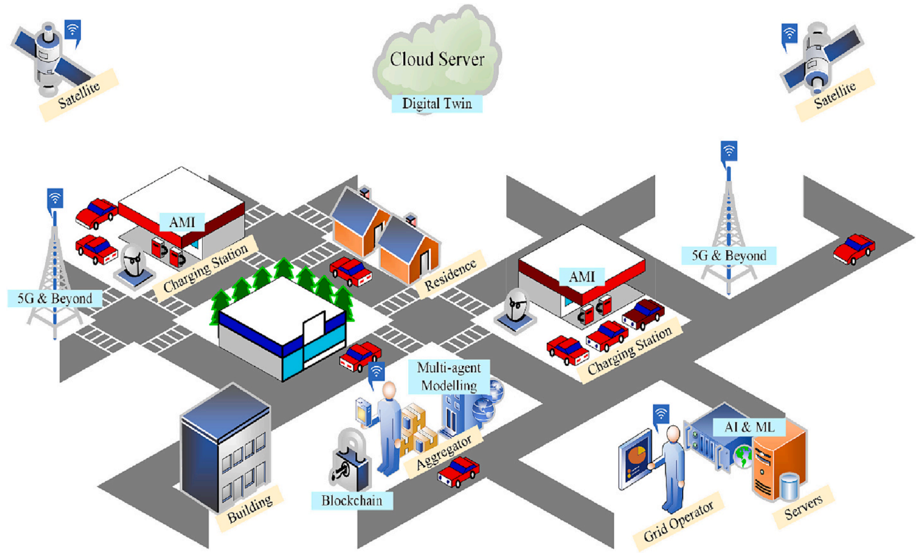

Fig. 13. Advanced EV charging infrastructure.

involves ML and deep learning (DL) processes. ML approaches include random forest, K-nearest neighbour (KNN), linear regression (LR), support vector machines (SVM), K means clustering, etc. [125–129]. DL involves long short-term memory (LSTM), recurrent neural network (RNN), artificial neural network (ANN), etc. [130–132]. Accurate prediction of immediate charging demands holds special significance for intelligent scheduling in EV charging. Anticipating and projecting short-term charging loads can be viewed as an indirect examination of charging patterns, as it heavily relies on when EV drivers arrive and depart. Several ML algorithms were used [133] to forecast the energy requirements at a charging outlet during the following 24 h. Since EVs are becoming increasingly popular worldwide, more data on major cities is required to understand better how each city handles charging. Researchers must make the datasets utilized for their studies available online for additional analysis and validation. Additionally, only a small number of the examined studies included predictive models for intelligent scheduling. Scheduling continues to be a crucial component of managing EV charging, and it is essential to consider the consequences of both long-term and short-term ML forecasts.

4.2. Blockchain

The blockchain system acts as a decentralized operating platform for trading power and oversees verifying transactions, chaining, and using smart contracts to carry out power transaction functions like matching, bidding, and settlement involving more than three blockchain nodes. Three servers (an orderer server and two peer servers) are part of the necessary hardware. Receiving transaction requests from the front-end user interface, the orderer server oversees sending chaining transaction verifications and innovative contract calculation jobs to the two peer servers. Each peer server may be utilized to carry out transaction chaining verification and transaction matching, settlement, and bidding using built-in smart contracts. Adopting a collaborative transaction model based on blockchain for EV charging and discharging is vital for the grid, charging businesses, and EV owners. Smart charging is used to assess and use the EV load flexibility to establish a stable grid using the charging demand (kWh) and maximum length of the charging event supplied by the EV user. Connecting EV owners and CSs via the blockchain platform reduces the number of participants in the EV charging ecosystem [134]. Stored transaction data in the blockchain would eliminate inequities in information sharing between charging operators and the power system and simplify the analysis of EV driving and charging-related data by industry groups and related firms in the case of the grid [135]. The scalability of the blockchain is one of the numerous problems and difficulties that blockchain technology encounters when it comes to grid development. Further study is required to incorporate blockchain technology into developing advanced smart grids.

4.3. Advanced metering infrastructure

The immense deployment of advanced metering infrastructure (AMI) is a unique prospect that characterizes the features and functions of large-scale DER and EV usage and DSM solutions. The V2G framework, which states that EVs should be able to inject electricity into the grid, describes basic and sophisticated AMI features. These features consider the possibility of charging in both residential and outdoor settings. The EV AMI regularly determines, gathers, and analyses EVCSs' energy usage via communication links. The term “AMI infrastructure” refers to a network that connects measuring equipment to utility servers, allowing data collection and information delivery to consumers, suppliers, utility companies, and service providers. Because the effect of real-time energy use on users' charging behaviour has been demonstrated, interactive communication holds a particular value for AMI. With timely information, utilities may readily monitor energy consumption on a time-and-place basis. [136] discusses the usage of AMI within the Vehicle to Home (V2H) architecture. V2H management using AMI involves three cases: EV and appliances management; EV, microgrid, and appliances management; and isolated management. EV AMI is an operative tool that helps reform the load profile of EV charging by using DSM. [137] offers a complete EV charging service platform solution based on the power line and internet connection. The Third-Party Customer Service enables EV owners to receive a single bill. As a result, EV owners understand their energy use and may engage in energy-saving activities more effectively. It helps reduce 36 % of power consumption and increases ‘off-peak power consumption’ by 54 %. Integrating a distributed test system with intelligent meters and EVCSs helps analyze communication constraints and assess the effect of the EV supervision approach in a real test network [138].

4.4. Multi-agent modeling

As the number of EVs grows, greater charging infrastructure is needed to supply energy for mobility while saving costs. Nowadays, multi-agent systems (MAS) have seen a rise in popularity, and it has been widely used in EV-based research. Distributed, flexible, and concerted multi-agent management systems for power systems, including smart EV

Table IX
Summary of various enable technologies studied in different literature.

Enable technologies	Contribution	Ref.
Artificial Intelligence	- Predict EV driver charging behaviour using K-nearest neighbour, LSTM, CNN, GRU, RNN, ANN, and LR. - The reinforcement learning (RL) method optimizes EV charging based on dynamic pricing; RL with ANN reduces charging costs and increases grid reliability. - Fuzzy logic maintains a balance between the EV owner and the system operator.	[68,126,130,132,146–148]
Blockchain	- Design the charging/discharging operations between EVs. - It can autonomously dispatch power transactions and perform power trading, forecasting analysis, and schedule management.	[149–151]
Advanced metering infrastructure	- AMI-based Volt Var optimization can reduce grid loss and Volt-VAR control equipment running expenses while increasing conservation voltage reduction benefits. - Multi-objective optimization is proposed that employs a -constraint technique to minimize operating expenses and CO_2 emissions for charging/discharging EVs in an innovative distribution system. - Using AMI information, an accurate prediction of the load imposed by PHEV is made.	[152–154]
Multi-agent modeling	- A multi-agent-based EV charging scheduling scheme is proposed to curtail the charging cost, voltage variation, - Minimizing total travel time by considering charging requests' dynamic and random arrival.	[155,156]
5G communication	- 5G network facilitates the energy and spectral efficiency of mobile devices. - Detect the cyber-attack by remoting the SCADA system. - Performance evaluation for V2X networks is advised for spectrum management to boost reliability, throughput, and latency performance. - Support for extremely high data rates, thorough quality of service, and expanded coverage naturally improve vehicular communication.	[157–160]
Digital twin	- LSTM was used to create a DT model of the connection between voltage and SoC. - To enhance the user's driving experience, a DT method was designed for adaptive traffic signal settings. - 5G-enabled internet of vehicles in real-time traffic utilizing the DT concept was created to optimize traffic resource allocation and alleviate potential traffic congestion during peak hours.	[161–163]

charging networks, can be effectively designed using MAS techniques. EV aggregators, CS operators, utility companies, grid managers, and DSOs are the agents participating during V2G and G2V power transfer. These agents communicate and exchange data with one another to share information and make judgments concerning CS status, energy pricing, grid load, and user preferences. The MAS comprises several agents that provide services and allow for scalability, flexibility, and reuse in other metropolises. With the help of MAS, such as traffic, pole, urban, and user interface agents, a system has been modeled to secure the electricity supply for charging EVs in the city and improve savings in CSs [139]. The power distribution and scheduling centre agents coordinate the distributed station to solve the overloading problem [140]. Agents oversee all interactions between EV owners and the power retailer based on parameters like the load on the grid, the charging capacity, and the various client profiles [141]. Various research is still going on how agents help in ancillary services to condense the load in a grid and afford profits to EV owners.

4.5. 5G and beyond

The rapid expansion of power infrastructures and the rise in EVs have sparked great interest in V2G technologies in academia and business as an energy management solution for the 5G smart grid. 5G technology has improved communication between EVs, CSs, and the grid system. This technology enables low-latency connectivity, remote control, and monitoring of CSs. An EV charging behaviour analysis (EV-CBA) system has been proposed based on hybrid artificial intelligence in the 5G smart grid to efficiently deliver on-demand charging services for EV consumers [142]. Ref. [143] presents a novel viewpoint on enhanced services for drivers and pedestrians utilizing 5G and more excellent connectivity between cars and sensors. Combining 5G technology with V2X (vehicle to everything) technology offers several benefits, including low service latency, good reliability, comprehensive communication coverage, and enhanced safety. Although the 5G network and EVs solved many problems, it also generated a lot of controversy and insecurity. As a logical progression in the growth of EVs, the features that enhance the safety of all road users upgrade the degree of safety and extend the life of the EV while also contributing to a cleaner environment and protected nature.

4.6. Digital twin

A digital twin (DT) improves model accuracy by integrating actual data from the physical environment back into the virtual environment. This method minimizes the slit between the actual and simulated worlds by making practical simulation possible. The potential of DT technology is dependent on a few factors, including tracking, monitoring, security, data analytics, and intrusion detection, which might improve effective network management for autonomous and EVs. The EV model is simulated using the DT to imitate the EV in the real world. Using the DT model, flexibility behaviours and interactions of EVs can be replicated easily to analyze the effectiveness of the charging poles and EVs from both the demand and supply sides. The maintenance and power infrastructure of EV services are profitable. DT is a cost-effective choice since the EV's DT model can be tested before deployment, which lowers maintenance expenses [144]. The DT simulation is also applied to evaluate the charging infrastructures and effectiveness by examining virtual model data. DT technology lessens data attacks, which increases the mechanism's security against attacks and protects EV users' privacy

[145]. The DT allows for creating high-accuracy models for real-time systems by combining vast amounts of operational data with expert insights. The wide applications of demonstrating DT's potential for integrating the real and digital worlds have increased tremendously.

5. Research challenges and future scope

EVs can solve most of the problems associated with conventional transportation, such as the high depletion of fossil fuels, the rise in greenhouse gas emissions, and global warming. However, deploying EVs has technical and economic constraints, such as overloading, interoperability, battery degradation, charging accessibility, etc. Fig. 14 shows the research challenges associated with EV charging. The issues related to EV charging include EVCS infrastructure, impact on DNs, security, and social and political barriers. After reviewing the various literature associated with EV charging, some dominant challenges are provided to improve charging infrastructure:

5.1. Energy management and scheduling

Handling EV charging in extensive network topologies poses distinct hurdles, including offering broad coverage, guaranteeing fair access to charging facilities, and effectively integrating charging services with the current energy grid infrastructure. In the smart grid, EVs serve as an electric burden, transportation medium, and energy storage system and perform a crucial role in integrating communication, traffic, and electrical networks. Thus, the abovementioned elements should be considered while planning an EV charging scheduling system. Coordinated charging of EVs includes several objectives, such as congestion management and power loss reduction, from the perspective of different stakeholders [74]. However, numerous mathematical and innovative approaches suggest that iterative methods can cause scheduling delays for large EV problem spaces. Influential and innovative distributed algorithms must be investigated to handle computationally tricky challenges due to large-scale EV penetration [18] and solve complex and real-time scheduling.

5.2. Integration of renewable energy sources

The rapid rise in wind and solar-based CSs alleviates the heavy burden on the grid during peak load periods. The deployment of EVs with RES technologies has experienced cost reduction due to technological advancement and production learning curves. RESs-based EV charging infrastructure is sanctified from both environmental and economic viewpoints, which require planning of complex network architecture, power electronic technologies, and hierarchical control functions. A few significant challenges in the smart charging of EVs with RESs include infrastructure planning, voltage and frequency stability, resource optimization, EVs as energy storage, and net energy metering of prosumers [19]. A power electronic converter and energy storage systems must be integrated with RESs to control their intermittent behaviour and mitigate the above challenges.

5.3. V2G

Implementing bidirectional charging infrastructure capable of charging EVs and discharging stored energy in EV batteries back to the grid requires significant investment and deployment efforts. Establishing technical standards for V2G communication protocols, hardware interfaces, and interoperability is crucial to enable widespread adoption and compatibility among different EV models and charging infrastructure. However, integrating V2G with the existing electric grid requires coordination between utilities, grid operators, and EV owners to ensure compatibility and reliability. The main challenges associated with the V2G system are battery degradation issues, reduced stability margin due to increased time delay caused by the EV aggregators, and high investment cost in bi-directional converters [32]. A tariff scheme must be proposed for EV owners to compensate for battery degradation and the aggregator during V2G services to maximize income from participation in competitive energy and other regulatory reserve markets.

5.4. Profitability of stakeholder

A profitable EV charging infrastructure requires a combined effort

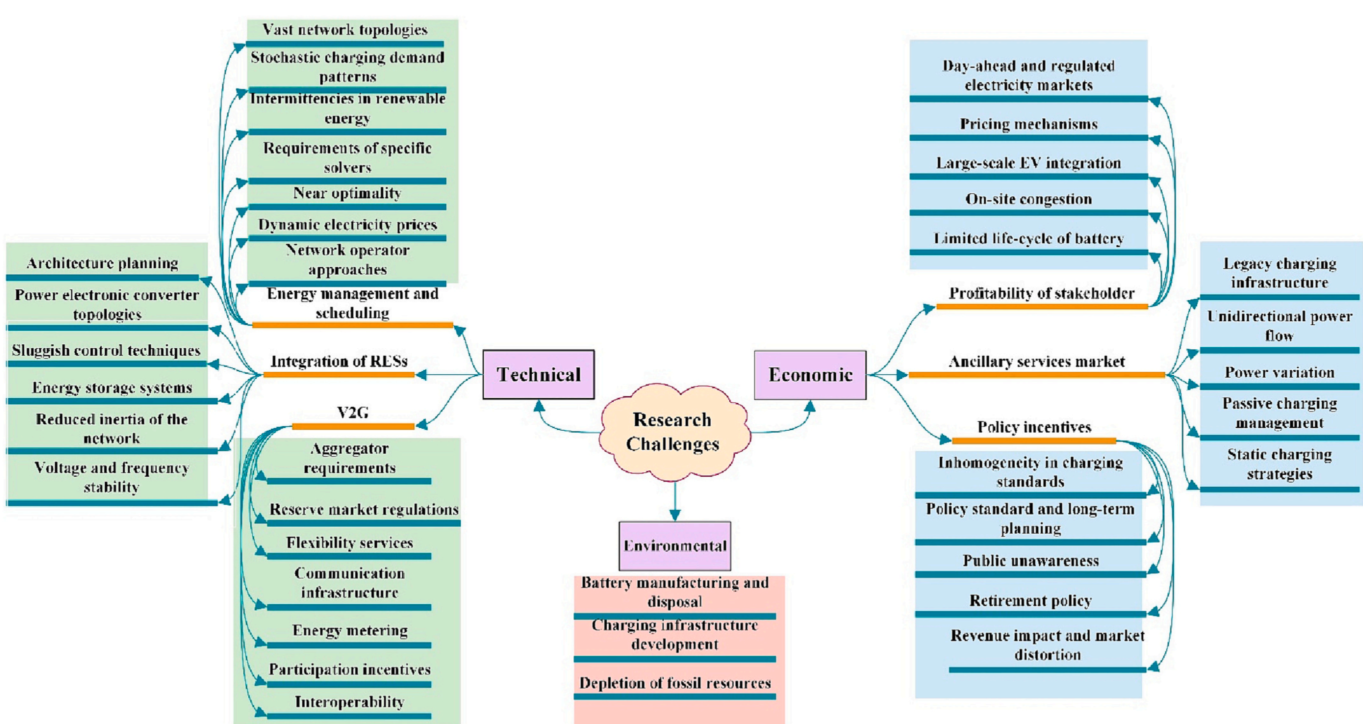

Fig. 14. Challenges associated with EV charging.

from various stakeholders, including grid operators, charging point operators (CPOs), EV owners, and regulators. With low EV adoption rates, it becomes challenging to recoup the initial investment costs spent on capital and operation of an EV charging infrastructure. Moreover, day-ahead and regulated electricity markets are unpredictable due to factors such as variations in EV charging demand patterns due to user behaviour and dynamic pricing schemes [67]. This uncertainty challenges DSOs, EV users, and CPOs in achieving profitability. Large-scale integration of EVs makes the grid system unstable and increases its burden; considering the DSO perspective, it is one of the most challenging tasks to manage the charging among all the EVs. The impact of charging loads on the distribution system and the uncertainties in EV charging require research on the optimal placement for charging stations, considering DSO, EV users, and CPOs.

5.5. Ancillary services market

Due to their fast dynamic response capabilities, the load demands and renewable generation imbalances may respond quickly through ancillary services provided by EV fleets. An aggregator assists as a representative among the grid operatives and EV owners to facilitate their cooperative coordination for voltage regulation, frequency regulation, spinning reserve, load smoothening, and congestion mitigation [19]. Various schemes have been proposed in the literature to improve the scheduling of ancillary and associated amenities to the grid operators. However, a more practicable and efficient scheme must involve the preferences of EV users in the ancillary services scheduling model for economic viability while respecting the technical limitations of the network.

5.6. Policy incentives

The provision of EV charging infrastructure can be broadly classified into four distinct business models: manufacturing, installation, operation, and sales. Moreover, the cost charioteers for EV charging infrastructure encompass capital costs for forthright installation and operating costs for network management. These costs depend on the size of charger equipment, grid connection requirements, local electricity tariffs, and regional policies. Research shows that public investments may be needed to support high upfront costs, particularly for fast-charging infrastructure with low payback periods [164]. However, policies governing retail electricity tariffs can be a barrier for EV charging service providers and grid operators. A range of incentive-based schemes, free parking spots, and public-private partnerships will bolster public adoption of EVs through local, regional, and national policy measures.

5.7. Environmental issues

The emissions levels of EVs can be compared with the conventional ICE-based vehicles based on wells-to-wheels emission parameters. The location of charging equipment, the architecture of the charging infrastructure, and the type of EV powertrain are the main factors that affect the well-to-wheel emission of an EV. Lithium-ion batteries are the most widely used battery technology in EVs, and they contain cobalt, nickel, and lithium. After reaching 70–80 % of their nominal capacity, EV batteries can be regarded as having reached the end of their first life [165]. Minerals in EV batteries can be recycled for their second life; however, recycling is quite expensive and requires a lot of energy. Globally, the current rate of recycling lithium-ion batteries is only around 5 %, thus leading to a high discard rate of retired EV batteries as e-waste. Alternatively, a few research works on retired EV batteries with low nominal capacities show their potential applications in residential households or grid services.

6. Discussion

The reliance of the conventional transportation sector on fossil fuels contributes to a considerable share of annual GHG emissions. Large-scale deployment of EVs has the potential to reduce GHG emissions through electrification while providing various services to the utility grid. A few key benefits of transportation electrification include the complemented hosting of RESs, energy storage facilities, reduced operational costs and voltage and frequency regulation in the power network. Global efforts are underway to increase awareness of EVs and to encourage their purchase by depressing the price gap between EVs and other conventional forms of transportation. Attractive governmental schemes are being promoted to reduce their initial capital costs by invoking tax relief, subsidies, and CO_2 emission standards to encourage the adoption of EVs. Despite having fiscal benefits and being eco-friendly, large-scale public adoption is challenging due to poor charging management and infrastructure. Poor management of many EVs at a CS will increase the burden on the utility grid, grid expansion, and additional investments. Therefore, this paper comprehensively surveys the policy frameworks, energy management systems, enabling technologies, and research challenges in the context of EV charging infrastructure. The central focus of this study is to highlight the coordinated charging strategies for EV charging in the power distribution network with architecture, techniques, control approaches, communication systems, pricing schemes, and load profiles for EV charging. Coordinated charging strategies help in the active management of EV fleet charging and other techno-economic services, such as peak load management, cost saving, aggregator response, demand response, grid resiliency, and stability. These services are subject to multiple linear and non-linear system constraints, so optimal scheduling solutions can be obtained using heuristic or meta-heuristic algorithms. The emerging technologies in computing, communication, and security play a crucial role in ensuring the reliable operation of EV charging infrastructure in conjunction with the power network. Furthermore, the challenges in deploying EV charging infrastructure and their origin are extensively discussed.

7. Conclusion

The public adoption of EVs is anticipated to rise dramatically in the next decade due to improvements in EV technology, charging infrastructure, and grid integration facilities. The advancement in RESs-based charging infrastructure, dependable communication systems, and coordinated EV charging systems will be crucial to accommodate the large-scale adoption of EVs. This paper reviews the present global status of transportation electrification, related policy reforms at both international and national levels, and various charging standards. A detailed discussion on each significant aspect of coordinated charging of EVs is presented, including energy management strategies, optimal scheduling, RESs-assisted charging infrastructure, and ancillary services.

Additionally, this article proposes various optimization techniques to accomplish multiple goals, including minimizing power loss and energy costs, reducing load demand, regulating voltage, and minimizing distribution infrastructure overloading. This paper highlights the emerging and advanced technologies widely used for optimal energy management and the security of EVCSs. The comprehensive review of state-of-the-art coordinated charging technologies for large-scale EVs could deliver a broad view of the limitations of existing EV charging infrastructure and identify challenges and potential opportunities of coordinated charging, which may be beneficial for grid operators in the long run. The findings indicate that additional research and specialized work are required to address the present challenges in developing and scheduling EVs in the power distribution infrastructure to satisfy the interests of multiple stakeholders.

CRediT authorship contribution statement

Isha Chandra: Conceptualization, Investigation, Methodology, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. **Navneet Kumar Singh:** Conceptualization, Investigation, Methodology, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. **Paulson Samuel:** Formal analysis, Methodology, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data supporting this study's findings are available from the corresponding author upon reasonable request.

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