Studies in Infrastructure and Control

Ashutosh K. Giri
Madhusudan Singh *Editors*

Electric Vehicle Charging Infrastructures and its Challenges

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Preface

For reducing the greenhouse emissions in the environment, electric vehicles (EV) are the best alternative of the internal combustion engine (ICE)-based commercial and private vehicles. However, production of merely EVs are not just sufficient as electrical vehicle charging infrastructures (EVCI) is equally important for market growth of these vehicles. Since these vehicles are electrically powered, there are certain challenges in installing these charging infrastructures. Former major problem is reliability and integration of renewable energy sources to grid for reducing the overloading. Also, the load forecasting and load diversity is another major issue to avoid the long queue of vehicles at charging stations. The other major issue is to focus on reducing the charging time of commercial and private vehicles.

Therefore, the main aim of the proposed book is to present about the basic terminologies of charging infrastructures such as types, levels and suitable power converters applications. To overcome the aforesaid challenges, various energy storage technologies such as lithium ion batteries charging strategies and battery management system (BMS) and battery swapping have been discussed. Since, various governments have reduced the tax on EVs and are providing subsidy for installing charging infrastructures, this is an easy task. Hence, in this book certain guidelines by the Ministry of Power and Ministry of Housing (Government of India) is discussed which can help an individual to set up a charging infrastructure at their end. Also, the novel idea and concepts developed by the researchers/academia and practising engineers working in the domain of the EV charging infrastructures are incorporated. The extensive use of power electronics infrastructures are used for improving the system reliability and efficiency in on grid and off grid EV charging system. The infrastructures of distributed power generation based on wind, solar, hydro and many other renewable energy sources have also incorporated to create better charging facility. The active and reactive power control strategy along with other parameters estimation and control are also included to make this book popular among the readers. The use of various control algorithms varying from techniques, intelligence techniques for estimation and control of charging parameters are added features of the proposed book. In addition to it, some classical control algorithms and adaptive type control algorithms for improved power quality have created big impact among all stakeholders of EV infrastructure segment.

The main features of this book are given as follows:

1. The opportunities and challenges in EV infrastructure development, selection and control of various power converter topologies used in it.
2. Integration of renewable power sources such as solar, wind and small and micro hydropower generation into EV charging infrastructures.
3. This book contains the traditional as well as advanced control algorithms for power control and other EV charging parameter estimation. The adaptive control and optimization techniques in EV charging application are value addition in it.

The readers will be able to understand the concept presented in this book and can utilize further in their research to boost this domain. Simulation results based on various infrastructure topology of EV charging will create the good interest among readers. Mathematical modelling of control algorithm and its experimental validation will also create good impact on readers' minds.

The teachers, students and practising engineers can take some insight for their work from this book. This book provides extensive coverage of recent developments in the area of EV charging infrastructures and its grid integration, power converters, use of power electronics and its control.

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About the Editors

Dr. Ashutosh K. Giri received his Bachelors of Engineering in Electrical Engineering from College of Technology, G. B. Pant University of Agriculture and Technology, Pantnagar, Uttarakhand, India, in 2002, M.E. in Electrical Engineering with specialization in Power System from the L. D. College of Engineering, Ahmedabad, Gujarat, India in 2005 and Ph.D. from the Department of Electrical Engineering, Sardar Vallabh National Institute of Technology, Surat, India in 2020. In May 2011, he joined the Department of Electrical Engineering, Government Engineering College, Bharuch, as Assistant Professor. He has authored and co-authored more than 60 research articles in reputed journals such as IEEE Transactions, IET Journal, Wiley, Tailor Francis, Springer, etc. He has also authored and co-authored 10 book chapters published in Elsevier, Springer Publication and CRC Press. Also, he has edited or authored 5 books in Elsevier, CRC Press and Springer Nature, Singapore, respectively. He is working on four sponsored research projects. He is supervising or co-supervising 6 Ph.D. students (1 completed in DTU New Delhi and 5 in progress in GTU, Ahmedabad and other universities) and coordinated 6 short-term courses. He has delivered more than 35 national and international level expert talks at various reputed universities across India. He had received a Research Opportunity Week (ROW) scholarship and visited Technical University of Munich Germany in March–April 2019. He has also served as a Technical Programme Committee member in Conferences organized at Scientific Federation of Dallas, USA and Kenitra, Morocco and as a track chair for IEEE IAS/IES/PELS IPRECON 2021 at Kerala. He has also chaired Technical Session in IEEE sponsored international conferences at IIITDM Kancheepuram, Chennai and MANIT, Bhopal. He had organized a special session in the IEEE-ECCE 2020 Conference at Detroit, Michigan, USA and in ECCE-ASIA 2021 at Singapore. He is also serving as a potential reviewer in various reputed journals such as *IEEE Transactions on Power Electronics*, *IEEE Transactions on Industrial Electronics*, IET, Wiley, etc. He has served as a lead guest editor for a special issue in Electrical Engineering, Springer and was editorial board member of *International Journal of Power Electronics*. He is also working as a member of the editorial board of *Discover Electronics*, Springer Journal. He is also a member of board of studies, ALARD University, Pune, Maharashtra, India.

Madhusudan Singh (Senior Member, IEEE) was born in Ghazipur, India, in 1968. He received his B.Sc. degree in Electrical Engineering from the Faculty of Technology, Dayalbagh Educational Institute, Dayalbagh, Agra, India, in 1990, M.E. degree in control and instrumentation from the University of Allahabad, Allahabad, India, in 1992 and Ph.D. degree from the Faculty of Technology, University of Delhi, New Delhi, India, in 2006. His research interests include modelling and analysis of electrical machines, power quality in power systems, renewable energy systems, and voltage-control aspects of self-excited induction generators, power electronics and drives.

Chapter 1
Powering the Future: An In-Depth Exploration of Global Electric Vehicle Charging Infrastructure

Prasanta Kumar Mohanty, Rudranarayan Pradhan, Premalata Jena, and Narayana Prasad Padhy

Abstract Building a strong electric vehicle (EV) infrastructure is fundamental to achieving widespread EV adoption and advancing the transition to sustainable transportation. This chapter delivers a thorough and detailed exploration of the key elements of EV infrastructure that are vital for accommodating the rising demand for electric mobility. We start by outlining the fundamental components of EV charging infrastructure, such as charging stations, connectors, and the interface with the electrical grid. The chapter then delves into the challenges and opportunities inherent in the development of EV infrastructure, including technological innovations, cost implications, and the incorporation of renewable energy sources. A comprehensive overview of the architectural frameworks for EV charging infrastructure is presented, highlighting the design principles and strategies for efficient and scalable infrastructure deployment. Various charging methods are discussed, ranging from slow and fast charging to ultra-fast and rapid charging, along with the technical specifications and standards that guide their implementation. The chapter delves into the global and Indian landscape of EV chargers, providing insights into the types and distribution of chargers worldwide and within India. The role of software application interfaces in managing and optimizing charging infrastructure is also explored, emphasizing the importance of interoperability and user-friendly design. Innovative solutions like battery swapping and wireless charging are examined for their potential to address specific challenges in EV infrastructure. Additionally, the chapter covers the role and strategies of charging point operators (CPOs) globally and across India, highlighting best practices and business models that facilitate the efficient operation of charging

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networks. In conclusion, this chapter offers a holistic view of the EV infrastructure ecosystem, addressing the multifaceted challenges and opportunities that lie ahead. By understanding the components, architecture, and global practices, stakeholders can better navigate the complexities of EV infrastructure development and contribute to a sustainable and efficient transportation future.

Keywords Ev charging infrastructure · Electric vehicle architecture · Battery swapping systems · Wireless charging · Charging point operators

1 Introduction

The escalating urgency to mitigate climate change and decrease greenhouse gas emissions has accelerated the global shift toward electric vehicles (EVs). Conventional internal combustion engine vehicles are major contributors to air pollution and global warming, thus underscoring the critical need for this transition. EVs, which produce zero tailpipe emissions, offer a sustainable alternative that can help mitigate the environmental impact of transportation. Furthermore, as countries strive to meet international climate targets, the adoption of EVs is becoming essential for achieving a low-carbon future [1].

Despite the evident environmental advantages, the widespread adoption of EVs encounters several challenges, with the most critical being the establishment of a robust and comprehensive charging infrastructure. Unlike conventional vehicles that rely on an established network of fuel stations, EVs require a different kind of support system. This infrastructure includes charging stations, connectors, and the integration with the electrical grid, which collectively ensure that EVs can be conveniently and reliably charged.

The lack of adequate charging infrastructure can lead to range anxiety among potential EV users, a concern about the vehicle running out of power before reaching a charging point. This anxiety is a major barrier to the adoption of EVs, making it imperative to develop a widespread and reliable network of charging stations. Furthermore, integrating renewable energy sources into the charging infrastructure can significantly enhance the sustainability of EVs, thereby reducing their overall carbon footprint.

Beyond environmental considerations, the development of a comprehensive EV charging infrastructure presents numerous economic opportunities. It has the potential to drive technological innovation, generate employment in the installation and maintenance of charging stations, and introduce new business models within the energy and automotive sectors. Governments and private entities are increasingly recognizing these opportunities, leading to significant investments and policy initiatives aimed at expanding the EV charging network.

This chapter delves into the various aspects of EV infrastructure, providing a detailed examination of its components, architecture, and challenges. We will explore the different types of charging methods, the global and Indian landscape of EV chargers, and innovative solutions such as battery swapping and wireless charging. Additionally, the role of software application interfaces and the strategies of charging point operators worldwide and in India will be discussed. By offering a comprehensive overview, this chapter aims to equip readers with a deep understanding of the current state and future potential of EV charging infrastructure.

2 EV Charging Infrastructure

2.1 Components of EV Charging Infrastructure

The development of EV charging infrastructure is essential to facilitating the widespread adoption of EVs. The infrastructure encompasses three main components: hardware, software, and services, each playing a vital role in ensuring efficient and reliable charging operations (Fig. 1).

Firstly, the hardware component includes Electric Vehicle Supply Equipment (EVSE) and chargers. EVSE is the physical device that provides the electrical connection between the power source and the EV, ensuring safe and efficient energy transfer. It includes various connectors and adapters to accommodate different types of EVs. Chargers are essential for converting AC power from the grid into DC power suitable for charging EV batteries, and they come in various capacities to support different charging speeds and requirements [2–7].

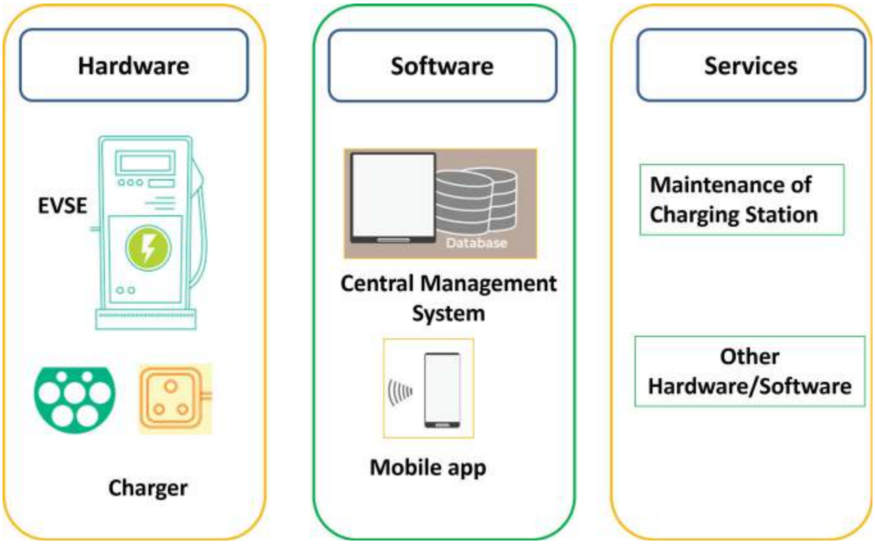

Fig. 1 Components of EV charging infrastructure

Secondly, the software component involves the Central Management System (CMS) and mobile applications. The CMS is a backend platform that manages and monitors the charging infrastructure, handling tasks such as user authentication, payment processing, and data analytics. It ensures the smooth operation of the charging network and provides insights into usage patterns and performance metrics. Mobile applications enhance user experience by allowing EV owners to locate charging stations, monitor charging sessions, and make payments seamlessly [5, 8, 9].

Finally, the services component includes the maintenance of charging stations as well as other associated hardware and software services. Regular maintenance is vital to ensuring the reliability and longevity of the charging infrastructure, encompassing routine inspections, repairs, and software updates to maintain system efficiency. Additionally, service providers offer a range of support services, such as customer assistance and troubleshooting, to enhance the overall user experience[5, 10].

In conclusion, the successful development and integration of hardware, software, and services components are critical for establishing a robust EV charging infrastructure. These elements collaboratively ensure a seamless and efficient charging experience for EV users, thereby facilitating the transition to sustainable transportation.

2.2 Architecture of EV Charging Infrastructure

The architecture of EV charging infrastructure comprises several key components that collaboratively ensure safe, efficient, and user-friendly charging experiences. Central to this infrastructure is the communication between EVs and EVSE. This communication is vital for ensuring the safe and secure delivery of power to the EV's battery, thereby preventing issues such as overcharging or electrical faults. (Fig. 2).

The EVSE interacts with the Central Management System (CMS) to facilitate several critical functions. Through EVSE-CMS communication, grid-related parameters are gathered, user authorization is verified, billing information is managed, and other charging-related data is processed. This communication ensures that the charging process is not only efficient but also secure and transparent for users.

Additionally, the CMS communicates with mobile applications, providing users with the ability to locate charging stations, make reservations, view billing details, and check the charge status of their vehicles. This level of connectivity and integration enhances the user experience by offering convenience and real-time information. The interaction between these components-EV, EVSE, CMS, and mobile applications-forms a comprehensive system that supports the growing demand for EV charging infrastructure [9, 11].

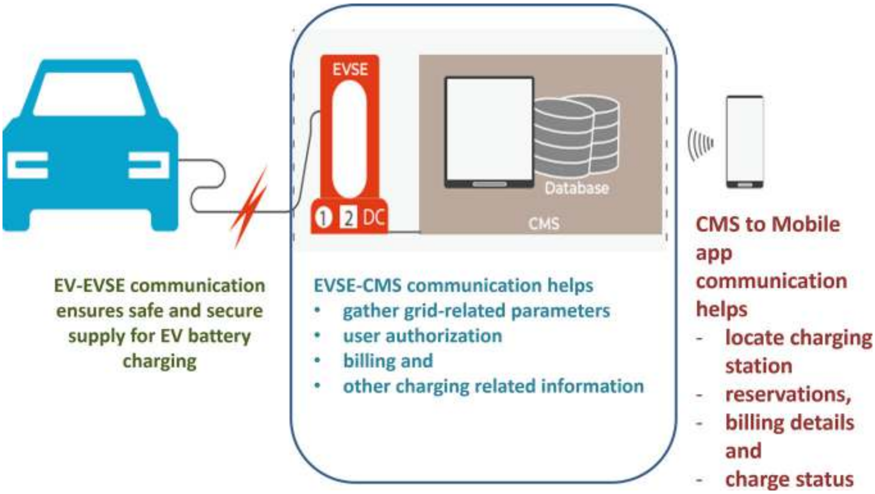

Fig. 2 Architecture of EV charging infrastructure

3 EV Charging Methods

3.1 Types

The advancement of EVs has driven the need for the creation of various charging methods to address diverse user requirements and technological progress. EV charging techniques generally fall into three categories: conductive charging, battery swapping, and wireless charging. Each approach aims to optimize the balance between charging convenience, the technical demands of the vehicles, and the infrastructure's capabilities.

3.1.1 Conductive Charging

Conductive charging, the most prevalent method, involves directly connecting the EV to a power source through a cable. This approach is categorized into onboard and offboard charging. Onboard charging encompasses both Level 1 and Level 2 options. Level 1 charging utilizes standard household outlets, making it ideal for overnight home charging, typically supplying power at 120 V AC for a gradual but consistent charge. Level 2 charging, on the other hand, requires specialized equipment and operates at 240 V AC, commonly found in public charging stations and in residential setups with dedicated EV chargers, offering a significantly faster charging experience for users. Offboard charging, referred to as Level 3 or DC fast charging, delivers high power directly to the vehicle's battery, drastically reducing charging

Table 1 Comparison of various electric vehicle models, their types, battery capacities, driving ranges, and connector types

Vehicle model	Type	Battery capacity (kWh)	Driving range (km)	Connector type
Chevrolet Volt	PHEV	18.4	8 5-Battery	Type 1 J1772
Mitsubishi Outlander	PHEV	20	84-Battery	CCS, Type 2
Volvo XC40	PHEV	10.7	43-Battery	CCS, Type 2
Toyota Priiis Prime	PHEV	8.8	40-Battery	SAE J1772
Nissan Leaf Plus	BEV	64	480	CHAdeMO, Type 2
Tesla Model S	BEV	100	620	Supercharger
Tesla Model X	BEV	100	580	Supercharger
Tesla Model 3	BEV	82	510	CCS, Type 2
Kia Niro-SUV	BEV	64	460	CCS, Type 2
Lexus UX 300e	BEV	54.3	320	CHAdeMO, Type 2
Ford Mustang	BEV	70	400	CCS, Type 2
Jaguar ev400	BEV	90	450	CCS, Type 2
Renault Zoe	BEV	52	390	CCS, Type 2
BMW i3	BEV	37.9	310	CCS, Type 2
Chevrolet Bolt	BEV	65	402	CCS, Type 2
Honda e	BEV	28.5	220	CCS, Type 2
Porsche Taycan	BEV	93	410	CCS, Type 2
Volkswagen e-Golf	BEV	35.8	230	CCS, Type 2
Mercedes-EQA	BEV	66.5	420	CCS, Type 2
Audi e-tron	BEV	95	400	CCS, Type 2
BMW iX3	BEV	80	460	CCS, Type 2
Toyota Mirai	FCEV	1.6	647	
Hyundai Nexo	FCEV	95.3	666	
Honda Clarity	FCEV	25.5	550	
BYD Atto 3	E-REV	60.4	420-Battery	CCS, Type 2
Hyundai Kona	E-REV	64	577-Battery	CCS, Type 2

times and facilitating long-distance travel with minimal downtime. Extreme fast charging (XFC) is also included in this category, providing even greater power levels for ultra-fast-charging capabilities[12, 13].

Table 1 provides a comprehensive comparison of various EV models, detailing their types, battery capacities, driving ranges, and connector types. It includes a mix of plug-in hybrid electric vehicles (PHEVs), battery electric vehicles (BEVs), and fuel cell electric vehicles (FCEVs). The data highlights that battery capacities vary significantly, ranging from 8.8 kWh in the Toyota Prius Prime (PHEV) to 100 kWh in both the Tesla Model S and Model X (BEVs). Correspondingly, driving ranges also differ, with the shortest being 40 km for the Toyota Prius Prime and the longest being 647 km for the Toyota Mirai (FCEV). Additionally, it outlines the diversity in connector types used by these vehicles, such as Type 1, Type 2, CCS, CHAdeMO, and Supercharger, indicating the varying charging infrastructure requirements across different EV models. This overview underscores the advancements and variations in EV technology, which cater to different consumer needs and preferences.

3.1.2 Battery Swapping

Battery swapping offers a cutting-edge solution to the challenges posed by lengthy charging times, enabling EV users to replace their depleted batteries with fully charged units, thereby minimizing downtime and enhancing the overall convenience of electric vehicle operation. This method eliminates the waiting time associated with conventional charging and can be particularly beneficial for commercial fleets and heavy-duty vehicles that require rapid turnaround. Battery swapping stations are equipped with automated systems to quickly and efficiently replace batteries, ensuring minimal disruption to vehicle operation.

3.1.3 Wireless Charging

Wireless charging, often referred to as inductive charging, allows EVs to recharge without the use of physical connectors. This technology is categorized into capacitive, inductive, and resonant inductive charging. Capacitive charging utilizes electric fields to transmit energy, whereas inductive charging relies on magnetic fields for energy transfer. Resonant inductive charging enhances this method by using resonant frequencies to improve efficiency and range. Wireless charging offers the convenience of simply parking the vehicle over a charging pad, making it ideal for residential, commercial, and public applications. It also holds potential for dynamic charging scenarios, where vehicles can charge while in motion, such as on specially equipped roadways [14].

These diverse charging methods play a crucial role in fostering the widespread adoption of EVs by catering to the varied needs of EV owners, whether for daily commuting or long-distance travel. Conductive charging provides reliable and accessible solutions for both slow and fast charging, while battery swapping offers a quick alternative to traditional charging. Wireless charging introduces a new level of convenience and innovation, paving the way for future advancements in EV infrastructure. By offering a range of charging options, the EV ecosystem can support the transition to a sustainable and electric-powered transportation future, meeting the growing demand for clean and efficient mobility solutions.

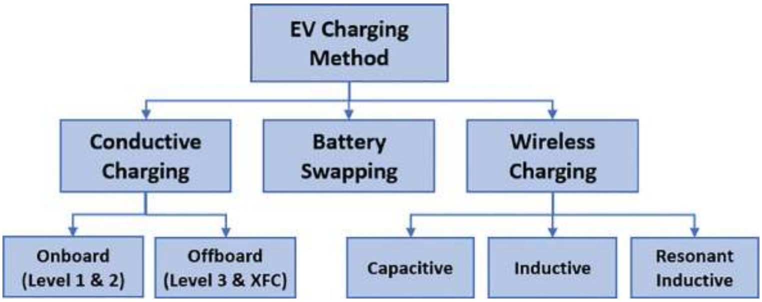

Fig. 3 Different types of EV charging methods

3.2 *EV Charging Methods Importance*

Figure 3 illustrates the different types of EV charging methods, each catering to specific user requirements and technological advancements. Conductive charging, battery swapping, and wireless charging all play a significant role in the EV infrastructure landscape.

3.2.1 Conductive Charging

Conductive charging remains the dominant method in EV charging infrastructure, favored for its straightforward design and proven effectiveness. Onboard conductive chargers, encompassing Level 1 and Level 2 chargers, are particularly suited for residential and workplace environments. These chargers facilitate direct connection to the power grid, allowing EV owners to recharge their vehicles during extended periods, such as overnight or throughout the workday. In contrast, offboard chargers, including DC fast chargers (Level 3) and XFC, deliver substantially higher power levels directly to the vehicle's battery, thereby significantly reducing charging durations. These high-capacity chargers are indispensable for long-distance travel and are strategically deployed at public charging stations and along major highways to support extended EV journeys.

3.2.2 Battery Swapping

Battery swapping presents an innovative approach to overcoming one of the major challenges of conventional EV charging: the lengthy time needed to recharge a battery. This method allows EV owners to replace their depleted battery with a fully charged one, effectively eliminating the downtime typically associated with the recharging process. Battery swapping is particularly advantageous for commercial fleets and public transportation systems, where minimizing vehicle downtime is critical. The development of standardized batteries and automated swapping stations is essential for this method to be widely adopted.

3.2.3 Wireless Charging

Wireless charging represents a futuristic approach to EV charging, providing unparalleled convenience by eliminating the need for physical connectors. This method includes capacitive, inductive, and resonant inductive charging techniques. Capacitive charging uses electric fields, while inductive charging employs magnetic fields to transfer energy. Resonant inductive charging enhances efficiency and range by using resonant frequencies. Wireless charging is ideal for residential use, public parking spaces, and potentially for dynamic charging applications, where vehicles can charge while driving on equipped roadways [15–19].

The variety of EV charging methods available today reflects the dynamic nature of the electric vehicle market and the ongoing advancements in technology. Conductive charging remains the backbone of EV infrastructure, providing reliable solutions for everyday charging needs. Battery swapping offers a fast and efficient alternative, particularly suited for high-utilization vehicles. Wireless charging offers a new dimension of convenience and has the potential to fundamentally change our approach to refueling electric vehicles. As the adoption of EVs expands, the advancement and integration of these varied charging technologies will be essential in facilitating the shift toward a sustainable and electrified transportation future.

3.3 Major EV Chargers in India

Electric Vehicle charging methods can be broadly classified into alternating current (AC) and direct current (DC) charging, each offering unique advantages and applications. AC charging, typically ranging from 2 kW to 22 kW, is predominantly utilized for residential and commercial settings. This method involves converting AC power from the grid to DC power through the vehicle's onboard charger. The standard AC charging connectors include the 3 PIN, Type 1, and Type 2, each varying in terms of power capacity and compatibility with different vehicle models.

In contrast, DC charging offers substantially higher power levels, typically ranging from 2 kW to over 200 kW, resulting in significantly faster charging times compared to AC charging. Unlike AC charging, where the conversion from AC to DC occurs within the vehicle's onboard charger, DC chargers perform this conversion externally. The DC power is then delivered directly to the vehicle's battery, bypassing the onboard charger entirely. This approach is ideal for public charging stations and situations where rapid charging is necessary. Widely used DC charging connectors, such as CHAdeMO, Combo 2 (CCS), and Type 2, are designed to comply with different international standards and meet the specific requirements of various electric vehicles.

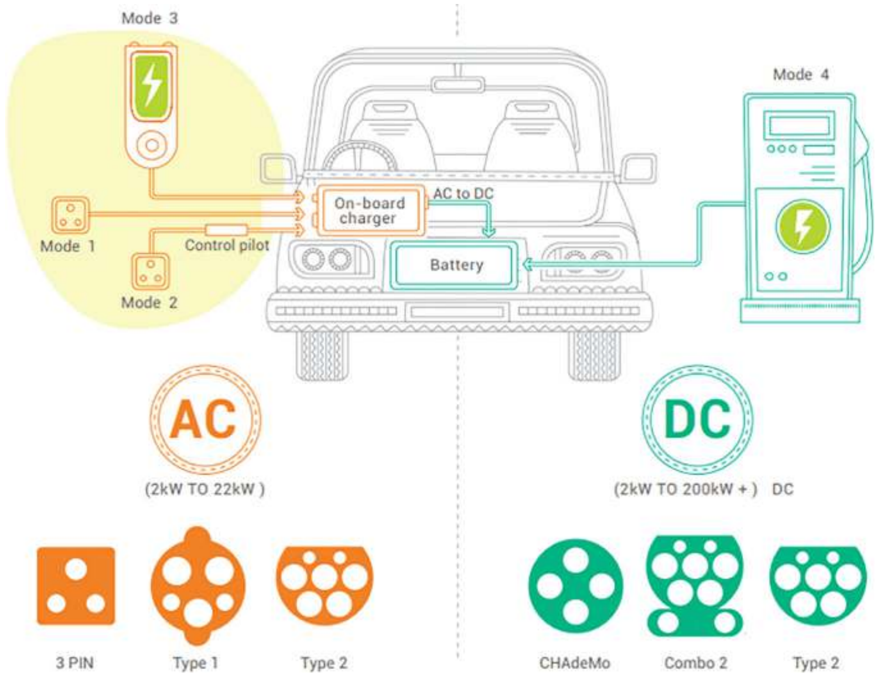

Fig. 4 EV charging methods [20]

Figure 4 illustrates various modes of EV charging. Mode 1 and Mode 2 involve lower power levels and simpler control mechanisms, typically for home charging setups. Mode 3 is a more advanced AC charging method with better control and safety features, suitable for both residential and commercial applications. Mode 4 represents DC fast charging, offering the highest power levels and quickest charging times, primarily used in public fast-charging stations.

The charging modes for EVs are categorized into four primary types. Mode 1 involves connecting an EV to a standard socket outlet, a method often referred to as "dumb charging" because it lacks communication between the EV and the EVSE. Due to the absence of built-in safety features, Mode 1 charging is generally discouraged and considered unsuitable for regular use. Mode 2 introduces inbuilt protection and control capabilities, making it suitable for home charging. It enhances safety through features like ground fault protection and automatic disconnection of the power supply if an issue is detected.

Modes 3 and 4 provide more advanced charging solutions. Mode 3 involves a dedicated EVSE that supplies power to the EV with improved control systems, making it suitable for both residential and commercial applications. Mode 4 represents DC fast charging, offering the highest power levels and quickest charging times,

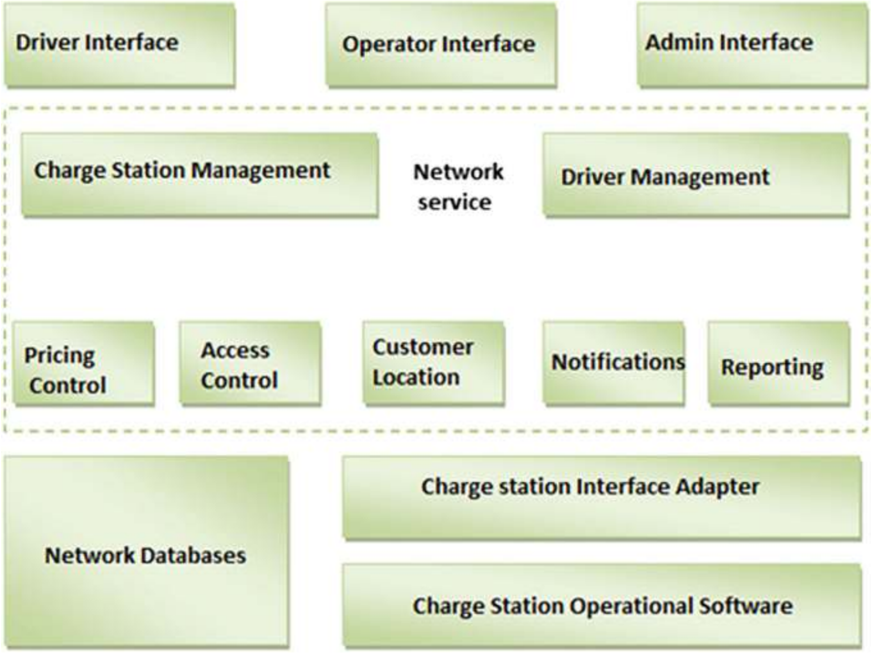

Fig. 5 Software application interface in conductive charging

primarily used in public fast-charging stations. These advanced modes ensure better communication between the EV and the EVSE, enhancing safety, efficiency, and user experience.

Table 2 provides a snapshot of major EV charger manufacturers in India, including Delta Electronics, Masstech Controls, and ABB, among others. It outlines various charger types, such as the low power Bharat AC001 (3.3 kW) and high power fast DC chargers (over 50 kW), detailing their compatibility with different EV types (2W, 3W, 4W). Compatible vehicle models include the Mahindra e2o, Tata Tigor, and Hyundai Kona, highlighting the diverse and expanding infrastructure supporting EV adoption in India.

3.4 Software Application Interface

The software application interface (Fig. 5) for EV charging infrastructure is designed to facilitate efficient management and operation across various levels of the system. The interface is segmented into three primary user types: drivers, operators, and administrators, each having their dedicated interaction points. For drivers, the interface provides essential functionalities such as charge station management and driver

Table 2 Major EV chargers in India

Manufacturers	Charger type	EV Class	Compatible e-Models
Delta Electronics, Masstech Controls, Exicom, Magenta Power, Ather, EvTeQ	Low Power EV Charger Bharat AC001 3.3kW	2W, 3W, 4W	Mahindra e2o, Mahindra e2o Plus P6, Tata Tigor (Charging Time: 6 h)
ABB, Delta Electronics, Masstech Controls, Exicom	Medium Power EV Charger Type 2 AC Charger 7kW to 22kW	2W, 3W, 4W	-
Okaya, Delta Electronics, Masstech Controls, Exicom, RRT Power Systems	Medium Power EV Charger Bharat EV DC Charger (BEV DC001) 15kW	2W, 3W, 4W	Mahindra e2o Plus P8, Mahindra e-Verito, Tata Tigor (Charging Time: 1.5 h)
ABB, Delta Electronics, Masstech Controls, Exicom, Tritium	High Power Fast DC Charger CCS/Chademo > 50kW	4W	Hyundai Kona, MG ZS EV, Tata Nexon EV

management, ensuring a seamless user experience during the charging process. Operators can leverage tools for network services and driver management, allowing them to oversee and control multiple charging stations effectively. Administrators benefit from advanced controls over the entire system, including network databases, pricing control, access control, customer location, notifications, and reporting features, ensuring comprehensive oversight and operational efficiency [21].

The system architecture integrates various modules such as charge station interface adapters and operational software to support these functionalities, ensuring robust and scalable solutions for the EV charging ecosystem. This integration not only enhances the operational capabilities but also improves the user experience across different levels of interaction. By providing a well-structured and modular interface, the software application enables effective management and optimization of the EV charging infrastructure, contributing significantly to the advancement of electric mobility.

3.5 AC and DC Charging Systems for Electric Vehicles

EVs rely on two primary types of charging systems: AC charging and DC charging. These systems differ in their operational mechanisms, infrastructure requirements, and efficiency levels. The figures provided illustrate the detailed architecture and components involved in both AC and DC charging systems.

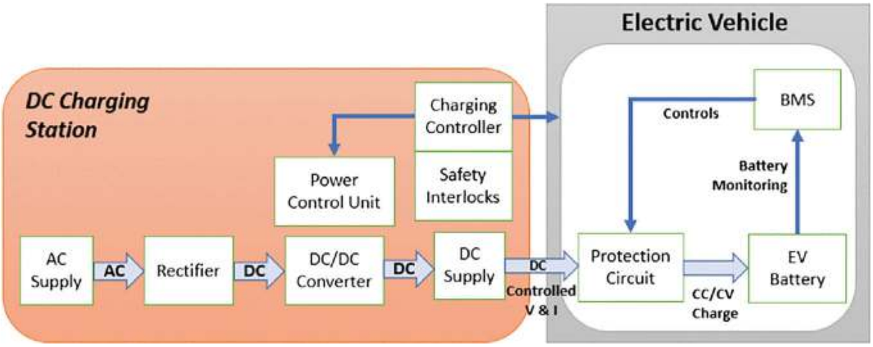

Fig. 6 DC charging system

3.5.1 DC Charging System

The DC charging system, as illustrated in Fig. 6, is engineered to deliver high power directly to the EV battery, thereby significantly reducing charging times. The DC charging process begins at the charging station, where an AC supply is first converted to DC using a rectifier. The rectified DC power is then regulated by a Power Control Unit (PCU) and further conditioned through a DC/DC converter. This converter ensures that the voltage and current levels are precisely adjusted to meet the specific requirements of the EV battery [15, 19, 22–25].

A crucial element of the DC charging system is the Charging Controller, which oversees the entire charging process. It communicates with the EV's BMS to monitor the battery's state of charge and overall health, ensuring that charging is conducted safely and efficiently. Safety interlocks are also integrated into the system to protect against overvoltage, overcurrent, and thermal issues.

Once the DC power is conditioned and controlled, it is delivered to the EV through a DC supply interface. Inside the vehicle, the power passes through a Protection Circuit, which safeguards the battery from potential faults. The EV battery then receives the DC power, where it undergoes a Constant Current/Constant Voltage (CC/CV) charging process managed by the BMS. This process ensures optimal charging speed while maintaining battery health and longevity.

3.5.2 AC Charging System

The AC charging system, as shown in Fig. 7, functions differently by supplying AC power to the vehicle, where it is converted to DC onboard the EV. The AC charging process starts with an AC supply from the charging station, which is then routed to the vehicle's onboard charger. This charger consists of several key components that facilitate the conversion and management of power to ensure efficient charging of the EV battery [16, 26–30].

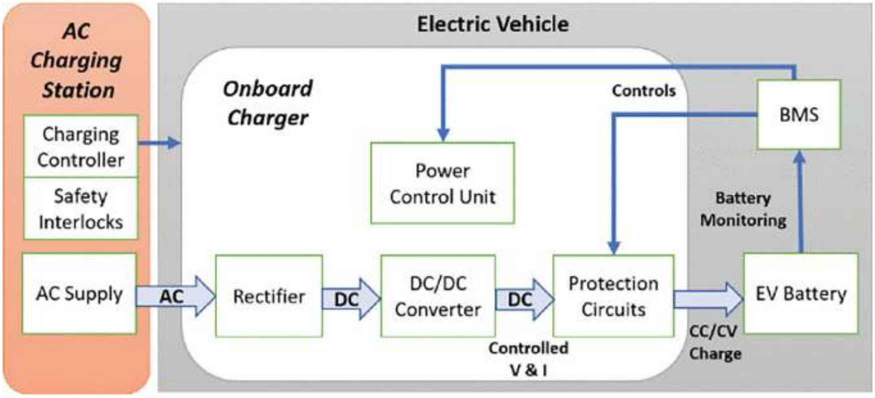

Fig. 7 AC charging system

The onboard charger begins with a rectifier, which converts the incoming AC power to DC. This DC power is then processed by the Power Control Unit (PCU) and subsequently fine-tuned by a DC/DC converter to align with the specific voltage and current requirements of the EV battery. Much like the DC charging system, the Charging Controller plays a critical role in overseeing the entire process, facilitating communication between the charging station and the EV's BMS to ensure safe and efficient charging.

Safety interlocks are included to prevent electrical faults and ensure user safety. The processed DC power is then routed through Protection Circuits within the vehicle, which provide an additional layer of security before the power reaches the EV battery. The BMS manages the final charging process, ensuring the battery receives the power under optimal conditions using the CC/CV charging method.

3.5.3 Comparison and Implications

The fundamental distinction between AC and DC charging lies in the location of the AC-to-DC conversion. In DC charging, this conversion takes place externally at the charging station, enabling the delivery of higher power and significantly faster charging times. Conversely, AC charging carries out the conversion onboard the vehicle, making it more suitable for slower, more convenient charging sessions, such as those typically conducted at home or work.

DC fast charging is crucial for alleviating range anxiety and facilitating long-distance travel, as it drastically reduces the time needed to recharge an EV. However, it requires more complex and expensive infrastructure compared to AC charging systems. AC charging, while slower, is more widespread and easier to implement, making it ideal for regular, daily charging needs.

Both charging systems are integral to the overall EV ecosystem, addressing different user needs and scenarios. The development and deployment of these systems continue to evolve, driven by advancements in technology and growing demand for efficient and reliable EV charging solutions. The integration of robust safety mechanisms and intelligent control systems ensures that both AC and DC charging methods provide safe, efficient, and user-friendly experiences for EV owners.

3.6 Battery Swapping Stations

Battery swapping stations are gaining traction as a promising alternative to conventional battery recharging methods for EVs. This technology is being tested across multiple EV segments, including two-wheelers, three-wheelers, electric cars, and electric buses. The primary advantage of battery swapping is the reduction in downtime associated with recharging, enabling a quicker turnaround for EV users. Battery swapping stations come in two main types: manual and autonomous.

3.6.1 Types of Battery Swapping Stations

Firstly, manual battery swapping stations involve the manual placement and removal of batteries from individual slots. This method is commonly used for 2W and 3W battery applications. The process is relatively straightforward and can be handled by one or two persons. One of the key benefits of manual swapping is its cost-effectiveness, making it an attractive option for regions with lower labor costs or where automated solutions are not feasible. Additionally, the simplicity of manual swapping reduces the need for advanced technology and infrastructure, facilitating easier implementation and maintenance [26, 28, 30–32].

Secondly, autonomous battery swapping stations utilize robotic arms to handle the placement and removal of batteries. This technology can be semi or fully automated, significantly reducing the need for human intervention. Autonomous swapping is particularly suited for 4W and e-bus applications, where the size and weight of the batteries make manual handling impractical. While more expensive to set up and operate, autonomous swapping stations offer the advantage of higher efficiency and precision. They can operate continuously with minimal downtime, making them ideal for high-demand environments. However, they also require more space and sophisticated infrastructure, which can be a limiting factor in densely populated urban areas.

The implementation of battery swapping technology presents both opportunities and challenges. On the one hand, it can significantly enhance the convenience and accessibility of EVs by reducing the time required for recharging. On the other hand, it requires substantial investment in infrastructure and technology, particularly for autonomous stations. Moreover, the success of battery swapping depends on standardization across the industry to ensure compatibility between different vehicles and swapping stations.

In conclusion, battery swapping stations represent a promising solution for improving the efficiency of EV operations. By offering a faster alternative to traditional charging, they can help to accelerate the adoption of electric mobility. However, careful consideration must be given to the type of swapping station deployed, balancing the cost and complexity with the specific needs of the EV market.

3.6.2 Advantages and Disadvantages of Battery Swapping Stations

Battery swapping stations for EVs offer distinct advantages and face specific barriers that influence their adoption and implementation.

One significant advantage of battery swapping is the speed of recharging. EV recharging can be completed in minutes through swapping, as opposed to the hours required for traditional charging methods. This quick turnaround is especially advantageous for commercial and public transport vehicles that require continuous operation and cannot tolerate extended downtimes for recharging. Additionally, the ability to charge batteries away from the swapping location offers greater flexibility in establishing swap facilities and enables operators to optimize charging processes under controlled conditions. By separating the charging and swapping locations, the upfront cost of EVs is reduced, as battery ownership is replaced with a battery leasing model. Furthermore, charging under controlled conditions can lead to improved predictability and extended battery life, thereby enhancing the overall efficiency and cost-effectiveness of the system.

However, battery swapping faces several barriers that need to be addressed. One of the primary challenges is the lack of standardization among EV batteries, which makes it difficult to implement a universal swapping system. Battery packs often vary significantly in terms of weight, dimensions, and ergonomics, complicating the design and operation of swapping stations. Furthermore, the need for a greater number of batteries to power the same number of EVs can be a logistical and economic challenge. This increased demand for batteries requires careful planning and management to ensure availability and sustainability.

Another challenge is the shorter commercial lifespan of battery packs, driven by customer preference for newer batteries that offer higher range and better performance. This preference can lead to increased turnover and potential waste if not managed properly. Additionally, the higher costs associated with battery leasing over the life of the EV, as well as the discrepancy in Goods and Services Tax (GST) rates-where separate batteries incur a higher tax rate compared to batteries sold with the EV-pose economic challenges to widespread adoption.

In conclusion, while battery swapping stations offer significant benefits in terms of speed and flexibility, they also face substantial challenges related to standardization, economic viability, and operational logistics. Addressing these barriers is crucial for the successful implementation and scalability of battery swapping infrastructure for EVs.

Table 3 Classification of charging infrastructure

Category	Usage	Locations	Ownership and Operation
Private	Dedicated charging for personal EV or EV fleet owned by one entity	Independent homes, dedicated parking spots in apartments/offices	Individual EV owners, EV fleet owners/operators, self-operated or CPO-managed (for EV fleet charging)
Semi-public	Shared charging for a restricted set of EV users	Apartment complexes, office campuses, gated communities, shopping malls, hospitals, universities, government	Host properties, OEMs & CPOs, CPO-managed
Public	Open for all EV users	Public parking lots, on-street parking, charging plazas, petrol pumps, highways, metro stations	Municipal authorities, PSUs, CPOs, host properties, CPO-managed

4 Classification of Charging Infrastructure for Electric Vehicles

The classification of charging infrastructure for EVs can be categorized into three main types: private, semi-public, and public (Table 3). Each classification caters to different user needs and operates under varied management structures, impacting their accessibility and functionality.

4.1 Private Charging Infrastructure

This category is specifically designed for personal EVs or EV fleets owned by a single entity. Private charging stations are commonly found in locations such as independent homes and dedicated parking spots in apartments or office buildings. Ownership typically rests with individual EV owners or EV fleet operators, who may either manage the charging stations themselves or enlist the services of Charge Point Operators (CPOs) for managing fleet charging. This arrangement provides convenience and security for owners, ensuring reliable access to charging facilities as per their needs. Private charging infrastructure plays a crucial role in facilitating the initial adoption of EVs by providing essential charging solutions for early adopters[33–37].

4.2 Semi-public Charging Infrastructure

Semi-public charging stations cater to a limited group of EV users and are typically located in places such as apartment complexes, office campuses, gated communities, shopping malls, hospitals, universities, and government buildings. These stations provide charging access to a specific community or group, rather than the general public. Ownership and operation are generally managed by host properties, Original Equipment Manufacturers (OEMs), or CPOs. This setup provides access to a specific group of users, balancing between private convenience and broader accessibility.A semi-public charging infrastructure supports the transition toward more sustainable transportation by enabling shared access to charging resources in strategic locations.

4.3 Public Charging Infrastructure

Public charging stations provide the highest level of accessibility, being open to all EV users. These stations are strategically placed in locations such as public parking lots, on-street parking areas, charging plazas, petrol stations, highways, and metro stations. The ownership and management of these stations often involve a combination of municipal authorities, Public Sector Units (PSUs), Charge Point Operators (CPOs), and host properties, with CPOs frequently overseeing the operation and maintenance to ensure efficiency. Public charging infrastructure plays a crucial role in mitigating range anxiety and fostering widespread EV adoption by offering convenient and accessible charging options across both urban and suburban areas. This infrastructure is essential for the long-term growth of EVs, as it ensures that charging facilities are readily available where they are most needed [1, 13, 25, 38, 39].

4.4 Key Market Drivers

The growth of EV charging infrastructure is primarily driven by strong governmental support and proactive industry initiatives. These factors work together to accelerate the adoption and expansion of EV charging networks, thereby promoting broader acceptance and integration of electric mobility.

4.4.1 Strong Government Push

The role of government is pivotal in driving the adoption of EV charging infrastructure. Governments across various regions have implemented policies and incentives to encourage the development and usage of EVs. These measures include subsidies for EV purchases, tax benefits, funding for charging infrastructure projects, and mandates for setting up charging stations in new building constructions and public spaces. Governmental policies are crucial in overcoming the initial market barriers and accelerating the deployment of EV charging stations, thereby supporting the transition to sustainable transportation.

4.4.2 Industry Initiatives

In addition to governmental support, industry initiatives play a significant role in advancing EV charging infrastructure. Companies are increasingly forming partnerships and collaborations to expand the charging network. These initiatives include tie-ups with fleet operators, petrol pump owners, and shop owners to integrate charging stations into their premises, making it more convenient for EV users to access charging facilities. Community charging stations and charging plazas are also being established to cater to the growing demand for public charging options.

- Tie-Ups with Fleet Operators: Collaborating with fleet operators ensures that a significant number of electric fleet vehicles have access to dedicated charging infrastructure, promoting the use of EVs in commercial and public transport sectors.
- Tie-Ups with Petrol Pumps: Integrating charging stations at existing petrol pumps leverages the established refueling infrastructure, providing a familiar and accessible location for EV users to charge their vehicles.
- Tie-Ups with Shop Owners: Charging stations at retail locations enhance convenience for EV users, allowing them to charge their vehicles while shopping, thereby encouraging longer visits and increased customer satisfaction.

4.5 Community Charging Stations and Charging Plazas

These stations are strategically located in residential areas, providing convenient charging solutions for local residents. They play a crucial role in urban areas where private parking with charging facilities may not be available.

Charging plazas are larger facilities that house multiple charging stations, catering to a high volume of EVs. These plazas are typically located in busy urban centers, transport hubs, and highways, offering fast and efficient charging services to commuters and long-distance travelers.

By integrating these key drivers, the market for EV charging infrastructure is set to grow, addressing the current limitations and paving the way for a more extensive and efficient network of charging stations.

Fig. 8 Challenges in EV charging infrastructure

5 Challenges in EV Charging Infrastructure

The development and deployment of Electric Vehicle (EV) charging infrastructure face several challenges that involve multiple stakeholders, including end-users, Charging Point Operators (CPOs), private fleet operators, and Distribution Companies (DISCOMS). Addressing these challenges is crucial for the effective and efficient implementation of a robust EV charging network (Fig. 8).

5.1 End-User Challenges

5.1.1 Range Anxiety

Range anxiety continues to be a major concern for EV users. A study conducted by Castrol, involving 1000 consumers, fleet managers, and industry specialists across India, reveals that drivers expect an average range of 401 km from a single charge. This expectation underscores the need for widespread and reliable charging infrastructure to mitigate fears of being stranded with a depleted battery.

5.1.2 Time Anxiety

Time anxiety pertains to the concern over how long it takes to charge an EV. The same study by Castrol indicates that drivers expect an average charging time of 35 min or less. Meeting these expectations by reducing charging durations, particularly through the deployment of fast-charging stations, is crucial for enhancing user satisfaction and encouraging broader EV adoption.

5.1.3 Charge Anxiety

Charge anxiety revolves around concerns about locating a functional and available charging station. Users often experience trust issues with electric charging stations, questioning whether their vehicle is charging correctly and if the station is operating properly. Addressing these anxieties by ensuring the reliability and availability of charging stations is essential for boosting user confidence in EVs and promoting their widespread adoption.

5.2 Charging Point Operators' Challenges

5.2.1 Sub-Optimal Utilization Rates

Public charging stations often experience low utilization rates, around 10–15%, given that a fast-charging station can charge a car in approximately 1.5 h, with no more than 2–3 cars typically coming in on any given day. The capital expenditure (CAPEX) per station, excluding land cost/rent, is high, making the economic viability challenging under current utilization rates. This underutilization is a significant barrier to the economic sustainability of public charging stations.

5.2.2 Limited Parking Lands

Acquiring parking spaces in most cities is a significant challenge, as land lease alone can constitute more than 40% of the operational cost of a charging station. This high cost necessitates government intervention to facilitate the allocation of suitable lands for charging infrastructure. The availability of affordable and accessible land is critical for expanding the charging network and supporting the widespread adoption of EVs.

5.3 Private Fleet Operators and DISCOMS

5.3.1 Private Fleet Operators

Securing a reliable electricity connection for EVSE at charging stations owned and operated by fleet operators is a major challenge. Cab aggregators and fleet operators encounter difficulties due to the varying tariffs for EV charging across different states, with many states designating EVs as a separate tariff category. These discrepancies can complicate operations and increase costs, presenting a significant barrier to the broader adoption of EVs in fleet management. This variation creates challenges for fleet operators who operate across multiple states and need consistent and predictable charging costs.

5.3.2 DISCOMS

Distribution network and frequent overloading of system components are significant issues for Distribution Companies (DISCOMS). The unpredictable electricity demand caused by the growing number of EVs can strain the existing infrastructure. Developing a resilient distribution network that can handle the additional load is essential for supporting EV adoption. According to studies, ensuring that the distribution network can meet the increased demand without frequent overloads is crucial for the successful integration of EVs into the grid.

6 Conclusions

This chapter has offered a thorough exploration of the critical elements and challenges related to the development of EV infrastructure. By analyzing key components such as charging stations, connectors, and their integration with the electrical grid, we have highlighted the foundational aspects necessary to support the expansion of electric mobility. The exploration of challenges and opportunities highlighted the technological advancements and cost considerations critical for sustainable infrastructure development.

A detailed analysis of architectural frameworks emphasized the need for efficient and scalable designs that can accommodate the increasing demand for EVs. The discussion on various charging methods, including slow, fast, ultra-fast, and rapid charging, along with the technical standards that govern them, provided a clear understanding of the options available to EV users. The global and Indian landscapes of EV chargers were examined, shedding light on the types and distribution of chargers. The importance of software application interfaces in optimizing and managing charging infrastructure was emphasized, highlighting the need for interoperability and user-friendly solutions. Innovative approaches such as battery swapping and wireless charging were explored for their potential to overcome specific challenges in EV infrastructure. The role of charging point operators (CPOs) was also discussed, illustrating best practices and business models that ensure the efficient operation of charging networks.

In conclusion, the chapter has offered a holistic view of the EV infrastructure ecosystem, addressing the multifaceted challenges and opportunities that lie ahead. By understanding the components, architecture, and global practices, stakeholders are better equipped to navigate the complexities of EV infrastructure development. This understanding is vital for promoting a sustainable and efficient transportation future, advancing the widespread adoption of electric vehicles, and contributing to global environmental objectives.

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Chapter 2
Electric Vehicles: Exploring Types, Benefits, Challenges, Policies, and Smart Charging Innovation

Prasanta Kumar Mohanty, Rudranarayan Pradhan, Premalata Jena, and Narayana Prasad Padhy

Abstract The shift to electric vehicles (EVs) marks a crucial transformation in the transportation sector, driven by the pressing need to lower greenhouse gas emissions, improve energy efficiency, and promote sustainable urban mobility. This chapter offers a comprehensive introduction to the world of electric vehicles, addressing key aspects critical to understanding their role and impact. We start by examining the different types of electric vehicles, such as Battery Electric Vehicles (BEVs), Plug-in Hybrid Electric Vehicles (PHEVs), and Fuel Cell Electric Vehicles (FCEVs), each offering distinct features and advantages. The discussion then moves to the compelling need for EVs, underscoring environmental benefits, energy security, and economic advantages. Challenges and opportunities inherent in the adoption of EVs are thoroughly examined. This includes technological hurdles such as battery performance and range anxiety, infrastructure development, and market acceptance. Conversely, opportunities such as advancements in battery technology, renewable energy integration, and government incentives are highlighted as driving forces behind EV adoption. The chapter also delves into EV policies, examining global and regional frameworks that support EV growth. Policies promoting research and development, infrastructure investments, and consumer incentives are discussed to provide a comprehensive view of the regulatory landscape. An in-depth look at the EV ecosystem is presented, emphasizing the interconnected elements necessary for a sustainable EV market. This includes manufacturing, supply chains, charging infrastructure, and grid integration. The concept of smart charging is introduced, detailing its significance in optimizing energy consumption, reducing costs, and supporting grid

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stability through technologies like Vehicle-to-Grid (V2G) and demand response. In conclusion, this chapter provides a foundational understanding of electric vehicles, highlighting their transformative potential in achieving a sustainable future. Through a holistic approach, readers are equipped with insights into the multifaceted dimensions of EVs, paving the way for informed discussions and future innovations in this dynamic field.

Keywords Electric vehicle adoption · Sustainable transportation · Ev policies · Smart charging · Sustainable transportation solutions · Green mobility · Vehicle-to-grid (v2g)

1 Introduction

The introduction to this document offers an in-depth overview of EVs, laying the foundation for understanding their crucial role in the modern transportation landscape. It begins with a section titled "Introduction to Electric Vehicles," which delves into the historical evolution, fundamental principles, and current technological advancements in EVs. Following this, the document provides a detailed classification and explanation of various EV configurations in the "Types of Electric Vehicles" section, covering BEVs, PHEVs, FCEVs, and HEVs, each with unique characteristics and specific applications. The subsequent "Need of Electric Vehicles" subsection highlights the pressing environmental and economic factors driving the shift toward EVs, emphasizing their critical role in reducing greenhouse gas emissions and decreasing dependence on fossil fuels.

Following this, we focus on the "Advantages of Electric Vehicles," highlighting benefits such as lower operating costs, reduced maintenance demands, and the potential for seamless integration with renewable energy sources. The document then turns to the "EV Policies in India" subsection, which offers a comprehensive overview of the various initiatives and regulatory frameworks implemented by the Indian government to encourage the adoption of electric vehicles. This includes significant programs like the FAME II initiative, state-level incentives, and production-linked incentives designed to enhance local manufacturing and infrastructure development. Collectively, these subsections establish a strong foundation for understanding the crucial role of electric vehicles in advancing a sustainable transportation future and the specific strategies India is employing to facilitate this transition.

1.1 Introduction to Electric Vehicles

EVs are transforming the automotive sector by providing an eco-friendly alternative to conventional vehicles powered by internal combustion engines. These vehicles are propelled by electric motors that convert electrical energy into mechanical energy,

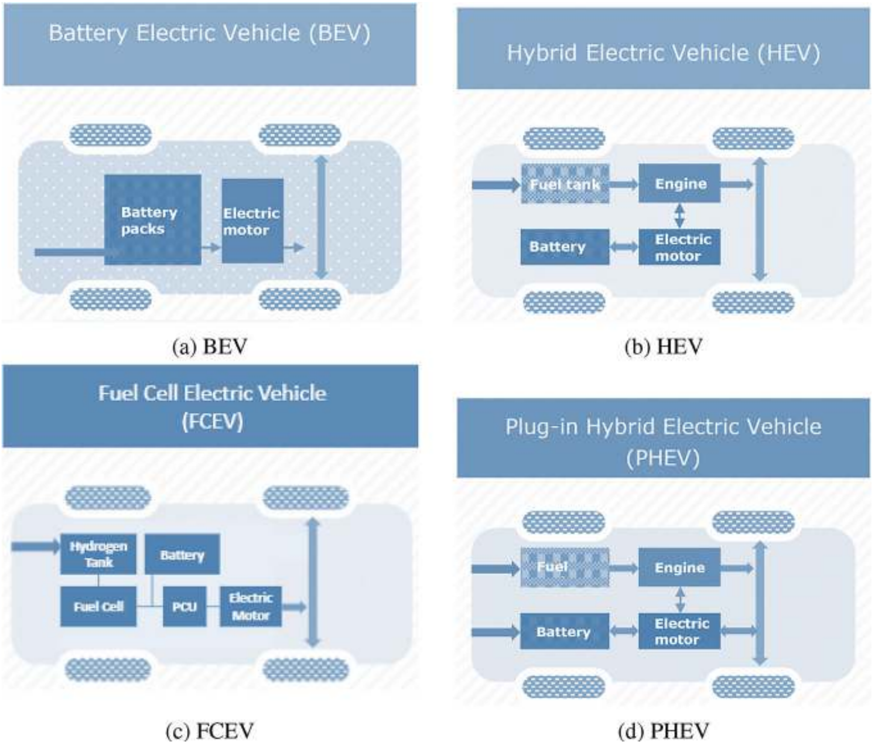

Fig. 1 Types of EVs [1]

facilitating motion. The energy required for this conversion is supplied by onboard batteries-typically high-capacity lithium-ion cells. These batteries are replenished through an onboard charging system that converts grid-supplied alternating current (AC) into the direct current (DC) required by the batteries.

A charger port facilitates the charging process, allowing the vehicle to connect to external power sources. The motor drive manages the power flow to the electric motor, optimizing its performance and efficiency, while the battery converter regulates the energy flow between the battery and the motor drive to ensure appropriate voltage and current levels. An auxiliary battery powers the vehicle's electronic systems and accessories. Unlike traditional vehicles, EVs use a simplified transmission system, which efficiently transmits power from the motor to the wheels.

EVs greatly diminish reliance on fossil fuels and significantly reduce greenhouse gas emissions, offering considerable environmental benefits. Additionally, they enable the integration of renewable energy sources and participation in smart grid initiatives, further boosting their sustainability and economic appeal. Consequently, EVs play a crucial role in the shift toward more sustainable transportation options.

1.2 Types of Electric Vehicles

EVs come in different types, each employing unique technologies to provide eco-friendly transportation options. The four primary categories of EVs are battery electric vehicles (BEVs), hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs), and fuel cell electric vehicles (FCEVs), as shown in Fig. 1 [1].

BEVs rely entirely on electric motors for propulsion, with energy provided by rechargeable battery packs. These batteries store the electricity needed to power the motor, eliminating the necessity for gasoline or diesel. BEVs are recognized for their high energy efficiency and zero tailpipe emissions, making them an environmentally friendly alternative to traditional vehicles.

HEVs combine an internal combustion engine with an electric motor, allowing the two power sources to work together or independently to optimize performance and fuel efficiency. The battery in HEVs is recharged through regenerative braking and the internal combustion engine, but it cannot be plugged into the grid for external charging. This hybrid system results in lower fuel consumption and reduced emissions compared to conventional vehicles.

PHEVs expand on the hybrid concept by incorporating larger batteries that can be recharged via an external power source. PHEVs can operate in electric-only mode for short distances, typically adequate for daily commuting, and can switch to hybrid mode for longer trips. This dual functionality significantly reduces fuel consumption and emissions.

FCEVs use hydrogen as a fuel to generate electricity through a chemical reaction in a fuel cell. Hydrogen is stored in a tank and combined with oxygen from the air in the fuel cell to produce electricity, which then powers the electric motor. The only emission from this process is water vapor, making FCEVs an exceptionally eco-friendly option. However, the development of hydrogen infrastructure remains a key challenge for their broader adoption.

These different types of EVs offer various solutions to cater to diverse needs and preferences, all contributing to the reduction of greenhouse gas emissions and the promotion of sustainable transportation. Each type has its own set of advantages and challenges, but together, they provide a comprehensive approach to reducing the environmental impact of the transportation industry.

1.3 The Need of Electric Vehicles

EVs are gaining recognition as a crucial solution for addressing air pollution and curbing carbon emissions, particularly in highly polluted and densely populated regions like India.

A major concern is the significant impact of air pollution on both public health and economic stability. For instance, a report from Greenpeace [2] highlights the severe consequences of air pollution in major Indian cities such as Delhi, Mumbai,

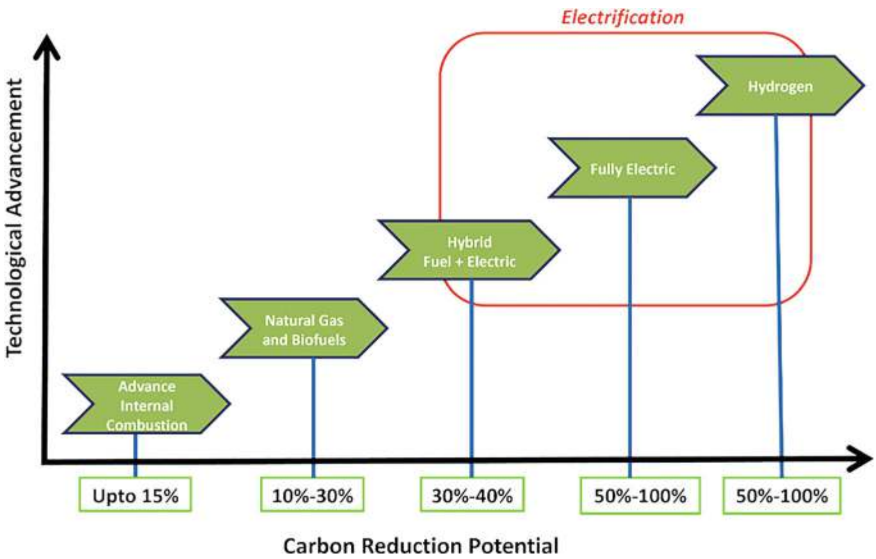

Fig. 2 Comparision of vehicles based on carbon reduction potential with technological advancement

Bengaluru, Hyderabad, Chennai, and Lucknow. Delhi, in particular, is noted for having the highest estimated fatalities and economic losses attributable to air pollution. In 2020, 22 of the 30 most polluted cities globally were in India, with vehicle emissions being a major contributor. In Delhi alone, vehicles were responsible for 41% of NOx emissions and 23% of PM2.5 emissions. These alarming figures underscore the critical need for cleaner transportation alternatives, strengthening the case for the widespread adoption of EVs as a solution to improve air quality and public health.

Secondly, EVs offer substantial potential for reducing carbon emissions as shown in Fig. 2. The transition from advanced internal combustion engines to fully electric and hydrogen-powered vehicles represents a technological advancement that could lead to significant emission reductions. Hybrid fuel and electric vehicles can reduce carbon emissions by 30–40%, while fully electric and hydrogen vehicles can achieve reductions of 50–100%. This spectrum of emission reduction capabilities underscores the critical role EVs play in mitigating the environmental impact of transportation.

Moreover, pollution-related deaths in India are alarmingly high compared to other countries. Studies done by Statista [3], indicate that deaths due to pollution in India are eight times higher than in neighboring Pakistan and more than sixteen times higher than in the USA. India's large population density exacerbates the situation, making pollution a more severe public health issue. In 2020, India led the world with approximately 2.51 million deaths attributable to pollution, followed by China with 1.83 million deaths. These figures emphasize the need for immediate action to adopt cleaner technologies like EVs to safeguard public health and the environment.

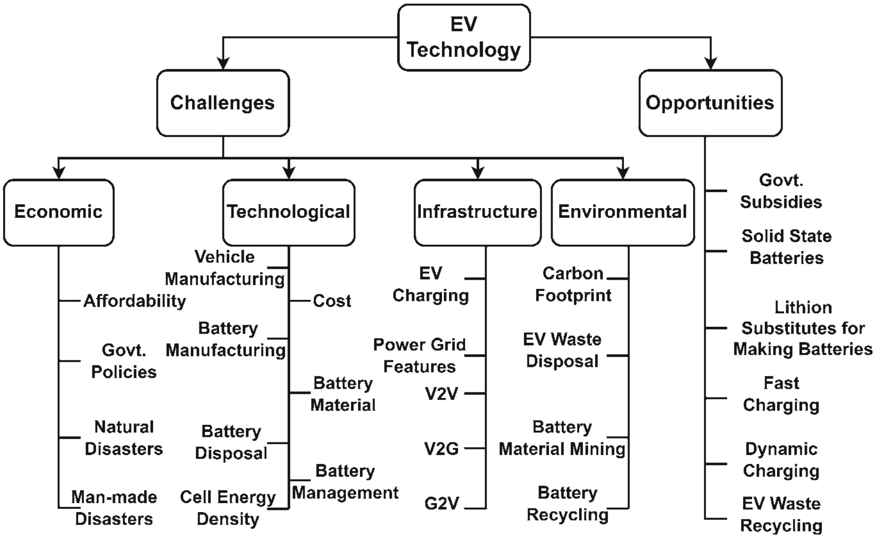

Fig. 3 EV challenges and opportunities [4]

In conclusion, the adoption of EVs offers a promising solution to address the severe air pollution and carbon emission challenges faced by India and other countries worldwide. By transitioning to electric mobility, we can achieve substantial reductions in harmful emissions, improve public health, and move toward a more sustainable and environmentally friendly transportation system.

2 Challenges and Opportunities in EV Technology

The transition to EV technology presents a myriad of challenges and opportunities across several dimensions, including economic, technological, infrastructure, and environmental aspects. Addressing these challenges while leveraging the opportunities is critical for the widespread adoption and sustainability of EVs (Fig. 3).

2.1 Economic Challenges and Opportunities

Economically, the affordability of EVs continues to be a major obstacle. The high upfront costs, largely due to the expensive battery technology and manufacturing processes, discourage many potential buyers, despite the long-term savings from lower operational costs. Government interventions, including subsidies, tax incentives, and rebates, are essential in alleviating this financial burden and making EVs more accessible to a broader range of consumers. Additionally, the industry faces risks from natural and man-made disasters that can disrupt supply chains and manufacturing processes. On the opportunity side, increased government subsidies and incentives can further alleviate financial barriers, enhancing market penetration and stimulating demand for EVs. The decreasing cost difference between EVs and internal combustion engine vehicles, fueled by advancements in battery technology and the benefits of economies of scale in manufacturing, is making EVs more affordable and accessible to a broader segment of the population [5].

2.2 Technological Challenges and Opportunities

Technologically, EVs face several hurdles, including the high cost of vehicle and battery manufacturing, the limited availability of battery materials, and the need for effective battery disposal methods. Improving battery cell energy density and overall battery management systems is essential to enhance the range and efficiency of EVs. Advances in solid-state batteries and the development of lithium substitutes for battery production offer promising opportunities. These innovations could lead to safer, more efficient, and longer-lasting batteries, addressing critical technological challenges in the EV sector. Furthermore, advancements in battery recycling processes can mitigate environmental impacts and reduce dependency on raw materials. The reduced complexity of electric motors, which have fewer moving components than internal combustion engines, translates into lower maintenance demands, significantly boosting the reliability and adaptability of EVs [6].

2.3 Infrastructure Challenges and Opportunities

The development of robust infrastructure is a critical determinant in accelerating the widespread adoption of EVs. A comprehensive and accessible network of EV charging stations is essential to alleviate range anxiety, a significant barrier for potential users. To ensure the seamless integration of EVs into the existing transportation ecosystem, it is imperative to focus on the strategic deployment of charging infrastructure across various environments, including residential, commercial, and public spaces.

The availability of charging stations must be ubiquitous, ensuring that EV owners have convenient access to recharging facilities, whether at home, work, or during long-distance travel. This widespread availability is crucial for fostering consumer confidence in EVs as a viable alternative to traditional internal combustion engine vehicles. Furthermore, the incorporation of advanced technologies such as Vehicle-to-Vehicle (V2V), Vehicle-to-Grid (V2G), and Grid-to-Vehicle (G2V) can significantly enhance the stability and efficiency of the power grid. These technologies enable bidirectional energy flows, allowing EVs to act as both energy consumers and providers, thus supporting grid management and renewable energy integration.

In addition to static charging solutions, the deployment of fast charging and dynamic charging technologies is essential for minimizing downtime and increasing the convenience of EV ownership. Fast charging stations, which can replenish an EV's battery in a fraction of the time required by standard chargers, are particularly critical for enabling long-distance travel and reducing the perceived inconvenience associated with EV charging. Dynamic charging, which allows vehicles to recharge while in motion, represents an innovative approach that could further revolutionize EV infrastructure by eliminating the need for stationary charging stops altogether.

The rapid expansion of this infrastructure is contingent upon significant investment from both governmental and private sectors. Public-private partnerships will be essential in financing, developing, and maintaining an extensive charging network that can support the growing number of EVs on the road. Government incentives, subsidies, and policy frameworks will play a pivotal role in encouraging private sector participation and ensuring that charging infrastructure development keeps pace with the increasing demand for EVs.

Ultimately, the creation of a comprehensive and resilient EV charging network is not merely a logistical necessity but a strategic imperative for the transition to sustainable transportation. By prioritizing the development of this infrastructure, we can address the challenges associated with EV adoption, enhance the user experience, and pave the way for a future where electric vehicles are the dominant mode of transport [7].

2.4 Environmental Challenges and Opportunities

From an environmental standpoint, reducing the carbon footprint of EVs and managing EV waste are key challenges. The extraction and disposal of battery materials demand effective recycling processes and the use of more sustainable materials. Solid-state batteries show promise for lower environmental impact and better performance. Dynamic charging systems can further cut the carbon footprint by optimizing energy use and incorporating renewable energy.

Initiatives like battery recycling and closed-loop supply chains can greatly reduce the environmental impact of battery production and disposal. Additionally, EVs offer public health benefits by producing zero tailpipe emissions, leading to lower levels of harmful pollutants and improved air quality [8].

The challenges and opportunities in EV technology are deeply interconnected and complex, necessitating coordinated efforts across economic, technological, infrastructural, and environmental domains. To overcome these challenges and unlock the full potential of electric vehicles, effective policies, technological innovations, infrastructure investments, and environmental strategies are crucial. Addressing these areas holistically will enable the EV industry to significantly contribute to global sustainability goals, reduce reliance on fossil fuels, and pave the way for a cleaner, more efficient transportation future. The benefits of EVs-including reliability, affordability, expanding infrastructure, and public health improvements-highlight their transformative potential in the transportation sector. As technological advancements continue and infrastructure development accelerates, EVs are set to play a central role in the global transition toward sustainable and eco-friendly transportation solutions.

3 EV Policy

EV policy is pivotal in driving the shift from conventional internal combustion engine vehicles to electric mobility, with the primary objectives of reducing greenhouse gas emissions, improving air quality, and enhancing energy security. A robust EV policy framework typically combines incentives, regulations, and infrastructure development to create a conducive environment for EV adoption. Governments globally are deploying a variety of measures to accelerate this transition. Financial incentives, such as tax credits, rebates, and subsidies, are critical in reducing the initial cost barrier, making EVs more financially accessible to consumers. These incentives not only stimulate demand but also encourage manufacturers to increase production, driving economies of scale and further lowering costs. Regulatory measures play an equally crucial role. Stricter emissions standards and fuel economy requirements for traditional vehicles are pressuring automakers to invest heavily in electric technology. These regulations not only promote cleaner vehicle production but also push the automotive industry toward innovation in battery technology, energy efficiency, and overall vehicle design.

Infrastructure development is another cornerstone of effective EV policy. Establishing a comprehensive, reliable network of charging stations is essential to mitigate range anxiety-a significant deterrent for potential EV buyers. Policies that incentivize private sector investment in charging infrastructure, alongside government-led initiatives, are fundamental to creating this network. Moreover, the integration of renewable energy sources into EV charging infrastructure is increasingly emphasized, maximizing the environmental benefits of EV adoption and contributing to the overall reduction of carbon footprints.

Policymakers are also prioritizing education and outreach programs to raise public awareness about the advantages of EVs and the available incentives. These programs are crucial for dispelling myths, increasing consumer knowledge, and fostering broader acceptance and adoption of electric vehicles.

In summary, a well-rounded and aggressively pursued EV policy framework is essential for accelerating the transition to electric mobility. By combining financial incentives, stringent regulations, comprehensive infrastructure development, and public education, governments can effectively drive the growth of the EV market, contributing to global sustainability efforts and the long-term reduction of greenhouse gas emissions.

3.1 Global EV Policies: Strategies and Impacts

EV policies have emerged as a critical component in global efforts to reduce greenhouse gas emissions, improve air quality, and transition toward sustainable energy systems. Among the myriad of policies implemented worldwide, several have proven to be particularly effective and have set benchmarks for others to follow. This discussion highlights some of the most prominent EV policies globally, with a focus on those that have significantly influenced EV adoption and infrastructure development.

Norway's comprehensive approach to EV incentives stands as one of the most influential policies in the world. The country offers significant tax exemptions for electric vehicles, including exemptions from value-added tax (VAT) and registration fees, which substantially lower the purchase price of EVs compared to internal combustion engine (ICE) vehicles. Beyond purchase incentives, EV owners in Norway enjoy additional benefits such as reduced tolls, access to bus lanes, free municipal parking, and exemptions from ferry fees. These extensive incentives have made Norway a global leader in EV adoption, with electric vehicles consistently representing over half of all new car sales in the country in recent years.

China has implemented a robust policy framework to become a global leader in EV adoption. The Chinese government offers significant subsidies for both manufacturers and consumers, along with tax exemptions and incentives for the development of charging infrastructure. The New Energy Vehicle (NEV) mandate requires automakers to produce a certain percentage of zero-emission vehicles, effectively driving the production and availability of EVs. Furthermore, China has invested heavily in public charging infrastructure, creating one of the world's largest networks of charging stations. These policies have not only increased EV sales but have also positioned China as a major player in the global EV market.

The European Union (EU) has established stringent emissions regulations and ambitious targets for reducing carbon dioxide emissions from vehicles. The EU's CO2 standards for new cars and vans require automakers to achieve fleet-wide average emissions reductions, incentivizing the production and sale of EVs. Additionally, many EU member states offer purchase incentives, tax benefits, and subsidies for home and public charging infrastructure. The EU's Green Deal further underscores the commitment to electrification by aiming for at least 30 million zero-emission vehicles on European roads by 2030. This comprehensive policy framework supports the transition to sustainable mobility across the continent.

The United States has also implemented a range of policies to promote EV adoption. The federal government offers a tax credit of up to $7,500 for the purchase of an EV, though this incentive phases out once a manufacturer reaches a certain sales threshold. Various states supplement federal incentives with additional rebates, tax credits, and non-monetary benefits such as carpool lane access. California, in particular, has been a leader in EV policy through its Zero Emission Vehicle (ZEV) program, which mandates that automakers sell a specific number of zero-emission vehicles. The state also invests heavily in charging infrastructure and provides grants for EV-related research and development.

Japan's EV policies emphasize a strategic mix of subsidies, tax incentives, and infrastructure development. The Japanese government provides substantial purchase subsidies and tax breaks for EV buyers, alongside financial assistance for expanding the network of charging stations. Japan's Next Generation Vehicle Promotion Center plays a crucial role by funding research and development efforts aimed at improving battery performance and lowering costs. Additionally, Japan prioritizes the integration of EVs with renewable energy sources, focusing on the development of V2G technologies that allow EVs to contribute to grid stability. These comprehensive policies have solidified Japan's position as a leader in automotive innovation and sustainability.

In summary, effective EV policies around the world share common features such as financial incentives for consumers and manufacturers, investments in charging infrastructure, and regulatory measures to drive the transition to electric mobility. These policies not only enhance the adoption of EVs but also support broader environmental and energy objectives. As the global automotive industry continues to evolve, the experiences of countries with successful EV policies will provide valuable lessons for others seeking to accelerate their transition to sustainable transportation.

3.2 EV Policy in India

India has taken significant steps to promote the adoption of EVs and reduce its reliance on fossil fuels through a series of proactive policies. These initiatives are designed to incentivize both manufacturers and consumers, fostering a nationwide transition toward sustainable transportation.

In 2010, the Indian government introduced a strategy to support Original Equipment Manufacturers (OEMs) with a budget allocation of INR 950 billion. This initiative aimed to boost EV production and encourage their adoption by providing financial incentives to manufacturers. By 2013, the government launched the National Electric Mobility Mission Plan (NEMMP) 2020, which set forth a comprehensive vision for the future of electric mobility in India. This plan detailed strategic objectives and actions necessary to achieve broad-based EV adoption across the country.

However, the initial incentive program launched in 2012 faced challenges and was scrapped, resulting in a significant 70% reduction in EV sales. Recognizing the need for a more robust approach, the Faster Adoption and Manufacturing of (Hybrid &) Electric Vehicles (FAME) scheme was introduced in 2015. FAME-I, with an allocation of INR 5.29 billion, ran until March 2019, offering subsidies and incentives to boost EV adoption.

Building on the earlier initiatives, the Indian government launched the second phase of the Faster Adoption and Manufacturing of Hybrid and Electric Vehicles (FAME II) scheme on April 1, 2019. With an approved budget of INR 10,000 crores (approximately USD 1.4 billion), FAME II represents a significant advancement in India's commitment to accelerating the adoption of EVs [9]. This phase includes crucial measures such as reducing taxes on EVs and electric chargers to 5%, further incentivizing their adoption. The scheme targets the deployment of 7,000 electric buses, 500,000 electric three-wheelers, 55,000 electric four-wheelers, and 1 million electric two-wheelers across the country. By offering substantial subsidies on these vehicles, FAME II aims to make EVs more affordable, encouraging a transition from conventional fossil fuel-powered transportation.

In addition to vehicle subsidies, FAME II places a strong emphasis on developing the necessary charging infrastructure to support the growing number of EVs. The scheme plans to establish approximately 2,700 charging stations nationwide, ensuring that EV users have convenient access to charging facilities, thereby addressing one of the main barriers to EV adoption-range anxiety.

Following FAME II, the Indian government has introduced several complementary policies to strengthen the EV ecosystem. One key initiative is the Production-Linked Incentive (PLI) scheme for Advanced Chemistry Cell (ACC) battery storage, with an allocation of INR 18,100 crores (about USD 2.4 billion). This scheme is designed to encourage domestic production of high-efficiency batteries, which are crucial for the EV industry, thereby reducing reliance on imported batteries and bolstering local manufacturing capabilities.

Furthermore, various Indian states have implemented their own EV policies, providing additional incentives such as tax rebates, reduced registration fees, and subsidized charging infrastructure to attract both manufacturers and consumers. The National Mission on Transformative Mobility and Battery Storage also plays a pivotal role by promoting innovation in battery technology and electric mobility, ensuring that India remains competitive in the global shift toward sustainable transportation.

These comprehensive efforts by the Indian government reflect a multifaceted approach to promoting the widespread adoption of electric vehicles, reducing pollution, and achieving long-term energy security. The combined impact of these policies is expected to significantly advance India's transition to a cleaner, more sustainable transportation system.

On a global level, achieving net zero emissions by 2050 is a formidable yet imperative goal for combating climate change and ensuring a sustainable future. This ambitious target involves drastically reducing greenhouse gas emissions and balancing any remaining emissions with equivalent carbon removal efforts. The roadmap to net zero emissions encompasses several critical strategies. Firstly, it necessitates a significant shift from fossil fuels to renewable energy sources such as wind, solar, and hydropower, ensuring that the energy sector is predominantly clean and sustainable. Enhancing energy efficiency across industries, buildings, and transportation is also crucial, reducing overall energy demand and wastage. Figure 4 shows the roadmap to net zero emissions by 2050 [10].

Moreover, the electrification of transport and the widespread adoption of EVs play a pivotal role in curbing emissions from one of the largest contributing sectors. Integrating smart grid technologies and battery storage solutions further supports the reliability and flexibility of renewable energy. Additionally, advancements in carbon capture, utilization, and storage (CCUS) technologies are essential for mitigating emissions from hard-to-abate sectors such as heavy industry and aviation. The roadmap also emphasizes the importance of reforestation, afforestation, and soil car-

Fig. 4 Net zero emission roadmap by 2050 [10]

bon sequestration to enhance natural carbon sinks. International cooperation, robust policy frameworks, financial investments, and public engagement are indispensable components of this comprehensive approach. Collectively, these efforts aim to create a resilient, low-carbon economy by 2050, averting the worst impacts of climate change and fostering a healthier, more sustainable planet.

4 The EV Ecosystem

The development of the EV ecosystem is a multifaceted endeavor involving various stakeholders and components working together to support the widespread adoption of EVs. The ecosystem can be broadly categorized into three main areas: charging infrastructure, users, and electric vehicles themselves, all interconnected by the electricity network. Figure 5 shows various stakeholders of the EV ecosystem.

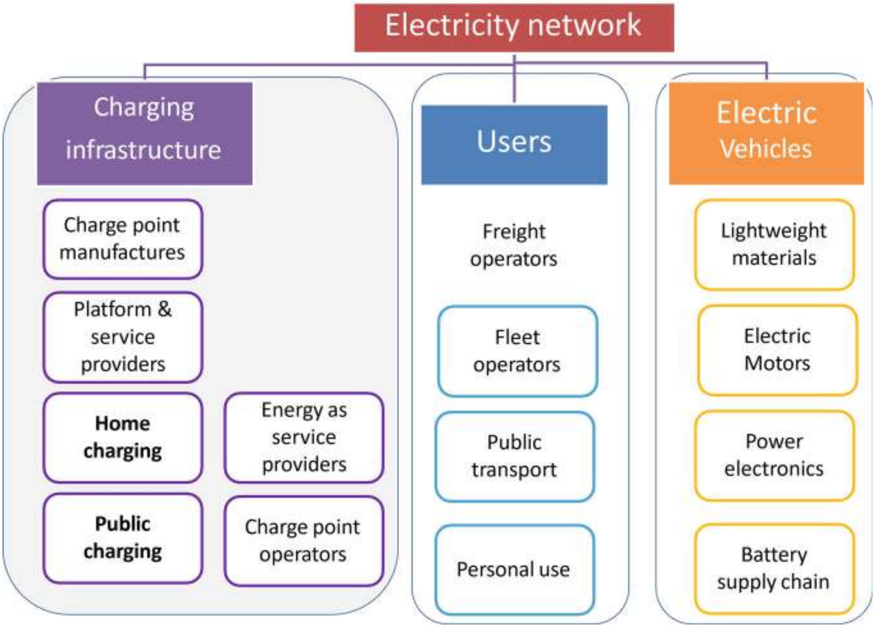

Fig. 5 Various stakeholders of the EV ecosystem

Firstly, the charging infrastructure is a critical component of the EV ecosystem, ensuring that vehicles have access to reliable and efficient charging solutions. Key players in this area include charge point manufacturers, who produce the necessary hardware, and platform and service providers, who offer software solutions for managing charging networks. Energy service providers supply the electricity needed to charge the vehicles. Charging infrastructure encompasses both home charging solutions for individual users and public charging stations for broader accessibility. Charge point operators are responsible for the installation and maintenance of these charging stations, facilitating seamless energy access for EV users.

Secondly, the user segment of the EV ecosystem is diverse, encompassing various types of vehicle operators. Freight operators utilize EVs for transporting goods, reducing the carbon footprint of logistics. Fleet operators manage a large number of vehicles, often for corporate or governmental use, and benefit from the lower operating costs of EVs. Public transport systems, such as buses and taxis, are increasingly integrating EVs to provide cleaner and more sustainable mobility solutions. Lastly, personal use of EVs by individual consumers is growing as more people recognize the environmental and economic benefits of electric mobility.

Thirdly, the vehicles themselves are at the core of the ecosystem, incorporating advanced technologies and materials. Key components include lightweight materials that enhance vehicle efficiency by reducing weight, electric motors that provide propulsion, power electronics that manage the flow of electrical energy within the vehicle, and the battery supply chain that ensures a steady supply of high-capacity batteries. These elements work together to produce vehicles that are not only environmentally friendly but also efficient and reliable.

Moreover, the electricity network serves as the backbone that connects all elements of the EV ecosystem. It supplies the necessary energy to charging infrastructure and supports the operation of electric vehicles. Ensuring a robust and resilient electricity network is crucial for the sustainable growth of the EV ecosystem.

In conclusion, the integration of these components forms a comprehensive and cohesive EV ecosystem in India, driving the transition toward sustainable transportation. By fostering collaboration among manufacturers, service providers, users, and policymakers, India can build a resilient infrastructure that supports the growth and adoption of electric vehicles, contributing to a cleaner and greener future.

4.1 EV Market in India

EV market in India is witnessing rapid expansion, fueled by substantial investments and a supportive policy framework. By 2021, total EV investments in India had surpassed USD 2 billion, reflecting the growing financial commitment to advancing electric mobility (Fig. 6) [11].

Projections indicate that the Indian EV market is expected to grow at an impressive Compound Annual Growth Rate (CAGR) of 94.4%, expanding from USD 0.38 billion in 2021 to USD 152 billion by 2030. This remarkable growth trajectory highlights the immense potential of the EV sector to revolutionize the automotive industry in India.

Moreover, the distribution of investments across different EV segments shows a diverse allocation of resources. Around 47% of the investments have been directed toward electric buses (E-Bus), reflecting the emphasis on transforming public transportation systems. Electric cars (E-Cars) account for 46% of the investments, indicating strong interest in passenger vehicles. Other segments, including electric three-wheelers (E3W) and electric two-wheelers (E2W), have also attracted investments, albeit to a lesser extent, with each receiving 3% and 1%, respectively. This allocation demonstrates a balanced approach to developing various segments of the EV market, ensuring comprehensive growth across different types of electric vehicles.

Also, the contributions from charging infrastructure and Indian battery companies play a critical role in supporting the EV ecosystem. Investments in these areas are essential for creating a robust and sustainable EV market, addressing one of the key challenges of EV adoption-adequate charging facilities and reliable battery supply chains.

The EV market in India has shown remarkable growth from 2019 to 2023, highlighting a significant shift toward sustainable transportation. Figure 7 shows the number of electric vehicles sold in India from 2019 to 2023 across the four segments [12]. According to the data, the sales of two-wheelers have surged from 30.36 thousand units in 2019 to 856.84 thousand units in 2023, reflecting the growing popularity

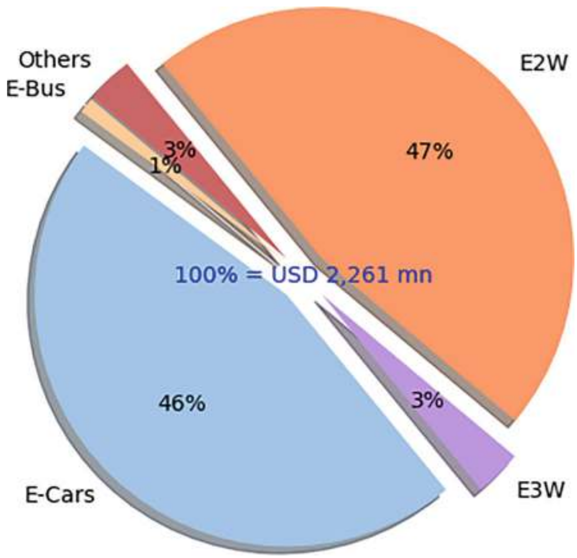

Fig. 6 The distribution of investments across different EV segments in India by 2021 [11]

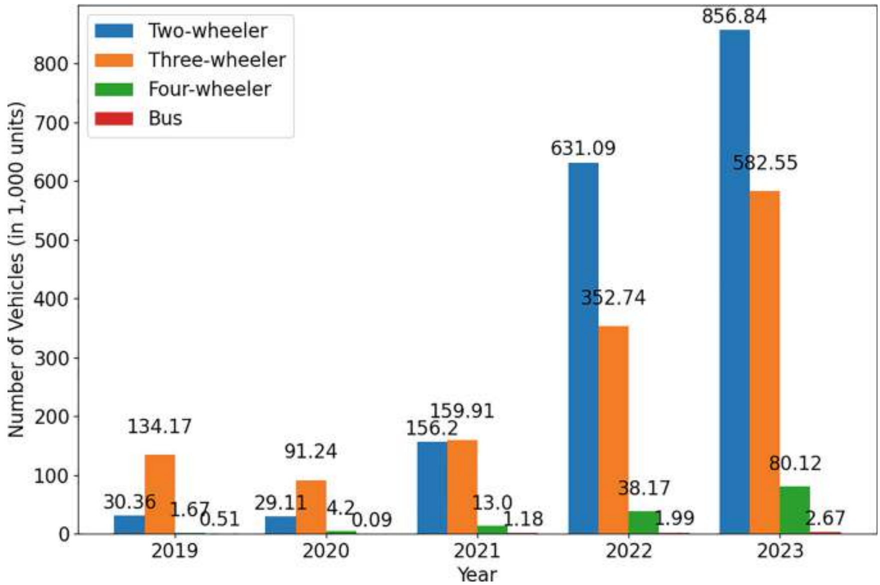

Fig. 7 Number of electric vehicles sold in India (2019–2023) by type [12]

and adoption of EVs among consumers. Similarly, three-wheelers have also seen a substantial increase in sales, rising from 134.17 thousand units in 2019 to 582.55 thousand units in 2023. This growth is indicative of the expanding use of EVs for commercial and public transportation purposes. Passenger vehicles, although starting from a lower base, have increased from 1.67 thousand units in 2019 to 80.12 thousand units in 2023, showing a growing consumer interest in electric cars. The sales of electric buses have also shown an upward trend, increasing from 0.51 thousand units in 2019 to 2.67 thousand units in 2023. This trend underscores the varying adoption rates across different segments of the EV market in India. These figures emphasize the rapid evolution of the EV market and the growing recognition of electric mobility as a practical and eco-friendly alternative to traditional fossil fuel-powered vehicles.

4.2 EV Market Dynamics: Drivers and Barriers

The global EV market is influenced by a myriad of factors that drive adoption, as well as notable barriers that impede growth. Key among the drivers is the implementation of favorable government policies and subsidies, which significantly promote EV adoption worldwide. Substantial investments from automakers further bolster the development and availability of EVs, expanding the market. The increasing diversity of EV products caters to a broad spectrum of consumer preferences, enhancing their appeal across different demographic groups. Additionally, growing awareness of air quality and environmental issues drives consumer interest in EVs, especially as global income levels rise and environmental consciousness increases. The lower total cost of ownership (TCO) of EVs compared to internal combustion engine (ICE) vehicles also makes them an economically attractive option, further encouraging adoption [13, 14].

Despite these drivers, the EV market faces several significant barriers. The complexity of criteria and processes required to benefit from government incentives, both on the demand and supply sides, can deter potential adopters globally. The economic downturn induced by the COVID-19 pandemic has impacted consumer spending power, affecting EV adoption rates, especially in emerging markets. A critical challenge to scaling up production is the limited availability of raw materials necessary for domestic manufacturing of EV batteries. Furthermore, the slow rollout of charging infrastructure remains a critical bottleneck, affecting the convenience and feasibility of using EVs in many regions. The high upfront costs of electric four-wheelers compared to ICE vehicles can also be a deterrent for consumers, particularly in markets where cost sensitivity is high. Lastly, reliability issues within electricity networks can affect the consistent and reliable operation of EV charging infrastructure, posing a significant hindrance to broader global adoption.

These factors collectively highlight the dynamic and complex nature of the global EV market, underscoring both the opportunities and challenges that lie ahead in the transition to sustainable transportation.

4.3 Challenges for EV Market in India

The EV market in India encounters several significant challenges that impede its growth and widespread adoption. One of the most critical obstacles is the insufficient charging infrastructure. Although EVs offer considerable environmental and economic benefits, their full potential is constrained by the scarcity of charging stations nationwide. This shortage not only diminishes the convenience and practicality of EVs but also exacerbates range anxiety among consumers-the concern that a vehicle may not have enough charge to reach its destination. Without a comprehensive and well-distributed network of charging stations, many consumers remain reluctant to shift from traditional internal combustion engine vehicles to electric alternatives [14–16].

Secondly, the Indian EV market's heavy reliance on battery imports presents a significant challenge. Batteries are a critical component of EVs, and the dependence on imported batteries not only escalates costs but also exposes the market to global supply chain disruptions. Additionally, the reliance on imported components and parts further complicates the manufacturing process, increasing production costs and limiting the growth of a self-sustained EV industry in India. This dependency highlights the need for developing a strong domestic supply chain and local manufacturing capabilities to mitigate risks and reduce costs [14].

Thirdly, incentives linked to local manufacturing are essential for fostering the growth of the EV market. However, the current incentive structures often fail to adequately support the establishment of local manufacturing facilities. This gap can discourage potential investors and manufacturers from setting up operations in India, thereby slowing down the growth of the domestic EV industry. Furthermore, the high initial costs of EVs, partly due to the reliance on imported components, make them less affordable for the average consumer. To overcome this barrier, there is a need for more substantial and targeted incentives that encourage local production and make EVs more accessible to the masses.

Moreover, the lack of options for high-performance EVs and inadequate electricity supply in parts of India are additional hurdles. High-performance EVs are essential to meet the diverse needs of consumers, particularly those looking for vehicles that offer more than just basic transportation. The limited availability of such options can deter potential buyers who seek performance and reliability. In parallel, inadequate electricity supply in various regions poses a significant challenge to the effective operation of EV charging infrastructure. Without consistent and reliable electricity, charging stations cannot function optimally, further exacerbating range anxiety and limiting the adoption of EVs.

Lastly, the broader automobile industry downturn affects the EV market as well. Economic slowdowns and reduced consumer spending power impact all sectors, including the emerging EV market. This downturn can slow investment, production, and sales, making it more difficult for the EV industry to gain momentum. Additionally, the lack of quality maintenance and repair options for EVs presents a challenge for long-term adoption. Consumers need assurance that their vehicles can be reliably serviced and maintained, and the current scarcity of specialized service centers can be a significant deterrent.

In conclusion, while the Indian EV market holds great promise, it is currently encumbered by several significant challenges. Addressing these issues through targeted policies, investments in infrastructure, development of local manufacturing capabilities, and ensuring reliable electricity supply is crucial. By overcoming these hurdles, India can pave the way for a more sustainable and widely adopted electric vehicle ecosystem.

4.4 Smart Charging Concept for Optimal EV Integration

Smart charging is an essential concept for integrating EVs into the power grid, facilitating efficient energy management and enhancing the stability of the electricity network. Different smart charging strategies can be implemented to achieve these objectives, each providing varying degrees of control and interaction with the grid and related infrastructures (Fig. 8).

A fundamental approach to smart charging is time-of-use pricing without automated control, where EV owners are incentivized to charge their vehicles during off-peak hours when electricity rates are lower. This method encourages users to adjust their charging habits to times of reduced demand, helping to alleviate grid strain during peak periods. However, it relies on manual intervention by the user to start the charging process, as it does not include automated control.

Another approach involves basic controlled (on/off) charging, where charging can be controlled remotely to start or stop based on grid demand signals or pre-set schedules. This method provides a level of automation that can help balance grid loads but still operates within a limited control framework.

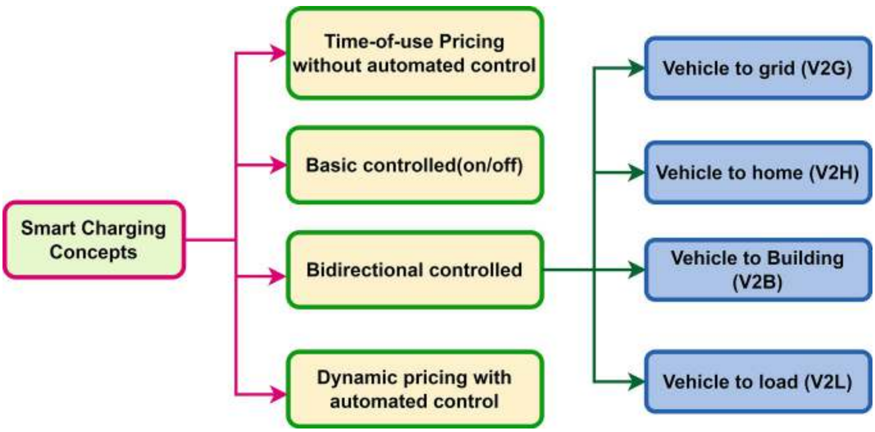

Fig. 8 Smart charging concept for optimal EV integration

Bidirectional controlled charging, commonly referred to as V2G technology, enables a two-way energy flow between the EV and the grid. With V2G, EVs can not only draw power from the grid but also feed stored energy back into it. This functionality enhances grid stability by offering a decentralized energy storage solution that can be utilized during peak demand periods or emergencies. V2G technology marks a significant advancement in smart charging, allowing EVs to actively participate in grid management [17–21].

Dynamic pricing with automated control takes smart charging to a higher level of sophistication. It involves real-time adjustments to charging schedules based on dynamic electricity pricing and grid conditions. Automated systems can respond instantly to price signals and grid demand fluctuations, optimizing charging times to minimize costs and support grid stability. This approach leverages advanced algorithms and real-time data to provide seamless and efficient energy management.

Smart charging concepts also encompass V2H, V2B, and V2L technologies, broadening the functionality beyond V2G. V2H allows EVs to supply power to a home, providing backup during outages or reducing household electricity costs by using stored energy during peak pricing periods. V2B enables EVs to contribute energy to larger building infrastructures, potentially lowering operational costs and supporting energy management strategies within commercial buildings. V2L expands this capability by allowing EVs to power specific loads directly, offering portable power solutions for various applications [22–24].

In conclusion, the integration of smart charging concepts for EVs is pivotal for achieving optimal energy management and enhancing the stability and efficiency of the power grid. The evolution from basic time-of-use pricing to sophisticated dynamic pricing with automated control reflects the increasing complexity and capability of smart charging technologies. By leveraging these advanced strategies, the potential of EVs to support grid stability, reduce energy costs, and provide decentralized energy storage solutions can be fully realized.

5 Bidirectional Controlled Methods

Bidirectional controlled methods represent a major advancement in integrating EVs with the power grid, offering diverse pathways for energy flow that enhance grid stability and energy management. These methods include V2G, V2H, V2B, and V2L, each delivering distinct benefits and applications.

V2G technology allows for a two-way energy exchange between EVs and the grid. In this system, EVs can return stored energy to the grid during peak demand periods or emergencies, thereby supporting grid stability and reducing the reliance on additional power generation. This bidirectional flow effectively transforms EVs into mobile energy storage units that can be dynamically used to balance supply and demand [17–19]. Integrating V2G is essential for enhancing the resilience of the electricity network and advancing the use of renewable energy sources.

V2H allows EVs to supply power to a household, providing backup power during outages or reducing electricity costs by using stored energy during peak pricing periods. This application is particularly beneficial in regions with unreliable power supply, offering homeowners an additional layer of energy security. V2H systems can seamlessly switch between grid power and the EV's battery, optimizing energy use based on real-time conditions [22]. V2B extends the concept of V2H to larger building infrastructures, such as commercial and residential complexes. By integrating EVs into the building's energy management system, V2B can help reduce operational costs and support demand response strategies. This method allows for efficient energy distribution within the building, utilizing EV batteries to store excess energy generated from renewable sources or during off-peak hours and discharging it when demand is high [23]. V2L offers a flexible solution for providing power to specific loads or devices directly from the EV. This capability is particularly useful for portable power applications, such as powering tools at construction sites or providing electricity in remote areas without grid access. V2L enhances the utility of EVs by allowing them to serve as versatile power sources in a variety of contexts [24].

In conclusion, bidirectional controlled methods such as V2G, V2H, V2B, and V2L are crucial for optimizing the integration of EVs with the power grid. These technologies enhance grid stability and energy management while offering substantial benefits in energy security, cost savings, and the promotion of renewable energy. By utilizing these advanced strategies, the full potential of EVs as key elements in a sustainable energy system can be fully realized (Fig. 9).

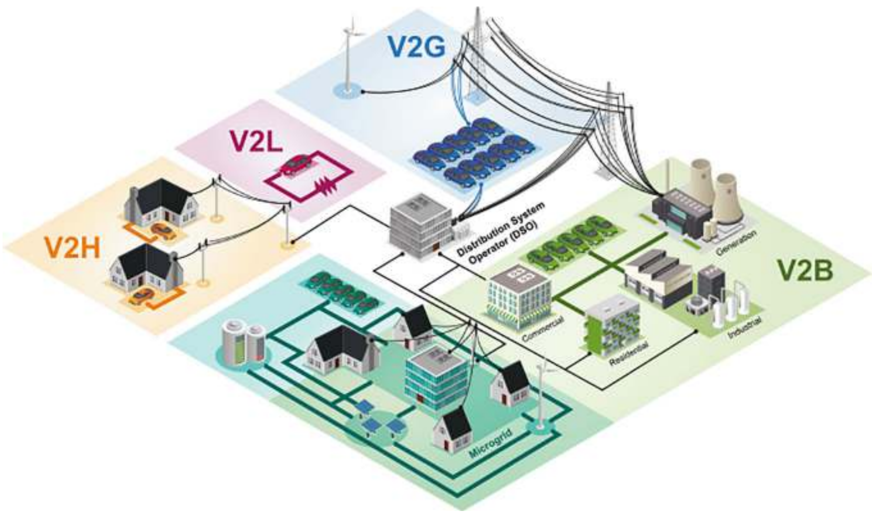

Fig. 9 Bidirectional controlled methods for optimal EV integration [25]

5.1 Advantages of Smart Charging

The advantages of smart charging extend across various stakeholders in the energy ecosystem, providing multiple benefits that enhance the efficiency and reliability of electricity distribution and consumption. For utility distribution network operators, smart charging offers increased hosting capacity, faster implementation, and reduced costs. By managing the charging times of EVs, utilities can optimize the use of existing infrastructure, defer costly upgrades, and integrate more renewable energy sources into the grid. Smart charging allows for a more balanced load distribution, minimizing peak demand pressures and reducing the need for additional generation capacity.

Utility transmission system operators also benefit significantly from smart charging through the limitation of system peak loads and the avoidance of constructing new generation capacities. By shifting the charging of EVs to off-peak periods, transmission operators can maintain system stability and reliability. This demand-side management technique helps in flattening the load curve, thus improving the overall efficiency of the power system and reducing operational costs. For building managers, smart charging facilitates time-of-use tariff optimization, photovoltaic (PV) balancing, and demand charge management. By aligning EV charging schedules with lower tariff periods, building managers can reduce electricity costs and optimize energy use. Additionally, smart charging systems can integrate with PV systems to maximize the utilization of locally generated solar energy, further reducing dependency on the grid. Demand charge management and load balancing are critical in managing peak loads within buildings, thus reducing the connection fees and enhancing the building's energy efficiency.

In summary, smart charging provides substantial advantages for utility distribution and transmission network operators as well as building managers. These benefits include enhanced grid stability, optimized energy use, reduced operational costs, and improved integration of renewable energy sources. As the adoption of EVs continues to rise, the implementation of smart charging strategies will become increasingly vital in achieving a sustainable and efficient energy system (Fig. 10).

5.2 Challenges of Smart Charging

The integration of smart charging for EVs into the power grid presents several challenges due to the complexity of the EV-grid ecosystem. This ecosystem involves numerous stakeholders, each with specific roles and interactions that must be seamlessly coordinated to achieve efficient and reliable smart charging solutions.

Firstly, the EV ecosystem includes various participants such as drivers and eMobility customers, eMobility service providers, auto manufacturers, fleet owners, parking providers, and charging station manufacturers. Each of these stakeholders plays a critical role in the deployment and operation of EVs and their associated infras-

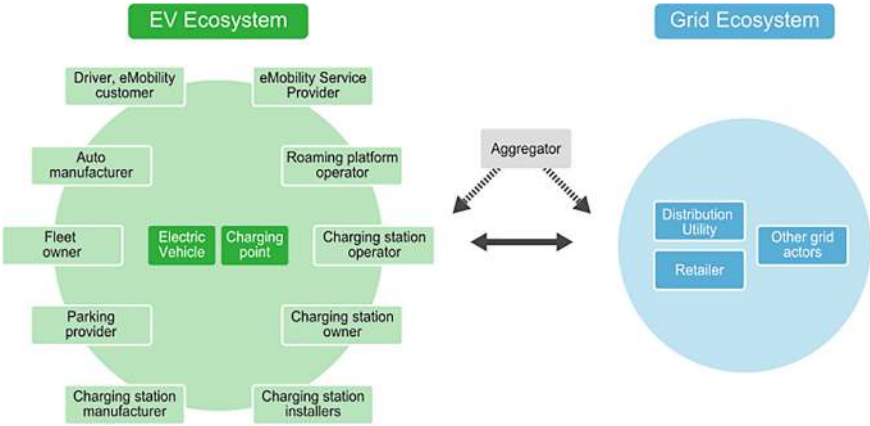

Fig. 10 Challenges for smart charging in a complex EV-grid ecosystem [25]

tructure. For instance, auto manufacturers are responsible for producing EVs with compatible charging technologies, while eMobility service providers manage the software platforms that facilitate charging services [26].

Secondly, the grid ecosystem comprises distribution utilities, retailers, and other grid actors. These entities are responsible for maintaining the stability and reliability of the electrical grid, ensuring that it can accommodate the additional load imposed by widespread EV charging. The coordination between the EV ecosystem and the grid ecosystem is essential to prevent overloading of the grid and to optimize the use of available resources [27, 28].

A crucial element in this coordination is the role of aggregators. Aggregators serve as intermediaries between EVs and the grid, managing the collective charging and discharging activities of multiple EVs to effectively balance supply and demand. They are essential in implementing demand response strategies and facilitating V2G interactions, where EVs can return stored energy to the grid during peak demand periods. This bidirectional energy flow is key to utilizing EVs as distributed energy resources (DERs) and improving grid stability.

However, the complexity of the EV-grid ecosystem introduces several challenges. The diverse range of stakeholders requires robust communication and coordination mechanisms to ensure that all parties are aligned in their efforts. Additionally, the integration of advanced technologies for dynamic pricing, automated control, and real-time data analytics is necessary to manage the varying demands and supply conditions effectively. These technologies must be interoperable across different platforms and devices to achieve a seamless smart charging experience.

Moreover, specific challenges such as the need for smart meters for dynamic pricing, the high cost of bidirectional chargers for V2G, and the lack of obligation for smart EV chargers due to cost burdens must be addressed. The absence of standards, especially in communications infrastructure, billing, roaming, and data semantics, poses significant obstacles. Cybersecurity compliance and data privacy in some regions add further complexity. Charges applicable to V2G (often referred to as 'double charging') and grid code limitations present additional barriers. The high cost of bidirectional chargers for V2G and the space for aggregators managing fleets of EVs, along with the ability to stack revenue of EV flexibility, are crucial concerns.

Addressing these issues requires coordinated efforts among stakeholders, including policymakers, utility providers, and the automotive industry. Effective collaboration, backed by advanced technological solutions, is crucial for optimizing energy management, enhancing grid stability, and accelerating the widespread adoption of EVs. As the EV market continues to grow, overcoming these challenges will be crucial to realizing the full potential of smart charging systems.

6 Conclusions

The electrification of transportation represents more than just a technological advancement; it is a vital step toward a sustainable future. This chapter has offered a thorough overview of electric vehicles, discussing their different types, the pressing reasons for their adoption, and the various challenges and opportunities they bring. The discussion on EV policies highlighted the essential role of government and regulatory frameworks in facilitating the transition. Moreover, the exploration of the EV ecosystem emphasized the interconnected elements necessary for a robust and sustainable EV market, including manufacturing, supply chains, and infrastructure. The concept of smart charging, with its potential to optimize energy consumption, reduce costs, and support grid stability, represents a significant advancement in the EV domain. By integrating renewable energy sources and enabling technologies like V2G, smart charging systems are set to revolutionize how we approach energy management in the context of electric mobility.

In conclusion, the transition to electric vehicles is a multifaceted challenge that requires coordinated efforts across various sectors. However, the benefits of reduced emissions, enhanced energy security, and economic advantages make it a compelling choice for the future of transportation. As technology advances and policies continue to evolve, electric vehicles will be instrumental in meeting global sustainability objectives. This chapter has laid a critical foundation, offering readers a comprehensive understanding of the multifaceted nature of electric vehicles, and preparing them for serious, informed discussions and innovations in this pivotal area.

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Chapter 3
Charging Technologies and Infrastructure for EVs: Trends, Technologies, and Integration Strategies for System Stability

Sarika S. Kanojia, Bhavik N. Suthar, Ashutosh K. Giri, and Madhusudan Singh

Abstract The global electric vehicle (EV) market is rapidly developing as many people choose EVs over conventional internal combustion engine (ICE) vehicles. Despite this transformation, there are still concerns regarding EV adoption due to perceived limitations in rapid charging technology and infrastructure. This paper gives a comprehensive overview of various elements of EV charging with the goal of addressing these concerns. It begins with examining different charging types, standards, levels, modes, and topologies utilized in EV charging systems. Understanding these components is crucial as they influence the efficiency, speed, and compatibility of charging solutions available to consumers and businesses alike. Furthermore, the article examines the current state of EV charging infrastructure, focusing on existing types and their geographic distribution. It also addresses the barriers to widespread EV adoption, such as the need for more robust and accessible charging networks. The EVCS impact with and without DG is tested in IEEE 33 bus distribution system which shows inclusion of DG with EVCS will increase the voltage stability and reduce the losses of the system. At last, the paper identifies potential future developments that could significantly enhance EV adoption rates. These include advancements in fast

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charging technologies, improvements in charging infrastructure deployment, and the integration of smart grid solutions to optimize energy usage and distribution.

Keywords Electric vehicles charging station (EVCS) · EV chargers · Standards · Levels of charging · Charging infrastructure

1 Introduction

Due to the increasing CO_2 emission and its adverse effect on our environment, it is important to limit the use of products producing CO_2 and other greenhouse gases. Global warming effects have increased in the past few years [1]. Transportation sector is one of the major CO_2 producers in the world [2, 3]. World is experiencing a radical change in transportation sector as conventional IC engine vehicles are being replaced by Electric Vehicles (EVs). Governments of many countries are imposing rules to limit the use of fossil fuels by promoting EVs. Government of India came up with policy for use of EVs in 2014 [4]. One major drawback of EVs is that it takes hours to charge its battery which limits the high penetration of EVs.

As EV penetration is increasing, it is important to manage the charging requirements of the EV user because charging EV batteries quickly like refueling IC engine vehicles is difficult. User needs to wait for tens of minutes or sometimes for several hours to charge their battery due to which queue at charging station may increase which is a waste of time. Solution to this problem is to increase the number of EV charging stations equipped with safe, smart, reliable, and fast charging facilities. For fast charging of EV, there are several technologies available and further research is going on [5, 6]. There are some safety measures that should be taken care of when going for fast charging or ultrafast charging (UFC) as high current value can degrade the battery's performance and its lifespan. Too high and too low temperature can also affect the performance and life span of the battery [7].

There are mainly three types of EV charging. Level-1, Level-2, and Level-3, where Level 1 and 2 are AC slow and fast charging, respectively and Level 3 is DC fast charging [6, 7]. DC fast charging may further be divided into Levels 1, 2, and 3 DC fast charging as shown in Fig. 1. There are several configurations of connectors for these charging types, each type has different designs based on their power ratings shown in Fig. 2. To convert the power from one type to the other type and to change the level of voltage according to need several topologies are used. Some of the popular topologies are AC–DC converter and DC–DC converter [8, 9].

For public charging, installation of charging stations at public places like fuel stations, restaurants, and parks is needed. Placing of charging station in such a way that people have to wait in queue for minimum time to charge their vehicle. Different types and technologies for EV charging are discussed in Sect. 2. In Sect. 3, various charging station configurations are shown. Charging station infrastructure has been discussed in Sect. 4.

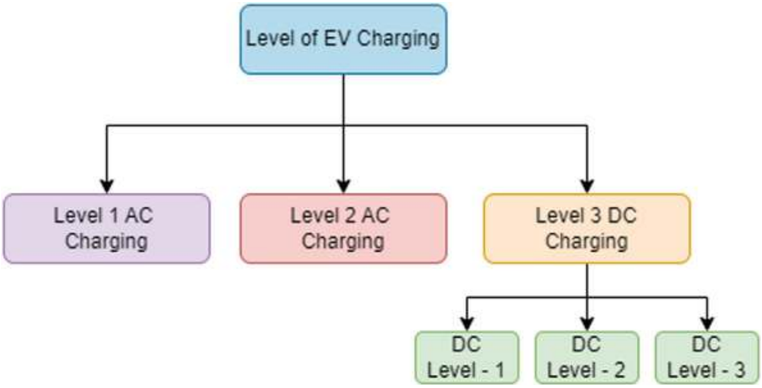

Fig. 1 Different levels of EV charging

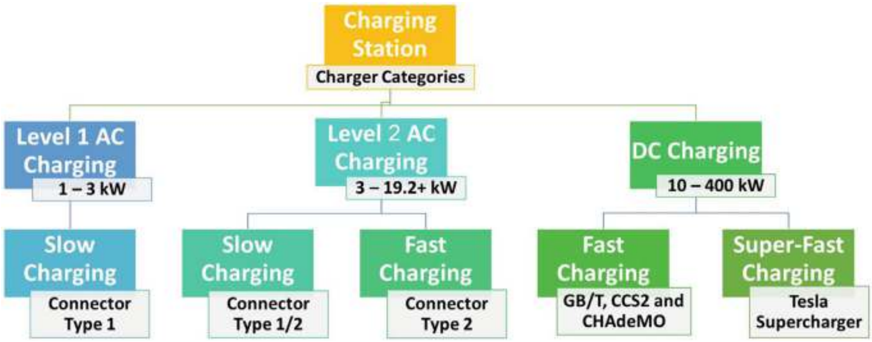

Fig. 2 Different charger categories widely used in EV industry

There are still many problems for EV penetration that need to be solved to increase the EV market share in transportation sector. In Sect. 6, several challenges and future scope to solve these challenges to achieve ultimate goal of EVs in place of IC engine vehicles [10] followed by conclusion are discussed.

2 Types and Technology of EV Charging

EV charging can be classified by various aspects, based on time of charging and connection type. Due to increasing penetration of EVs, requirement for fast charging is increasing and several research is going also on. Fast charging of EV can be further divided according to various standards followed in various continents and countries [6, 7, 11]. It can be mainly classified into two standards Society of Automotive Engineers (SAE) and International Electro Technical Commission (IEC). Other widely

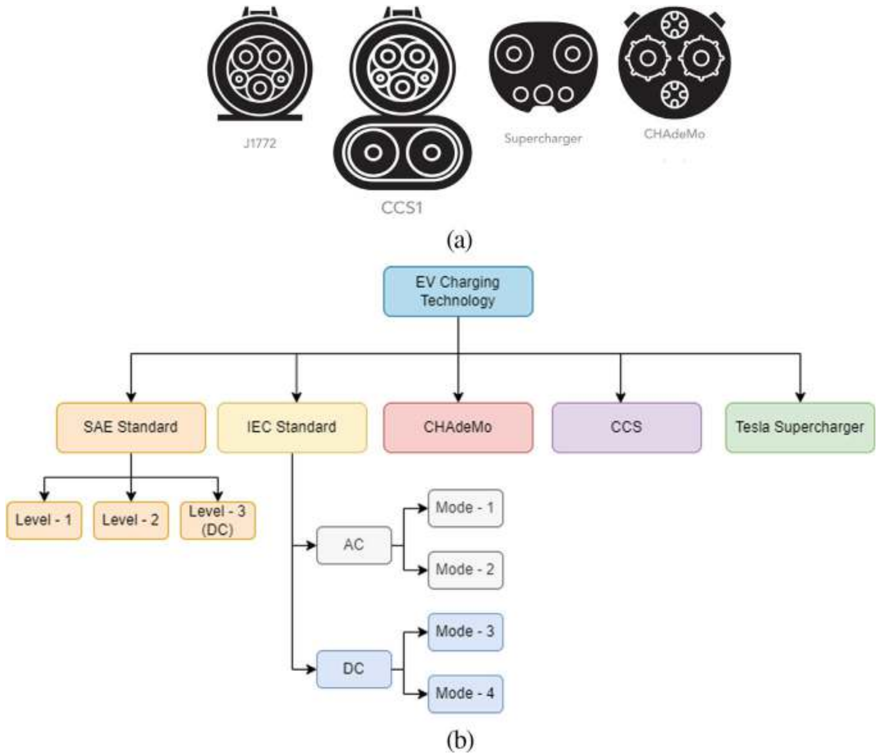

Fig. 3 **a** Various connector types used for EV charger [7]. **b** Classification of EV charging technologies

accepted standards are J1772, CHAdeMO, Combined Charging System (CCS), Tesla Supercharger as shown in Fig. 3a [7] and its various EV charging technologies are shown in Fig. 3b.

A. SAE standards

According to SAE standards, there are three levels of EV charging. Levels 1 and 2 are AC charging and level 3 is DC charging [12–14]. The comparison between different power level types for EV charging is shown in Table 1.

1. Level 1 AC charging

Level 1 AC charging is slow charging method for EV. It delivers 1–2 kW power delivery. It takes 8–12 h to completely charge the battery. This charging is generally employed at residence user. User can directly plug into the connector into the socket. Level 1 charging uses 120 V supply to charge EV battery. This method has advantage that it does not require any special safety equipment.

Table 1 Comparison between different power level types for EV charging

Power level type	Typical use	Power level (kW)	Charging time (h)	Supply connection	Merit	Demerit
Level 1	Slow charging for home or office	1–2	8–12	1-phase	Minimal installation expenses. Little utility impact	Slow rate of charging. Extended time of charging
Level 2	Primary charging at private or public use	Upto 19.2	6–8	1-phase	Quick charging time. Energy-conserving	High cost of installation. Effect on the utility
Level 3	Fast charging for public use	50–350	0.2–1	3-phase	High cost of installation. Effect on the utility	High cost of installation. High effect on the utility

2. **Level 2 AC charging**

Level 2 AC charging is fast charging method. It gives maximum power delivery of 19.2 kW. It generally takes 240 V power supply. It takes 6–8 h to completely charge the battery. It is employed at residential places, public parking, and commercial places. It has advantage that it charges the battery in lesser time compared to level 1 charging but it has high installation cost compared to level 1.

3. **Level 3 DC charging**

Level 3 DC charging is rapid charging method. It delivers 50–350 kW power. Generally, how much power can EV take depends on EV model. It is connected to 480 V dc supply. It charges battery from 0 to 80% in 15–60 min. Charging time from 80–100% is more in dc charging hence to measure time we consider 0–80% charging of battery [9]. The number of charging ports available for level 2 AC charging and DC fast charging in US public charging port is shown in Fig. 4.

Voltage at which DC charging occurs depends on the battery and control system. DC charge levels are defined based on power levels of charging. According to SAE, there are three DC charging levels [11]:

1. **DC Level 1**

This charging is done up to 36 kW rated power and 80 A rated current. Voltage level ranges between 200 and 450 V supply. It uses J1772 AC connector.

2. **DC Level 2**

This charging level can charge up to 10 kW power delivery having rated current of 200 A. It is done for voltage level of 200–450 V supply. It uses CHAdeMO or combo connector for charging.

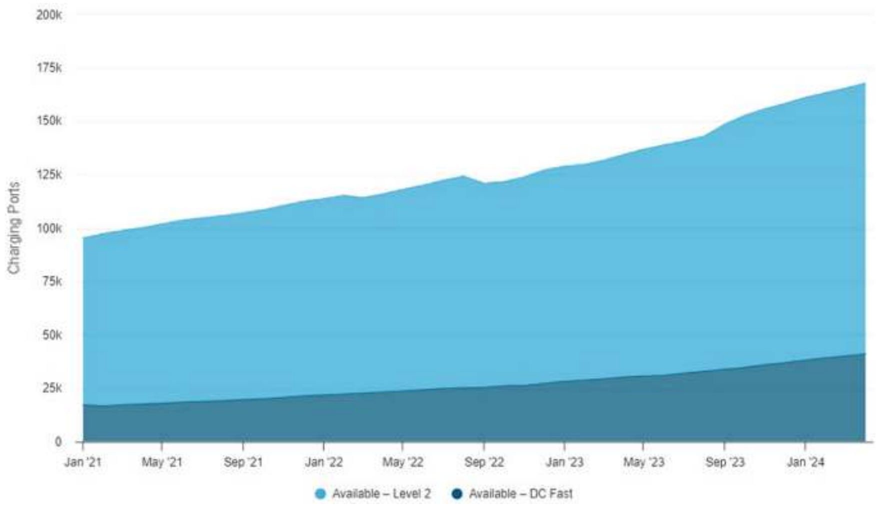

Fig. 4 US public charging port (Joint Office of Energy and Transportation)

3. **DC Level 3**

This level charges battery for voltage level of 200–600 V supply. It has rated power and rated current of 240 kW and 400 A, respectively. Connector for this level is to be designed.

B. **IEC standards**

According to IEC standards, there are mainly four charging modes for EV charging [15–17]. Various modes are shown in Fig. 5.

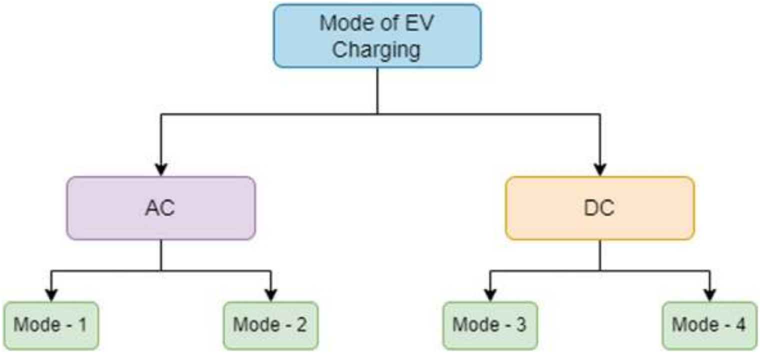

Fig. 5 Different modes of charging

1. **Mode 1**

Mode 1 EV charging is simple EV charging done at residence of user. User just needs to connect charging cable via household socket. It has 16 A rated current and supplies 11 kW rated power. Rated voltage levels for this mode are 240 and 480 V for 1-Φ and 3-Φ AC supply, respectively.

2. **Mode 2**

Mode 2 EV charging has rated current and power of 32 A and 22 kW. It also has 240 V and 480 V rated voltage levels for 1-Φ and 3-Φ AC supply, respectively. Similar to mode 1 this mode of charging is also used for residential purposes. This mode of charging differs from mode 1 by the charging cables. Mode 2 charging contains cable having shock protection against electric shocks and carries 32 A high current.

3. **Mode 3**

Mode 3 EV charging is generally done by grid-connected charging stations employed at public places. It has integrated protection and control circuits. It gives rated current and rated power capacity of 63 A and 43 KW. It charges battery at higher rate compared to above mentioned two levels.

4. **Mode 4**

This is the fastest available charging mode compared to other three levels. In this mode, DC power supply is used for charging purpose. Generally, this kind of charging facility is available in public places. Due to increase in number of EVs demand for this kind of fast charging is increasing. This type of charging is available at power delivery capacity ranging from 50 kW to 120 kW. It takes 400 A rated current. It can charge 80% of battery state of charge (SoC) in 30–50 min.

C. **CHAdeMO (CHArge de Move)**

Like other standards, it is also a charging standard for EV charging developed and used in Japan. It was developed in 2010. It is a DC fast charging standard. It got worldwide acknowledgement in 2014 [18]. First-generation CHAdeMO was capable of providing power delivery of 62.5 kW at 500 V and 125 A voltage and current ratings [19]. Next generation of CHAdeMO was able to deliver 400 kW power having maximum voltage and current values of 1000 V and 400 A.

D. **CCS (Combined Charging System)**

It uses type 1 and 2 connectors in addition to two extra DC power lines. Main advantage of this charging standard is that it doesn't require whole new connector like CHAdeMO. People can charge their EV in four modes by using this CCS standard which are as follows [7, 20].

1. Slow 1-phase AC charging.
2. Fast 3-phase AC charging.
3. Home DC charging.
4. Fast DC charging.

This standard has been widely accepted and nowadays all charging stations are implementing it to accomplish universal charge requirements. Some standard connector types used for EV charging across the globe by various countries are as shown in Table 2.

E. **Tesla Supercharger**

Tesla, an EV manufacturing company has built their own charging standard. It uses DC power supply for charging Tesla EVs. It was developed by company in 2012. It can provide 72 kW, 150 kW, or 250 kW depending on their generation. With increase in the supercharger version, the power rating handling capacity increases drastically shown in Fig. 6. Tesla is planning to open its supercharging facility for non-Tesla users too [11].

Table 2 Standard connector types used for EV charging across the globe

Type of Charging	North America	Japan	EU & rest of the market	China	All markets except EU	India
AC Type1: 1-3kW Type2: 3-22kW						
Plug Name	J1772 (Type 1)	J1772 (Type 1)	Mennekes (Type 2) IEC62196-2	GB/T		Commando (Type-1): IEC60309 Mennekes (Type-2): IEC62196-2
DC 10-400kW						
Plug Name	CCS1	CHAdeMO	CCS2	GB/T	TESLA	GB/T, CCS2, CHAdeMO

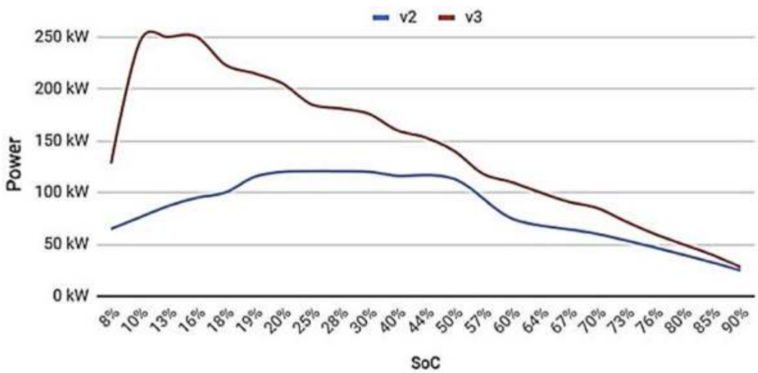

Fig. 6 v2 versus v3 Model-3 Tesla supercharger power comparison

3 Topologies for EV Charging

For different power levels of charging there is a need for different power converter topologies. Working principle of a power converter is to convert the power of one form to another form. Generally, a charging board at charging station contains AC/DC and DC/DC converters for off-board charging. These topologies can be made for two kinds of power flow. (1) Uni-directional power (2) Bi-directional power flow [8, 9].

1. **AC/DC converters**

AC/DC converter takes three-phase AC voltage as input and gives DC voltage as an output [20–22]. For AC/DC converters there are several topologies available but among them, Vienna Rectifier and Active Front-End rectifier are widely used.

AC/DC converter can be connected for charging in two ways, in each charging board or directly with AC bus. In first case, we need multiple AC/DC converters and in second case we just need only one AC/DC converter. In second case each charging board in charging station is connected to the DC bus.

a. **Vienna rectifier**

Vienna rectifier is a three-phase rectifier connected with a boost converter. It is uni-directional AC/DC converter. There are various types of Vienna rectifiers having different PWM techniques like carrier-based PWM, SVPWM, and discontinuous PWM. It has several advantages like high power density, high power efficiency, less switches, very low THD, etc. [23–25].

b. **Active front-end rectifier**

It has the advantage of bi-directional power flow, high efficiency, high reliability, reduces harmonic distortion, and operates near to unity power factor. It is a controlled rectifier. Controlling current to be sinusoidal in phase with grid voltage makes it operate near to unity power factor. PWM is used for controlling current [26].

2. **DC/DC converters**

DC/DC converters are the second stage of power conversion. It takes DC voltage generated by AC/DC converter as an input and converts it to DC voltage having magnitude compatible with the EV battery. DC/DC converters can be further divided into isolated and non-isolated DC/DC converters [27, 28]. Isolated converters are preferred. It is advised to use the minimum number of switches to reduce the complexity of gate circuit. Therefore, isolated Full Bridge based topologies are used for DC/DC converters [29].

3. **Dual active bridge converter**

It is a bi-directional converter having identical full bridge configuration on both sides of high frequency transformer. Two legs of both full bridges are given complementary square pulses. By changing the phase shift of pulses for one bridge w. r. t. other bridge we can change the direction of power flow between both bridges. Leading bridge delivers power to the lagging bridge. Advantages of this converter are high power density, implementation of zero voltage switching. There are certain drawbacks such as a lack of standardization, battery weight, number of batteries required, relevant infrastructure for the same, etc. [30].

4 EVCS Infrastructure

Lack of EV charging infrastructure is one of the major problems for adaption of EVs. According to type of charging and different power levels, there are several configurations of charging stations which are as follows [31–33]:

1. **Battery swapping technology**

This method will improve the battery's life expectancy because it takes too long to charge, and this method is also very simple in its implementation. There are certain drawbacks such as a lack of standardization, battery weight, number of batteries required, relevant infrastructure for the same, etc. [34].

2. **Charging station utilizing only grid power**

This kind of charging station is popular primarily because it offers the quickest method of charging. This kind of charging infrastructure must be built because Level 3 (DC charging), which takes a few minutes to charge, is used [34].

3. **Charging station utilizing energy storage system**

A sizable energy storage system needs to be installed for this kind of charging place, and effective control is necessary. Various optimization techniques, such as the computation of working and battery bus systems, are employed for controlling. Most commonly, batteries, flywheels, and super capacitors are used to store greater amounts of energy in smaller spaces [34, 35].

4. **Charging station utilizing grid power and renewable energy**

In view of the growing demand for electricity caused by an increase in EV production, so it is necessary to use wind and solar energy sources so that burden on conventional grid will be reduced [36, 37]. By using renewable energy sources, the charging stations shall be fitted with a DC converter that can so supply additional power from the grid in times of peak demand. There's not only a renewable resource in this kind of charging station but there are diesel generators, fuel cells, and hydrogenic as well.

5. **Off-grid charging station**

Here the microgrid is used to supply electricity for charging purposes. The factors that should be taken into account in implementing this type of charge station are appropriate design, suitable environment location and conditions as well as the energy storage device when renewable energy resources are not capable of being harnessed [38].

Due to the availability of sufficient energy, which is needed not only in the present but also in the future, the site for the installation of charging stations for commercial electric vehicles is a very significant element. The kind of electric vehicles and the demand for charging stations determine the best locations for their installation. Here are a few locations where electric charging stations might likely be implemented.

(a) Public parking lots
(b) Hotels and resorts
(c) Office buildings
(d) Fuel stations
(e) Shopping malls
(f) Warehouses
(g) Vehicle's depot set [39].

5 Test System

The growing ubiquity and quantity of electric vehicles have led to a broad need for effective, dependable, and efficient infrastructures supporting electric vehicle charging stations (EVCSs). However, there are significant obstacles in the way of the power system's stability, security, and power quality throughout the construction and deployment of such infrastructure. Based on the above review the EV charging station impact is tested considering VSI and AVDI in distribution system. IEEE standard 33-bus system is used for the testing which is shown in Fig. 7. In this paper, the impact of EVCS is observed in IEEE 33 bus system. The flow of work is given in Fig. 8. To calculate load flow, a forward-backward power flow approach has been used. After analyzing the system's performance without DG installation, the system's performance with DGs installed and the EVCS installed is compared. The EVCS rating which is shown in Table 3 is used based on Nissan Leaf car with battery capacity of 36 kWh, and nominal voltage of 350 V with 21 kWh per 100 km is considered. The DG of 1.33 MW rating is considered at bus 26. EVCS of 770 kW is connected at bus 28. The IEEE 33-bus system's stability and efficiency are greatly increased by integrating DG, especially when Electric Vehicle (EV) loads are added. Because EV charging requirements fluctuate, adding EV loads to the electrical system creates new problems like higher power losses and voltage swings.

The results have been obtained considering EVCS load with voltage stability index [40]. The average voltage deviation index (AVDI) [29] is used whose magnitude at all nodes is as given in Eq. (1) below.

$$\text{AVDI} = \frac{1}{N_n}\sum_{n=1}^{N_n}|1 - V_k|^2 \tag{1}$$

where, N_n indicates number of nodes in IEEE 33 system and V_a denotes node a voltage. The VSI [30] is evaluated using below equation;

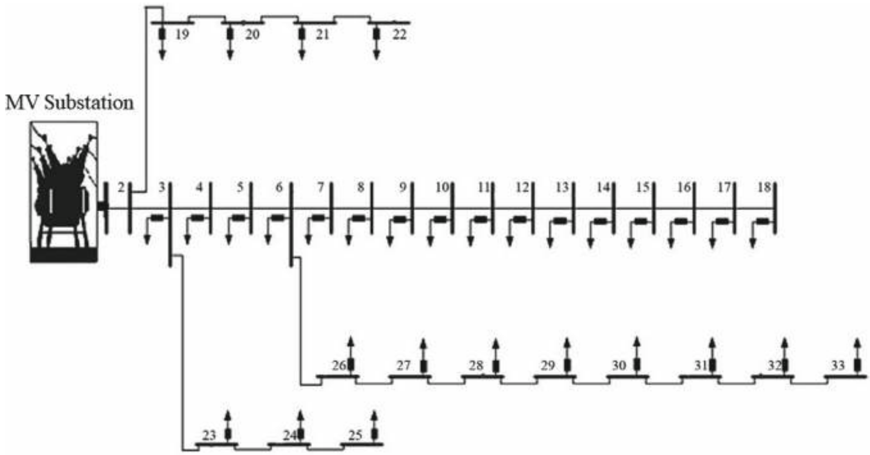

Fig. 7 IEEE 33 bus system

$$\text{VSI} = |V_b|^4 - 4(P_b X_{ab} + Q_b R_{ab})^2 - 4(P_b X_{ab} + Q_b R_{ab})|V_b|^2. \tag{2}$$

where, V_b denotes node b voltage, P_b indicat active power, X_{ab} signifies reactance in branches, Q_b represents reactive power, and R_{ab} denotes resistance between nodes a and b. The main aim is to minimize the AVDI, however, VSI should be maximized. As the charging load increases, the voltage at each bus keeps dropping. Figure 9 represents improved voltage profile with the addition of DG units. Actual and reactive power losses in distribution system affect the voltages on each bus. The results are taken for conditions listed below,

Case 1: Distribution IEEE 33 Base case.
Case 2: Distribution IEEE 33 with EVCS and without DG.
Case 3: Distribution system with EVCS and with DG.

The comparative analysis of average voltage deviation index (AVDI), Voltage stability index (VSI), and voltage profile of each bus for different cases listed above is shown in Table 4. It has been observed that the mean of AVDI is approximately 0.004 and there is less change in the AVDI for various cases but the VSI and voltage profile are improved after placing DG with EVCS. The loss comparison is shown in Table 5. The active power and reactive power loss are reduced to 133.48 kW and 96.88 kVar with EVCS with DG compared to 368.4482 kW and 239.04 kVar for EVCS only.

Fig. 8 Work flow diagram

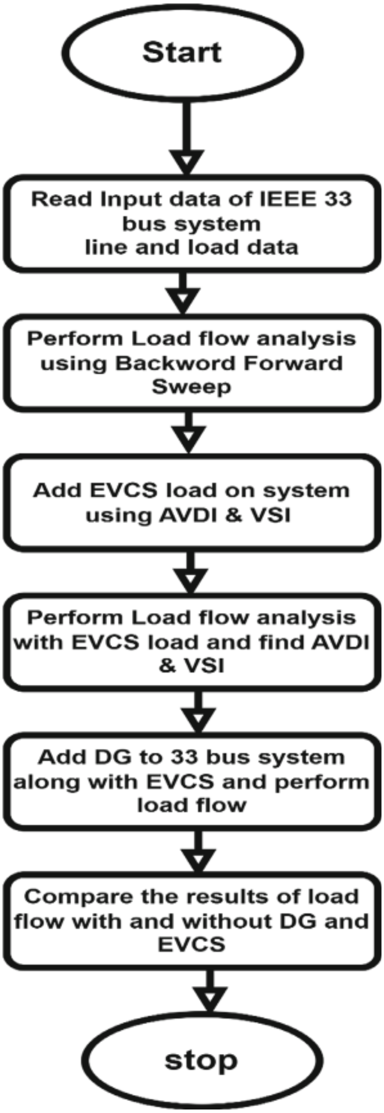

Table 3 EVCS specification

Rating of charging station	770 kW
Rating of charging point	22 kW
Number of charging point	35
Rated capacity	103Ah

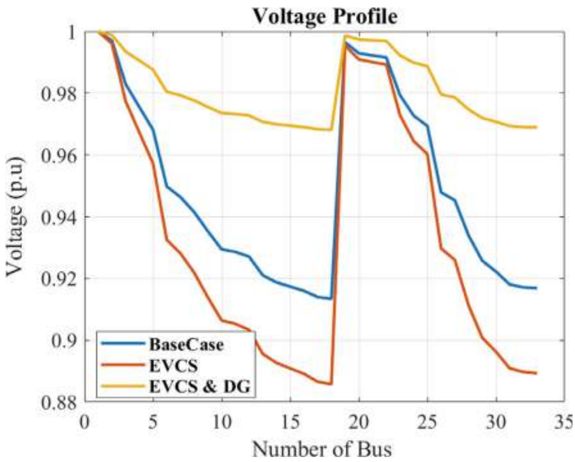

Fig. 9 Voltage profile

6 Future Scope and Challenges

The sales of EV in transportation sector have increased in past few years at significant rate but still, there are some challenges that are to be faced to achieve the environmental goals [10]. It is expected that fast charging requirements will increase as EV penetration increases. Therefore, fast charging solution is the current research topic for many researchers in this domain. Researchers are working on developing extremely fast charging methods. Here are several challenges for EV implementation [41, 42]:

1. **Impact on Grid**

For fast charging, we need to integrate power electronics converters in grid because of which power quality is hampered. It can cause voltage fluctuations, increased operation cost, harmonics injection, high power demand, etc. [43–51]. It is possible that not every load will be serviced by the electricity distribution network on a given day and time. EVs must be accurately predicted in order for power grid management to work with them because they are moving demands. This data is widely applied to the efficient placement of charging stations.

2. **Cost**

Due to the high cost of EVs, people are avoiding purchasing it. This high cost of EVs is due to the battery pack which is major portion of the cost.

3. **Government Policy**

For an efficient electric vehicle strategy, the government ought to offer owners improved policies for loans, taxes, charging stations, insurance, registration, and other related matters. To prolong the life of electric vehicles, road conditions need also be improved. The government may also suggest that cars have solar panels

Table 4 Comparative analysis of ADVI, VSI, and bus voltage profile for various cases

	Base case			With EVCS without DG			With EVCS and DG		
Bus no	AVDI	VSI	*V* (p.u.)	AVDI	VSI	*V* (p.u.)	AVDI	VSI	*V* (p.u.)
1	0	0.00632	1	0	0.00613	1	0	0.00561	1
2	0.000179	0.002752	0.9970	0.00021	0.002671	0.9960	0.000179	0.002444	0.9988
3	0.001023	0.013956	0.9829	0.001214	0.013522	0.9774	0.001023	0.012395	0.9935
4	0.001465	0.012345	0.9755	0.001773	0.01194	0.9672	0.001466	0.010964	0.9905
5	0.0019	0.006794	0.9681	0.002326	0.006566	0.9572	0.0019	0.006034	0.9876
6	0.002966	0.020957	0.9497	0.003638	0.020239	0.9324	0.002967	0.018612	0.9804
7	0.003165	0.048976	0.9463	0.003833	0.047379	0.9280	0.003166	0.043495	0.9793
8	0.003442	0.030995	0.9414	0.004111	0.029816	0.9218	0.003443	0.027526	0.9776
9	0.003798	0.0229	0.9352	0.004465	0.022104	0.9138	0.003799	0.020337	0.9755
10	0.004125	0.022804	0.9294	0.004792	0.02201	0.9063	0.004126	0.020252	0.9735
11	0.004174	0.001555	0.9285	0.00484	0.001492	0.9052	0.004175	0.001381	0.9732
12	0.004258	0.00434	0.9270	0.004925	0.004169	0.9033	0.004259	0.003854	0.9727
13	0.004599	0.032031	0.9209	0.005264	0.030884	0.8955	0.0046	0.028447	0.9707
14	0.004724	0.036656	0.9187	0.005388	0.035384	0.8926	0.004725	0.032554	0.9699
15	0.004802	0.015098	0.9173	0.005466	0.01459	0.8908	0.004803	0.013408	0.9694
16	0.004878	0.016254	0.9159	0.005541	0.015688	0.8890	0.004879	0.014435	0.9690
17	0.004989	0.043132	0.9139	0.005651	0.041687	0.8865	0.00499	0.038305	0.9683
18	0.005023	0.024343	0.9133	0.005684	0.023486	0.8857	0.005024	0.021619	0.9681
19	0.000211	0.007115	0.9965	0.000242	0.006905	0.9954	0.000211	0.006319	0.9986
20	0.000427	0.062803	0.9929	0.000457	0.060949	0.9909	0.000427	0.055777	0.9974
21	0.000469	0.020612	0.9922	0.000499	0.020004	0.9900	0.000469	0.018306	0.9971
22	0.000507	0.039263	0.9915	0.000538	0.038106	0.9892	0.000507	0.03487	0.9969
23	0.001236	0.014834	0.9793	0.001427	0.014373	0.9728	0.001236	0.013174	0.9922
24	0.00163	0.153925	0.9727	0.001821	0.149175	0.9644	0.001631	0.136703	0.9899
25	0.001826	0.151752	0.9694	0.002017	0.147067	0.9602	0.001826	0.134773	0.9887
26	0.003076	0.003587	0.9478	0.003808	0.003456	0.9297	0.003078	0.046527	0.9796
27	0.003223	0.005016	0.9453	0.004038	0.004829	0.9260	0.003307	0.073209	0.9786
28	0.003872	0.02688	0.9339	0.004689	0.025867	0.9113	0.003957	0.023822	0.9747
29	0.004333	0.038497	0.9257	0.005152	0.036888	0.9007	0.004418	0.034099	0.9719
30	0.004531	0.008781	0.9222	0.005352	0.009466	0.8962	0.004616	0.00796	0.9707
31	0.004764	0.064714	0.9180	0.005583	0.061896	0.8908	0.004849	0.05734	0.9693
32	0.004815	0.032869	0.9171	0.005634	0.064509	0.8896	0.0049	0.029128	0.9690
33	0.004831	0.0134	0.9168	0.00565	0.01282	0.8893	0.004916	0.011875	0.9689

Table 5 Comparison of power loss for various cases

Cases	Active power loss (kW)	Reactive power loss (kVar)
Base case	201.8925	143.6413
With EVCS	368.4482	239.0487
With EVCS and DG	133.48	96.88

installed as a way to save electricity and in case of a power outage. A plan for towing the cars should be in place in case of emergency so that the end users won't have to worry about arriving at their location on time.

4. **Range Anxiety**

Due to the limited range of EV, people prefer IC engine vehicles. People are expecting high-range providing EVs with fast charging capability so that they don't have to wait for EV to charge for a longer period.

5. **Availability of Charging Infrastructure**

Due to lack of charging infrastructure people need to locate charging stations and have to wait in queues to charge their vehicle [42, 52]. In future, we need to solve these problems which are becoming a problem for EV adoption. Government needs to implement new policies for building new charging infrastructure, making EVs cost-effective. Some of the solutions for above mentioned problems are as below:

6. Upgrading conventional grid to smart grid. So that utility can manage pick load hours, provide quality power, and reduce stress on grid.
7. By using alternatives of Li-ion battery, we can bring down the cost of battery, thus further decreasing the cost of EVs.
8. By enhancing power capacity of battery, we can increase the range of EVs.
9. By installing new charging stations at various public places, we can solve the problem of charging infrastructure.

7 Conclusion

Worldwide, interest in adoption of electric vehicles is growing. When compared to conventional vehicles, they significantly contribute to the decrease of environmental pollutants. As a result, there is a high demand for infrastructure related to EV charging. In developing and implementing EV charging stations, this paper reviews several charging technologies, and standards accepted in various countries. It reviews the widely accepted charging topologies for both AC/DC and DC/DC converters. It also reviews infrastructure requirements and various charging techniques implemented across the world. The challenges, stressing important issues and suggesting viable solutions and future scope to accomplish goal of EV usage instead of conventional IC engine vehicles have been discussed. The EVCS impact on distribution system is tested and in the test system, it has been clearly observed that with EVCS load the VSI, voltage profile, and power loss in the system increases. However, after placing DG with EVCS as a load on the system VSI and voltage profile is improved and losses are reduced.

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Chapter 4
Renewable-Energy-Based EV Charging Infrastructures

Surender Singh

Abstract The challenges and impact of incorporating RES and EVCS into distribution grid systems are investigated. It emphasizes the significance of this integration for modernizing the energy system and achieving environmental objectives. In addition to general performance measures and compatibility concerns, the investigation explores the particular challenges that on-grid power structures suffer. It provides a thorough examination of the characteristics of several renewable energy sources hybrid systems, along with innovations in solar, wind, battery, and biomass technologies. Consequently, due to the growing variety of EVs, the transportation sector is presently shifting away from oil-powered vehicles. The increasing adoption of EVs has led to the development of EVCS. Unplanned EVCS deployments may cause issues with the distribution system, including higher power losses and the worst voltage profile. As a result, both the integration of RES and EVCS must be arranged on the distribution system in the best possible location. This study proposes a conventional approach to integrating RES and EVCS adoption in distribution systems. The appropriate buses are added to the radial distribution system after the three radial distribution system zones are identified using the voltage deviation criterion. The voltage deviation, power loss, and reliability indices comparative results for the IEEE 33 bus system are presented in this chapter.

Keywords Electric vehicle charging stations · Radial distribution system · Voltage deviation · And real power loss

Abbreviations

DER	Distributed energy resources
ES	Energy storage
RDS	Radial distribution system

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P_L	Real power loss
DS	Distribution system
VD	Voltage deviation
EVCS	Electric vehicle charging stations
RES	Renewable energy sources
NRES	Non renewable energy sources
ASUI	Average service unavailability index
ASAI	Average service availability index
AENS	Average energy not supplied
ENS	Energy not supplied
SAIDI	System average interruption duration index
SAIFI	System average interruption frequency index
DG	Distributed generation
PV	Photovoltaic
ESS	Energy storage system
MG	Microgrid
BDC	Bidirectional control
MPPT	Maximum power point tracking
f_1	The real power loss function
f_2	The function of voltage deviation
f_3	The reliability indices
w_1, w_2 and w_3	Corresponding weight factors to the functions f_1, f_2, and f_3

1 Introduction

The increasing need for energy in the twenty-first century, coupled with the limited supply of natural resources, and the accelerating rate of global warming are the main problems faced by living beings. The transportation sector is one of the major contributors to CO_2 emissions, which are the main cause of climate change and the major causes of problems like droughts and increasing ocean levels. Therefore, scientists and engineers together try to find an alternate way to minimize the impact on the environment. As far as engineers are concerned the integration of RES to meet the demand of the new era in transportation as EVs is to be planned in an optimal location. Many researchers [1–34] have reported the controllers and techniques for the RES and EVCS incorporation into a grid. An autonomous MG is being established using an ESS, and SPV. An autonomous MG uses an enhanced phase-locked loop with a variable gain controller to detect phase angle and create unit templates for a power quality management system [1]. Power support, load leveling, harmonic reduction, and an improvement in the overall power quality of the isolated MG during load and energy source dynamics are all provided by the suggested adaptive techniques using VSC. To extract the most solar power possible, a BDC is interfaced at the DC-link of a solar PV array that uses perturb and observe MPPT control. The BDC with ESS maintains proper power flow and power equilibrium between energy sources and load through DC-link voltage regulation [2].

The limitation of DG on the grid system is shown in Fig. 1. Based on numerous studies, it has been confirmed that the transportation industry would benefit greatly from electrification since it will gradually replace internal combustion engines, resulting in less noise pollution, lower tailpipe emissions, and more efficient vehicles [3, 4]. While the growing popularity of electric vehicles would lead to lower harmful and greenhouse pollutants in the atmosphere, charging EVs could lead to some problems with the distribution system [5, 6]. The transportation market has seen a rise in the use of electric vehicles in recent years. It is expected that this trend will continue due to environmental issues and other factors like the extinction of fossil fuels. Many obstacles prevent electric vehicles from being adopted quickly, including their high cost, unavailability of charging points, and an overburdened infrastructure that disrupts the power supply. The integration of EVCS into the current grid puts additional strain on it, leading to degradation, system line and feeder temperature increases, and severe losses that can cause electrical failure. The adverse effects of penetration EVCS, including voltage variation, power loss, and peak load, have been demonstrated by several researchers [7–10]. The issue of the optimal location of EVCS is a complex that is addressed in various aspects [11]. A few researchers considered the parameter as cost optimization, encompassing cost elements like investment, operation, installation, and land cost. Conversely, other research offers ways to improve or preserve the distribution system's operating conditions. To mitigate the possible negative consequences of EVCS integration by using renewable energy sources is an alternate way suggested by the researchers [12–16]. To minimize the burden on a certain time frame economically, the idea of scheduling for EVCS is also suggested [17–19]. The impact of EVCS on RDS and integration of RES is done in such a way that the best-balanced condition is maintained by considering the minimization of power loss and voltage fluctuation. The recommended work is tested in the IEEE 33 bus system by solving the problem with a conventional method. The component of distributed energy resources is shown in Fig. 2.

The present book chapter is arranged as follows: In the first section, an introduction and extensive literature regarding the impact and challenges of RES and EVCS are presented. The formulation of the problem into two parts: impact and its challenges on a grid as well as EVCS integration is presented in Sect. 2. Section 5 provides a proposed methodology for the objective function into three zones selection based on VD and gets the optimal solution. Section 6 introduces a case study of IEEE 33 bus system integrating three EVCS in zone 1, zone 2, and zone 3 respectively. Detailed results and discussion of active power loss, reactive power loss, and voltage profile at each node for all the mentioned three zones and reliability indices for the base case and optimal EVCS are presented in Sect. 7. Section 8 presents the conclusion findings about the challenges of incorporating RES and the impact of EVCS on a grid.

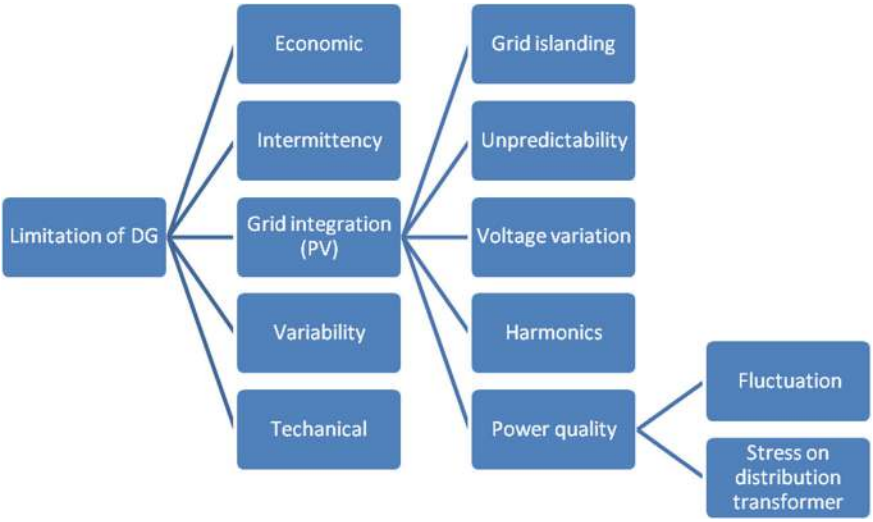
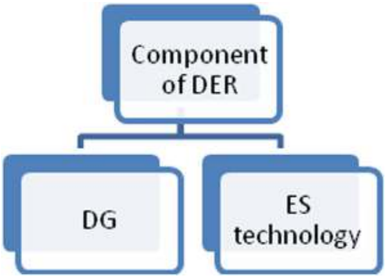


Fig. 1 limitation of DG on the grid system

Fig. 2 Component of distributed energy resources



2 Problem Formulation

The formulation of problem is categorized into two parts:

1. Challenges of renewable energy sources in grid system.
2. Impact of an electric charging station on a grid system. The challenges of RES and the impact of EVCS on a grid system are extensively investigated as under.

2.1 Challenges of Renewable Energy Sources in Grid System

The finding suggested by the researchers to mitigate the impact of the existing gradually increased load as well as the new requirement of EVCS is overcome with the help of RES. Here, this section first considers the challenges faced to integrate the RES

Table 1 Technical electrical parameter challenges for the RES into grid

Technical constraints	Challenges in quick capacity growth
Voltage fluctuations	Voltage fluctuation adversely affects on-grid reliability
Current and voltage harmonics	Current can lead to power loss issues Harmonics can lead to power quality issues
Grid islanding protection	Lack and failure of protection during islanding events
Power quality issues (e.g., flicker)	Poor power quality affects the consumer equipment efficiency and life span
Line losses	Increased line losses may cause poor voltage profile which lead to instability of system
System functionality	DER integration may challenge grid operations
Economic factors	Initial installation costs can be a barrier to adoption. DG can reduce grid electricity costs

and after that, its impact is focused. The technical electrical parameter challenges for the RES into grid are described in Table 1 [20].

The system parameter grid challenges for the integration of RES into grid and to mitigate these challenges are described in Table 2.

2.2 Impact of an Electric Charging Station on a Grid System

Due to negative impacts including voltage profile degradation, an increase in real power losses, sudden peak load, and overloading of the system, EVCS must be placed optimally. Power loss and voltage deviation are used as the basis for this interconnection. The objective function is a blend of power loss, and voltage deviation as minimizing with the enhancement of reliability indices after the interconnection of EVCS on RDS is investigated as the following equation:

$$\min\{w_1 \times f_1 + w_2 \times f_2 + w_3 \times f_3\} \tag{1}$$

The weight factors in this case, w_1, w_2, and w_3 stand in for the coefficients in the functions f_1, f_2, and f_3. To minimize the power loss value, one uses the objective function f_1. In the process of minimizing the voltage deviation value, the objective function $f_{2.}$

2.2.1 Power Loss

One of the factors used to locate EVCS in RDS is power loss. The following formula can be used to determine the overall power loss as well as the power loss on each line:

Table 2 System parameter grid challenges and its mitigation for the integration of RES

System parameter	Grid challenges	Mitigate the challenges on the grid
Demand pattern and load profile in DG	Diverse energy supply from RES Diverse power electronic devices exponentially by customers Unpredictable loading of EV charging	Better optimization techniques are used by incorporating a smart grid plan to meet the demand response [21] Encouraging smart load and energy-efficient materials are taken into consideration [22] Effective scheduling policy incorporating RES [23] Efficient load scheduling [24]
Reliability and resilience issues	Difficult for a smart grid to configure a crucial topology for a reliable operation [25]. MGs are less capable of these issues due to their priority routine operation [27]. Reliability indices: SAIDI, SAIFI, ENS, AENS, ASAI, and ASUI [25]	Resilience to absorb, recover, and adapt from the disturbance [25, 26]
Environmental factors such as carbon emission	Infrastructure cost is higher in RES than in NRES [28]	The reduction in CO_2 emission is 85% in transportation as reported in Denmark [29] In Montana, 2 kW of PV reduces CO_2 emission by 3643 lbs and 0.68 lbs NO_2 which is consumed by one acre of tree plant annually. In Ireland, in the case of wind energy, it reduces 9% emission in addition to 800 MW generation [30] Decentralized DG [31] and shunt capacitors [32] benefits: Reduces line losses Higher efficiency Enhanced voltage profile Grid reinforcement

$$
\begin{aligned}
f_1 &= \min\left[\text{Total power loss}\right] \\
&= \min\left[\text{Active power loss} + \text{Reactive power loss}\right]
\end{aligned}
$$

$$
f_1 = \min\left[\sum_{k=1}^{m} I_k^2 * R_k\right] \tag{2}
$$

where, I_k is the current of the branch N is the total branches.

$Z_k = (R_k \pm j \times X_k)$ is the branch impedance.

2.2.2 Voltage Deviation

Considerable voltage variations could occur when EVCS are installed randomly. The voltage quality of the entire power system will be improved by incorporating voltage deviation as a problem formulation index value to reduce this kind of influence. Voltage deviation reduction will therefore help with EVCS placement issues. The following formula can be used to compute voltage deviation:

$$f_2 = \min\left(\sum_{k=1}^{m}(1 - V_k)^2\right) \tag{3}$$

Here, V_k is the voltage of kth bus.

2.2.3 Reliability

Customer satisfaction about the availability of the energy provided to fulfill demand is assessed by reliability. The following indices are calculated to assess the reliability of the system:

- System average interruption frequency index (SAIFI)

  It represents the proportion of total interruptions to total users in a system.

$$f_2 = \frac{\left(\sum_{j=1}^{\mathrm{Nc}} \lambda_i \times N_j\right)}{\left(\sum_{j=1}^{\mathrm{Nc}} N_j\right)} \tag{4}$$

- System average interruption duration index (SAIDI)

  It represents the proportion of total interruption times to all system users.

$$f_3 = \frac{\left(\sum_{j=1}^{\mathrm{Nc}} U_j \times N_j\right)}{\left(\sum_{j=1}^{\mathrm{Nc}} N_j\right)} \tag{5}$$

- Energy not supplied (ENS)

  It is the total of the products of the annual outage duration and the average connected load at a particular system node.

$$f_4 = \sum_{j=1}^{\mathrm{Nc}} L_j \times U_j \tag{6}$$

- Average energy not supplied (AENS)

It is the proportion of energy that is not supplied to all of the clients that a system serves.

$$f_5 = \frac{(\text{ENS})}{\left(\sum_{j=1}^{\text{Nc}} N_j\right)} \tag{7}$$

- Average service availability index (ASAI)

It is the proportion of total customer hours on demand to total customer hours available for service.

$$f_6 = \frac{\left(\sum_{j=1}^{\text{Nc}} N_j \times 8760 - \sum_{j=1}^{\text{Nc}} U_j \times N_j\right)}{\left(\sum_{j=1}^{\text{Nc}} N_j \times 8760\right)} \tag{8}$$

- Average service unavailability index (ASUI)

It is the proportion of total customer hours on demand to total customer hours unavailable in service.

$$\text{ASUI} = 1 - \text{ASAI} \tag{9}$$

$$U = \lambda \times r \tag{10}$$

where,
U is the annual outage time.
λ is the average failure rate.
r is the outage time.

3 Equality Constraints

The grid-supplied electric energy used should cover system losses, EVs, and load demands.

$$P_{\text{T}} = P_{\text{Loss}} + \sum_{k=1}^{m} (P_{\text{load}\,k} + P_{\text{EVCS}\,k}) \tag{11}$$

4 Inequality Constraints

To ensure optimal power flow, the following constraints [Eqs. (5)–(7)] are used: minimum voltage, and distribution system power.

$$\text{Active power } P_k^{\min} \le P_k \le P_k^{\max}, \quad k = 1, 2, \ldots, \text{m} \tag{12}$$

$$\text{Reactive power } Q_k^{\min} \le Q_k \le Q_k^{\max}, \quad k = 1, 2, \ldots, \text{m} \tag{13}$$

$$\text{Bus voltage } V_k^{\min} \le |V_k| \le V_k^{\max}, \quad k = 1, 2, \ldots, m \tag{14}$$

where,

P_k: Real power of kth bus.
Q_k: Reactive power of kth bus.
V_k: Voltage of kth bus.

5 Proposed Algorithm

1. Initialize the line and load data [33].
2. Formulate the minimizing objective function which is a combination of real power loss and voltage deviation.
3. Evaluate the line flows using a backward/forward sweep approach.
4. Apply the traditional approach after the integration of three EVCS randomly in the existing 33-IEEE RDS [34]. In this approach, three zones are identified based on the voltage deviation index.
5. Apply the equality and inequality constraints in a traditional approach to evaluate the optimal solution.
6. Check the convergence criteria:
   i. If satisfied, print the results.
   ii. Otherwise, go to step 4.

6 Case Study

The objective of the function that is shown in Eq. (1) has three parts which include total power loss, voltage deviation, and reliability indices to get the optimal location of RES and EVCS using conventional approach in MATLAB software. The existing IEEE 33 bus RDS is used for the suggested strategy for finding the best way to distribute EVCS. This work includes three zones such as 1, 2 and 3which are selected based on the second part of the objective function with three charging stations correspondingly. Active power and reactive power values of EVCSs are 120 kW and 75 kVAR, 75 kW and 47 kVAR, and 150 kW and 95 kVAR were considered at different nodes, respectively, for the two- and four-wheeler EVs. A single bus is chosen for each zone to install EVCS. This system has three-lateral and five-tie lines sending and receiving nodes as 25–29, 18–33, 9–15, 8–21 and 11–22. Figure 3 shows the base case of the IEEE 33-bus RDS.

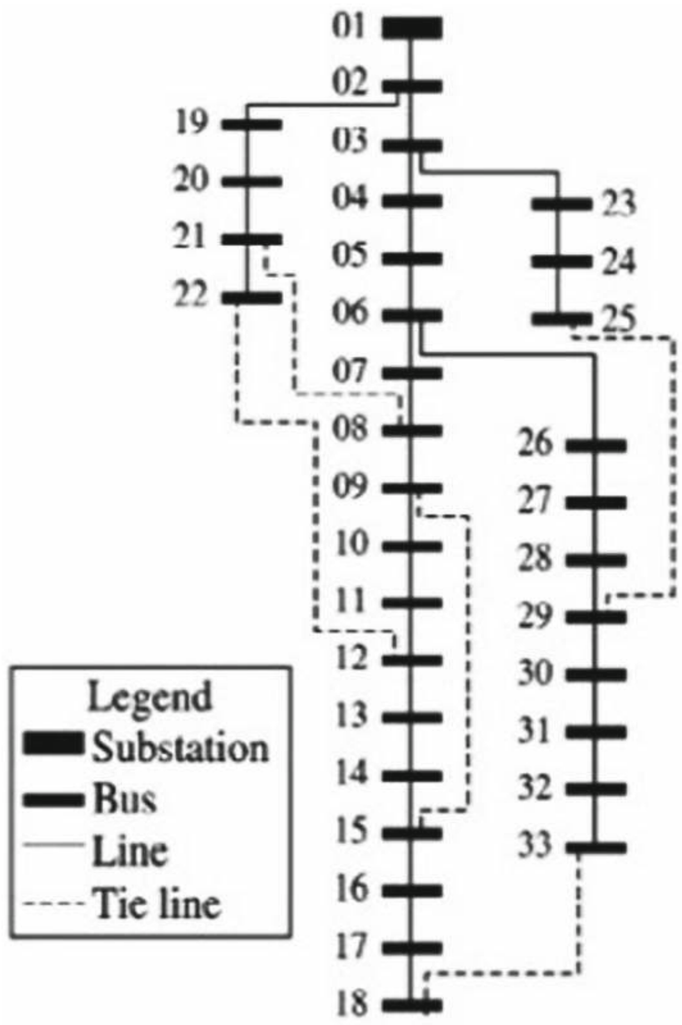


Fig. 3 Standard IEEE 33 bus system

7 Results and Discussion

As explained in the previous section, the three zones are identified on the basis of VD evaluation from Eq. (3). After the implementation of the traditional approach on the objective function as per the proposed algorithm to identify the zone in which the EVCS is interconnected. This system is divided into three zones on the basis of VD as shown in Fig. 4 as under: Zone 1 is decided based on VD value from 0 to 0.095, Zone 2 is dependent upon the value 0.105 to 0.582 and Zone 3 is based on the value 0.621 to 0.82. Furthermore, in this section, three cases are taken into consideration for the interconnection of EVCS in the existing 33 RDS system as follows:

Case 1: The base case: No EVCS.
Case 2: Integration of randomly three EVCS in the excising system.
Case 3: Placement of optimal integration of EVCS in each zone.

The optimal loading of EVCS estimated by applying traditional approach using proposed algorithm on RDS with reliability parameters are shown in Table 3.

In the first zone, include the buses as 2, 3, 4, 19, 20, 21, 22, 23, 24, and 25. In the second zone, the buses included: 5, 6, 7, 8, 9, 26, 27, 28, 29, and 30. In third zone, the buses included: 10, 11, 12, 13, 14, 15, 16, 17, 18, 31, 32 and 33.

- In Case 1: No EVCS is connected.
- In Case 2: The EVCS load values are respectively 120 KW/75 KVAR (Bus 25), 75 KW/47 KVAR (Bus 30) and 150 KW/95 KVAR (Bus 18) in zone 1, 2 and zone 3.
- In Case 3: The EVCS load values are respectively 120 KW/75 KVAR (Bus 2), 75 KW/47 KVAR (Bus 5) and 150 KW/95 KVAR (Bus 10) in zone 1, 2 and zone 3. The comparison of power losses in three different cases are shown in Table 4.

A comparison of active power loss, reactive power loss, and voltage of all three cases at each branch are shown in Figs. 5, 6, and 7, respectively.

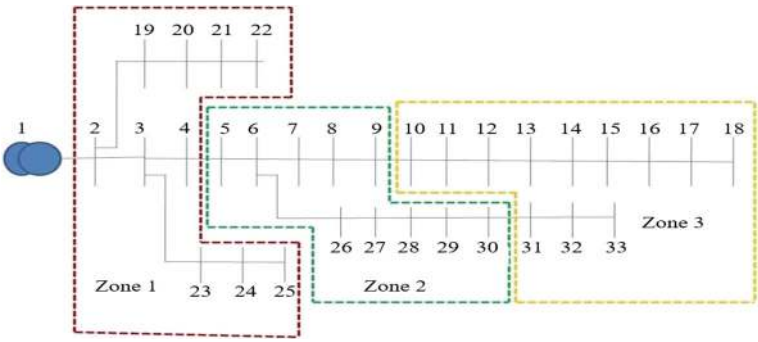


Fig. 4 IEEE 33 bus system with zones

Table 3 The optimal loading of EVCS on RDS with reliability parameter

Branch no.	Sending node	Receiving node	*R* (ohm)	*X* (ohm)	P at node including EVCS	Q at node including EVCS	Average failure rate	Outage time
1	1	2	0.0922	0.047	120	75	0.05	2.43
2	2	3	0.493	0.2511	100	60	0.07	3.35
3	3	4	0.366	0.1864	90	40	0.021	4.56
4	4	5	0.3811	0.1941	120	80	0.23	3.69
5	5	6	0.819	0.707	60	30	0.303	4.66
6	6	7	0.1872	0.6188	210	115	0.21	3.23
7	7	8	1.7114	1.2351	200	100	0.04	3.75
8	8	9	1.03	0.74	200	100	0.03	4.13
9	9	10	1.044	0.74	60	20	0.11	4.78
10	10	11	0.1966	0.065	60	20	0.22	3.79
11	11	12	0.3744	0.1238	45	30	0.23	2.78
12	12	13	1.468	1.155	110	67	0.09	2.98
13	13	14	0.5416	0.7129	60	35	0.08	2.78
14	14	15	0.591	0.526	120	80	0.07	3.89
15	15	16	0.7463	0.545	60	10	0.05	4.22
16	16	17	1.289	1.721	60	20	0.06	3.46
17	17	18	0.732	0.574	60	20	0.04	2.78
18	2	19	0.164	0.1565	90	40	0.1	2.8
19	19	20	1.5042	1.3554	90	40	0.03	4.12
20	20	21	0.4095	0.4784	90	40	0.05	3.11
21	21	22	0.7089	0.9373	90	40	0.22	3.98
22	3	23	0.4512	0.3083	90	40	0.06	4.56
23	23	24	0.898	0.7091	165	97	0.11	3.78
24	24	25	0.896	0.7011	420	200	0.09	4.31
25	6	26	0.203	0.1034	420	200	0.12	3.11
26	26	27	0.2842	0.1447	60	25	0.17	2.78
27	27	28	1.059	0.9337	160	88	0.07	3.55
28	28	29	0.8042	0.7006	60	20	0.5	4.12
29	29	30	0.5075	0.2585	120	70	0.08	3.15
30	30	31	0.9744	0.963	200	600	0.03	3.15
31	31	32	0.3105	0.3619	150	70	0.19	2.56
32	32	33	0.341	0.5302	210	100	0.04	3.56

(continued)

Table 3 (continued)

Branch no.	Sending node	Receiving node	*R* (ohm)	*X* (ohm)	P at node including EVCS	Q at node including EVCS	Average failure rate	Outage time
	Tie-sectionalize switch data				60	40	0.03	3.87
33	21	8	2	2				
34	9	14	2	2				
35	12	22	2	2				
36	18	33	0.5	0.5				
37	25	29	0.5	0.5				

Table 4 Comparison of power loss in three different cases

	Active power loss (kW)	Active power loss (kW)
Case 1 [20]	210.9	142.96
Case 2 [21]	272.44	186.45
Case 3 [Proposed]	247.39	167.81

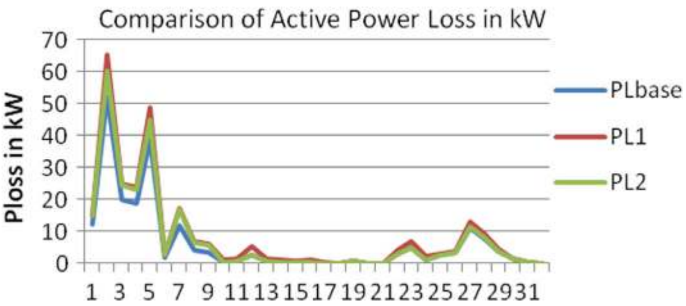


Fig. 5 Comparison of active power loss in kW

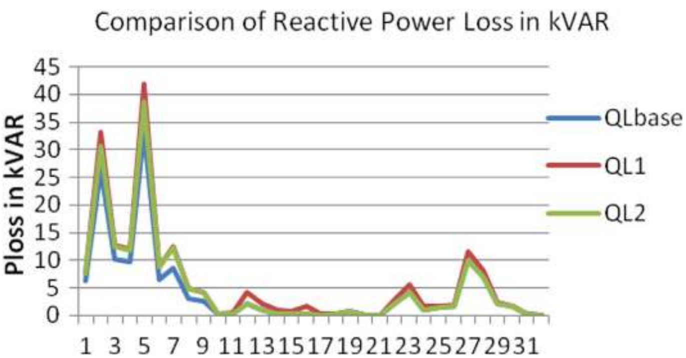


Fig. 6 Comparison of reactive power loss in kVAR

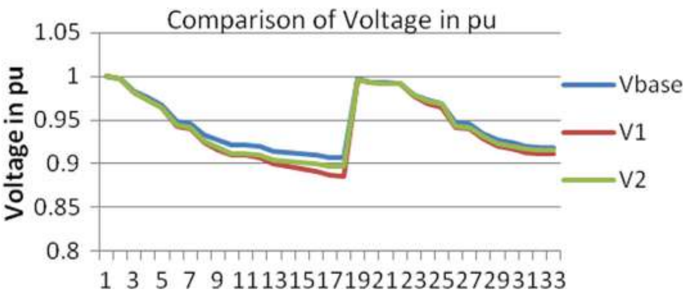


Fig. 7 Comparison of voltage

Table 5 Comparison of reliability indices with and without EVCS

Reliability indices	Case 2	Case 3
SAIFI	0.31001	0.120075
SAIDI	15.1515	14.15294
ENS	0.21565	0.294786
AENS	0.01373	0.014703
ASAI	0.98789	0.999192
ASUI	0.01211	0.000808

The reliability indices are estimated using equation from (4) to Eq. (10) for the two cases as under:

Case 2: Evaluation of reliability indices using traditional approach with EVCS.

Case 3: Evaluation of reliability indices by optimal location of EVCS using proposed algorithm. After evaluation of both the cases are tabulated in Table 5.

8 Conclusion

To reduce losses and voltage deviation, this study assists in determining the best site for EVCS. Voltage deviation is taken into account while deciding where to install EVCS. Three cases were examined, with additional constraints applied to each to improve the realistic aspect of the solution which first is the base case. In Case 3, power system losses and voltage deviation are low as compared to Case 2. To further enhance the scope of the deliberation, Table 1 provides an organized perspective of the many issues surrounding the integration of renewable energy (RE) into the grid. The secret to a resilient and sustainable energy future ultimately lies in the advancement of smarter grids and enhanced distributed generation capacities. Together, these tables complement the analysis by offering comparisons, empirical data, case studies, and creative ideas that enhance the well-supported investigation of this significant energy shift.

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Chapter 5
Technical and Economical Assessment of Renewable Energy-Based Electric Vehicle Charging with Energy Storage System

Fareed Ahmad, Theyab R. Alsenani, Mohd Bilal, and Tousif Khan Nizami

Abstract The rapid adoption of electric vehicles (EVs) necessitates a substantial increase in energy supply to meet the growing demand. Additionally, the transportation industry is a significant source of harmful emissions, such as SO_2 and CO_2. Therefore, the national grid must consistently provide a large amount of electricity to support the increasing load from EVs. This study explores the deployment of a renewable-based energy system, incorporating solar panels, wind turbines, and battery energy storage, to charge EVs in the Noida region. A technical and economic analysis was conducted for various combinations of these integrated energy system components. The primary goal is to determine the optimal sizing of system components to minimize energy costs and reduce the likelihood of power outages. To achieve these objectives, a novel metaheuristic-based optimization algorithm called the Giza Pyramid Algorithm is utilized. This investigation considers both the total net present cost and the renewable energy portion to optimize the component sizes. Simulation results demonstrate that the Giza Pyramid Construction Algorithm (GPCA) meets the desired objectives with high accuracy and resilience. The study also examines the impact of different grid purchase prices on the levelized cost of electricity. Findings reveal that the solar/wind/battery combination significantly reduces the levelized cost of energy and overall net present cost compared to other options.

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1 Introduction

The extensive use of fossil fuels such as coal, petroleum, petrol, and diesel is occurring at an alarming rate, leading to catastrophic climate change. Consequently, the availability of nonrenewable energy sources is diminishing, resulting in shortages for the population. Experts and academics are actively engaged in educating the public about the use of renewable energy sources (RES) as an effective substitute to address these supply shortfalls [1]. Therefore, the proper collection and deployment of RES are crucial. The abundance of energy generated from RES in India signifies a transformative shift towards cleaner and more sustainable energy practices. The combined efforts of the government, private sector, and various stakeholders have positioned India as a global leader in the renewable energy sector, contributing to environmental preservation and energy security. To mitigate the damage caused by traditional energy sources, it is essential to decrease emissions of CO_2, NO, SO_2, and air pollution. Broad adoption of plug-in electric vehicles (PEVs) is evolving as a solution to these challenges [2].

The challenge lies in the fact that consumer acceptance and understanding of plug-in electric vehicles are also in the formative stages [3]. This is mainly due to public worries about EV constraints, like limited range, high EV costs, issues with battery security, and insufficient charging infrastructure [4]. To mitigate hazardous emissions from road transportation, governments worldwide are accelerating the development of EVs [5]. Considering the advantages of energy efficiency and pollution reduction, EVs are likely to dominate the future automobile industry [6]. The Government of India (GOI) has established economic incentives and legislative frameworks to promote EV development. India is becoming a burgeoning market for EVs, particularly among financially well-off urban adults [7].

Another study evaluates the EV charging load and conducts a financial analysis for a multisource power system to improve the charging system's efficiency and reduce its capital requirements [8]. A techno-economic analysis is conducted in [9] for a commercial load profile of the Mecca transport company. This analysis compares various combinations of a hybrid WT/DG/fuel cell/ESS/electrolyzer system to determine the utmost result, focusing on the total present cost and the levelized cost of energy (LCE) as primary factors for comparison. In a case study of Northwest Delhi, the authors of [10] optimized technical and economic targets using a modified slap swarm algorithm. The findings were contrasted with those acquired from the slap swarm algorithm and HOMER software, providing insights into the proposed approach's efficiency. In [11], the author presented a hybrid pole group comprising RESs, street lighting, and EV charging capabilities, offering both fast and slow charging via a DC microgrid and storage device. An effective model of a smart hybrid poles group is presented to analyze the appropriate number in a group of smart hybrid poles. The efficiency model shows that the group approach outperforms a single pole, providing a theoretical foundation for practical fabrication and evaluating the viability and potential benefits of the proposed approach.

In [12], researchers examined the optimal system component sizing for EV charging stations in the Indonesian city of Labuan Bajo. They analyzed and acknowledged the most efficient mix of energy system parts, considering factors such as energy generation, storage, and demand, and established an economical mathematical model that considers operational costs and TNPC. In [13], researchers prioritized charging and monitored park-and-ride EV charging networks using RE and ESS. A mixed-integer linear programming method was used to optimize this issue, reducing component costs. This study highlights decision-makers' roles in expanding RES-based EV charging capacity. In [14], EV charging load planning in different distribution and transportation networks is thoroughly examined, focusing on the techno-economic advantages of such planning, considering charging infrastructure variables. In [15], the techno-economic advantages of a hybrid system that can function both independently and in conjunction with the grid are analyzed using various PV, WT, and ESS configurations. The goal is to meet EV charging demands by lowering energy costs and improving power supply reliability. The study optimizes system configuration to reduce power outages and save money.

2 Methodology

2.1 Modeling of Energy System Component

The following section presents the modeling of various components of the system to fulfill EV load requirements. The hybrid energy system comprises a PV unit, a wind turbine (WT), an energy storage system (ESS), and an inverter. The ESS, particularly the battery, is crucial for managing fluctuations in renewable energy generation and ensuring a more reliable energy source for EV load requirements.

2.1.1 Modeling of Photovoltaic Array

The energy generation of PV panel is influenced by solar radiation, temperature of solar panels and panel size, and the geographic coordinates of the location. These factors collectively determine the efficiency of the solar panel that generates electrical energy from the solar radiation from the sun. The amount of PV power can be calculated using Eq. (1) [16].

$$P_{\mathrm{PV}}(t) = \eta_{\mathrm{PV}} P_{\mathrm{PV}}^{\mathrm{upper}} n_{\mathrm{PV}} \eta_{\mathrm{wire}} \frac{I(t)}{1000}\left(1 - \bar{\lambda}_{\mathrm{T}}\left(T_{\mathrm{amb}} + \frac{(\mathrm{NOCT} - 20)}{800} I_{\mathrm{amb}}(t) - 25\right)\right) \tag{1}$$

where, n_{PV} indicates the amount of PV panels, $P_{\mathrm{PV}}^{\mathrm{upper}}$ indicates the highest power from the PV panels, η_{PV} and η_{wire} are the efficiency of PV and efficiency for wiring, $P_{\mathrm{PV}}(t)$ is the output power,λ_{T} is the thermal coefficient, T_{amb} indicates the ambient temperature, $I(t)$ denotes the solar radiation.

The generated power from the solar panel can be determined as written in Eq. (2).

$$P_{\mathrm{PV}}^{\mathrm{upper}}(t) = N_{\mathrm{PV}} \times P_{\mathrm{PV}}(t) \tag{2}$$

2.1.2 Modeling of Wind Turbine

The speed of wind and height of hub in the wind turbine is responsible for energy generation, which can be calculated using Eq. (3) [17]:

$$\frac{S_2}{S_1} = \left(\frac{h_2}{h_1}\right)^{\mu_{\mathrm{fr}}} \tag{3}$$

where, S_1 represent the speed of air at h_1, and S_2 indicates the speed of air at h_2, μ_{fr} is the coefficient of friction [18]. The nonlinear relation exists between power generation and wind speed. The output power generated for WT is analyzed as given in the Eq. (4) .

$$P_{\mathrm{WT}} = \begin{cases} 0 & V(\tau) \leq S_{\text{cut-in}} \text{ or } S(\tau) \geq S_{\text{cut-off}} \\ P_{\text{WT-rated}} \frac{S(\tau) - S_{\text{cut-in}}}{S_{\text{rated}} - S_{\text{cut-in}}} & S_{\text{cut-in}} < S(\tau) < S_{\text{rated}} \\ P_{\text{WT-rated}} & S_{\text{rated}} < S(\tau) < S_{\text{cut-off}} \end{cases} \tag{4}$$

In this context, $S(\tau)$ denotes the wind speed at a particular height. $P_{\text{WT - rated}}$ refers to the nominal power of WT, and air flow speed represents by V_{rated}.

3 Problem Formulation

In this study, the ESS/PV/WT system is optimized to minimize TNPC and LCE. This section offers a comprehensive explanation of how objective functions and operational constraints are modeled. It also describes the energy management technique employed for the optimal configuration. Additionally, the study introduces a novel metaheuristic-based optimization technique and details its implementation for optimizing the ESS/PV/WT system.

3.1 Technical and Economic Objectives

The principal purpose of optimizing the hybrid energy scheme is to achieve reductions in both the LCE and the TNPC. This cost reduction is achieved while enhancing load reliability, which is a critical consideration for energy system designers. The proposed methodology controls the optimum number of PV panels, WTs, and ESS. MATLAB is used to simulate the value of LCE, TNPC, and the relevant constraints.

3.1.1 Total Net Present Cost

The capital, maintenance, operation, and replacement costs are the parts of total net present cost. The TNPC of the structure can be determined using the equations below:

$$\mathrm{TNPC} = \mathrm{NPC}_{\mathrm{capital}} + \mathrm{NPC}_{\mathrm{O/M}} + \mathrm{NPC}_{\mathrm{rpl}} \tag{5}$$

$$\mathrm{NPC}_{\mathrm{capital}} = N_{\mathrm{PV}} \times C_{\mathrm{PV}}^{\mathrm{capital}} + N_{\mathrm{WT}} \times C_{\mathrm{WT}}^{\mathrm{capital}} + N_{\mathrm{ESS}} \times C_{\mathrm{ESS}}^{\mathrm{capital}} + N_{\mathrm{conv}} \times C_{\mathrm{conv}}^{\mathrm{capital}} \tag{6}$$

$$\begin{aligned}\mathrm{NPC}_{\mathrm{O/M}} = \mathrm{PWA} \times \Big(& N_{\mathrm{PV}} \times C_{\mathrm{PV}}^{\mathrm{O/M}} + N_{\mathrm{WT}} \times C_{\mathrm{WT}}^{\mathrm{O/M}} \\ &+ N_{\mathrm{ESS}} \times C_{\mathrm{ESS}}^{\mathrm{O/M}} + N_{\mathrm{conv}} \times C_{\mathrm{conv}}^{\mathrm{O/M}})\end{aligned} \tag{7}$$

$$\mathrm{PWA} = \frac{(1 + \mathrm{IR})^{N} - 1}{\mathrm{IR} \times (1 + \mathrm{IR})^{N}} \tag{8}$$

$$\mathrm{NPC}_{\mathrm{rpl}} = \lambda \times \left(N_{\mathrm{PV}} \times C_{\mathrm{PV}}^{\mathrm{rpl}} + N_{\mathrm{WT}} \times C_{\mathrm{WT}}^{\mathrm{rpl}} + N_{\mathrm{ESS}} \times C_{\mathrm{ESS}}^{\mathrm{rpl}} + N_{\mathrm{conv}} \times C_{\mathrm{conv}}^{\mathrm{rpl}}\right) \tag{9}$$

$$\lambda = \sum_{N=1}^{z} \frac{1}{(1 + \mathrm{IR})^{N \times L}} \tag{10}$$

where, PWA and λ are parameters used to change the replacement and operational costs into a single value. The interest rate is represented by IR, N represents the lifespan of proposed system, and L indicates the component number replacements during the lifespan of the proposed structure.

3.1.2 Levelized Cost of Energy

The LCE can be utilized to assess the profitability of the system that is interconnected. The LCE is computed using Eq. (11).

$$\text{LCE} = \frac{\text{TNPC} \times \text{PWA}}{\sum_{\tau=1}^{T} P_{\text{Gen}}(\tau)} \tag{11}$$

Numerous factors affect LCE, including initial cost, solar irradiation, tenure, operation, and maintenance costs, PWA and deterioration of the utilized PV units, etc.

3.2 Operational Constraints

During the optimization of an energy system, a balance is achieved between the cost function and technical boundaries. Concurrently, decision variables must be selected by implementing the proposed optimization technique. The decision variables in study have associated limits that define the upper and lower bounds of their values, as shown in the equations below:

$$N_{\text{PV}}^{\text{lower}} \leq N_{\text{PV}} \leq N_{\text{PV}}^{\text{upper}} \tag{12}$$

$$N_{\text{WT}}^{\text{lower}} \leq N_{\text{WT}} \leq N_{\text{WT}}^{\text{upper}} \tag{13}$$

$$E_{\text{ESS}}^{\text{lower}} \leq E_{\text{ESS}} \leq E_{\text{ESS}}^{\text{upper}} \tag{14}$$

$$P_{\text{conv}}^{\text{lower}} \leq P_{\text{conv}} \leq P_{\text{conv}}^{\text{upper}} \tag{15}$$

where, $N_{\text{PV}}^{\text{lower}}$ and $N_{\text{PV}}^{\text{upper}}$ denotes the lower constraint and upper constraint on PV, $N_{\text{WT}}^{\text{lower}}$ and $N_{\text{WT}}^{\text{upper}}$ denotes the lower constraint and upper constraint on WT, $N_{\text{ESS}}^{\text{lower}}$ and $N_{\text{ESS}}^{\text{upper}}$ denotes the lower constraint and upper constraint on ESS, $E_{\text{ESS}}^{\text{lower}}$ and $E_{\text{ESS}}^{\text{upper}}$ denotes the lower and upper battery capacity of ESS.

3.3 The Proposed Algorithm

The Giza Pyramid Construction Algorithm (GPCA) is a meta-heuristic optimization technique encouraged by the architectural principles of the ancient Egyptian pyramids. It leverages a hierarchical structure resembling the step-by-step construction process of pyramids, where each level represents a different phase of optimization.

A key forte of GPCA is its aptitude for managing complex optimization problems across various domains, including renewable energy system design, by integrating real-world data and constraints into its hierarchical optimization framework.

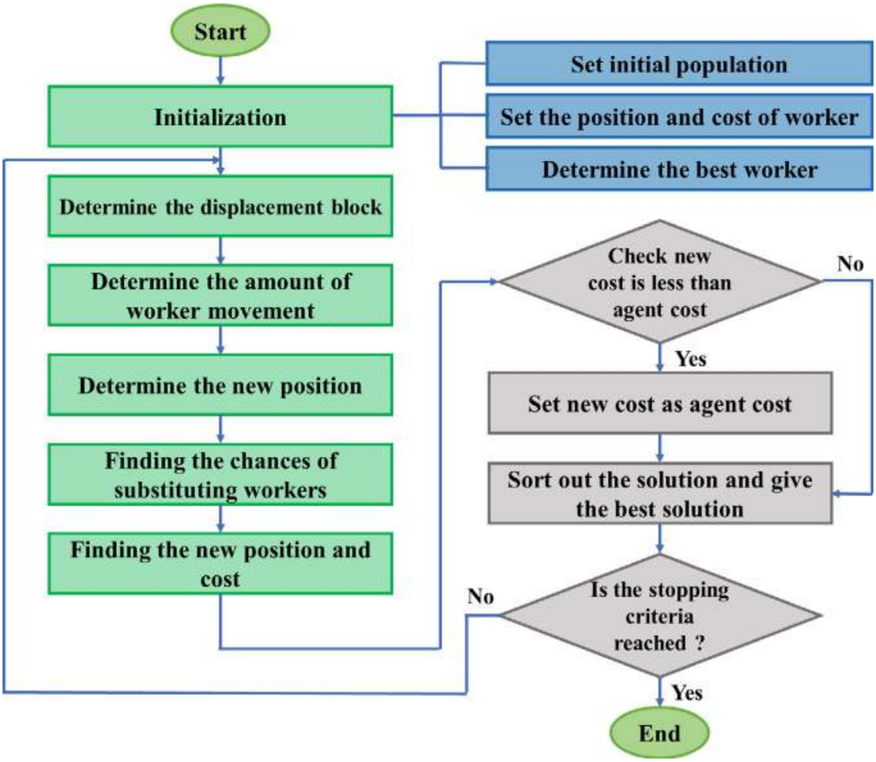

Fig. 1 Flow chart of GPCA

Its simplicity in implementation, coupled with robust performance in finding solutions, makes GPCA a promising tool for tackling challenging optimization tasks (Fig. 1).

4 Results and Discussion

The complete investigation of the simulation results and obtained findings for this research is analyzed. Initially, the proposed GPCA is validated on standard mathematical benchmark functions. The GPCA is then applied to perform the designing of EV charging station load considering three possible combinations such as ESS/PV, ESS/WT, and ESS/PV/WT by optimizing the LCE and TNPC.

Table 1 Used components cost data

Component	PV	WT	ESS	Inverter
Manufacturer	Generic	Generic	Generic lead acid	Generic
Capital cost ($)	1450	4550	475	280
Replacement cost ($)	950	2150	40	270
Operation and maintenance cost ($)	12	480	15	08
Nominal capacity (kW)	1	10	1 kWh	1
Lifespan (years)	24	20	15	15

4.1 Techno-Economic Analysis of EV Load for the Optimal Configuration (ESS/PV/WT)

This section examines various energy sources available to meet EV load demands. The objective is to evaluate combinations such as ESS/PV, ESS/WT, and ESS/PV/WT to optimize TNPC and LCE for designing an efficient energy system. Objective functions and decision variables are defined, encompassing components like PV, WT, ESS units, converter output, excess electricity, and the contribution of RESs. Additionally, the effect of purchasing power through the power grid is scrutinized, RES-based grid-connected systems with off-grid hybrid systems.

The selected renewable energy system for this study includes a 650-Watt PV module, a 1 kW WT, and a 12 V 100 Ah lead-acid battery. Detailed technical and economic specifications can be found in Table 1. Maintenance costs for the PV module and WT are determined based on averages reported in existing studies. Costs associated with the inverter and batteries are calculated considering both replacement costs and the expected frequency of replacements over the system's lifetime.

The analysis of optimal combinations to meet EV charging requirements in the Noida region is presented in Table 2. It shows that the LCE and TNPC values for the ESS/PV/WT configuration enhanced using proposed technique are the lowest among all other possible combinations. This configuration achieves minimal costs due to reductions in capital expenditure, replacement costs, and operation and maintenance expenses. Specifically, the optimized LCE and TNPC values using GPCA are $0.3697 per kilowatt-hour and $5,603,588.08, respectively, which are significantly lower compared to results obtained using other algorithms.

4.2 Hourly Result Analysis

This study focuses for three days from 4 to 6 May, which is the hottest month in the Noida region, analyzing the electricity generated from RES, electric vehicle load demand, and ESS profiles, as depicted in Fig. 2. The analysis considers the charging requirements of 40–50 EVs, with a preference for charging between 8:00 AM and

Table 2 Optimal data for different combinations to satisfy EV load

Configuration	ESS/PV	ESS/WT	ESS/PV/WT
TNPC ($)	8,507,427.23	13,501,232.67	5,581,477.12
LCE ($/kWh)	0.5713	0.86989	0.3712
Operating cost ($)	1,06,964	3,40,003.50	99,876.23
PV generation	4,502,404	–	1,798,534
Wind generation	–	6,293,942	1,254,143
Battery units used	5989	14,412	4296
Extra electricity (kWh/year)	3,198,714	5,010,332	1,723,350

8:00 PM, and fewer vehicles charging from 2:00 AM and 7:00 PM. Excess electricity generated by renewable sources is stored in the ESS when it exceeds the EV charging demand, and the ESS discharges stored energy when renewable energy output falls short of meeting the EV load.

In Fig. 2, the energy generation of the solar source is represented by the dark purple dashed line, while the energy generation of the wind is depicted by the green dashed line. The WT shows higher output during late night and early morning periods, indicating ample availability of wind power during those times. In contrast, peak solar energy output typically occurs around midday. The dark brown dashed line shows the profile of EV load demand in the Noida City. Any surplus electrical energy beyond the charging requirements is used to charge the ESS, depicted by the blue line indicating the SOC and energy storage capacity of the ESS. Excess energy after charging the ESS is directed towards a dump load. A bidirectional inverter is employed to convert WT output into usable DC power, playing a crucial role in managing energy flow within the system.

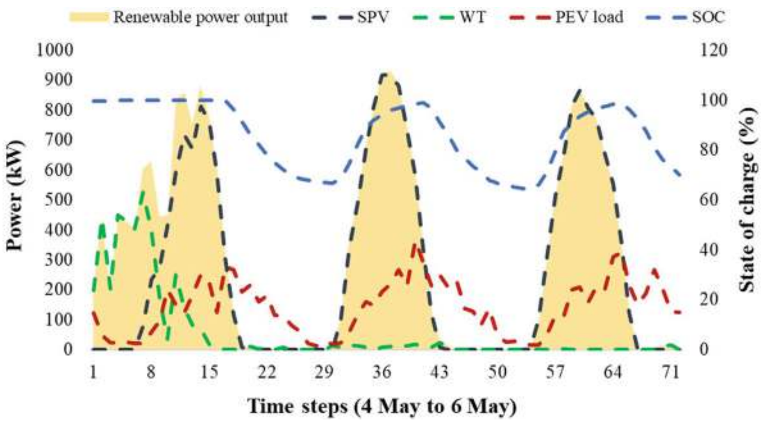

Fig. 2 Power supplied by various sources

This comprehensive analysis includes multiple convergence iterations and clarifies the interpretation of average execution time, providing a deeper understanding of the algorithm's convergence behavior and computational efficiency. During the summer months, particularly in May, the majority of EV load demand is met by solar power, with a smaller contribution from wind power as shown in Fig. 2. Solar and wind energy successfully met EV power demands during the observation period, resulting in surplus energy, particularly in the afternoon. However, due to constraints such as the battery's upper charging rate and historical charging patterns determined by the kinetic battery model, the battery was not fully charged despite the surplus energy. The energy management system prioritizes efficient charging strategies considering these limitations and usage patterns.

Throughout the simulation, if RES output falls short of meeting demand, the battery may experience energy depletion, leading to unmet loads or energy deficits. The simulation model indicated only 645 kWh per year of unmet load, representing a negligible 0.056% of the total load considered in the simulation. It's crucial to recognize that this result assumes a 0% annual capacity deficiency, indicating the system's design to fully satisfy energy demand throughout the year. Figure 3 highlights that during summer months, especially in May, the PV system primarily supplies the EV charging demand. Battery energy discharge is minimized because surplus electricity produced by solar source is utilized for ESS charging.

In terms of overall system scale, the bidirectional converter has a lower power output compared to PV and WT sources, resulting in surplus electricity generation exceeding system demand. This surplus electricity totals 1,892,312 kWh per year, constituting a significant 59.8% of total electricity production. This excess energy significantly contributes to overall renewable electricity generation. Figure 4 illustrates additional electricity generation, renewable energy output, and renewable penetration over three consecutive days in May, demonstrating increased electricity production and higher renewable energy proportion in the energy mix during this period.

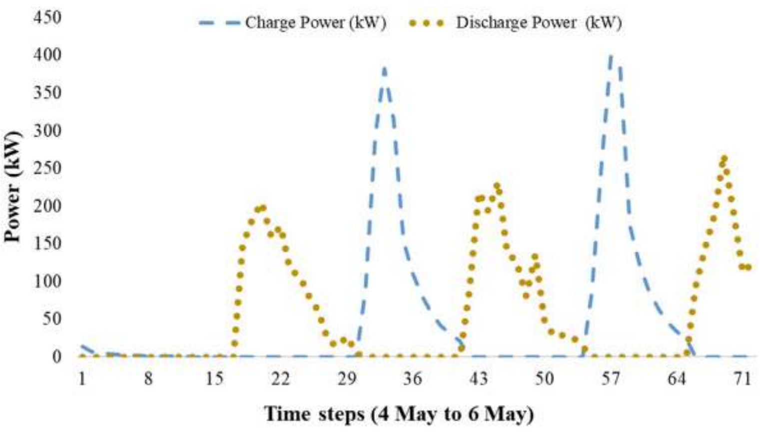

Fig. 3 Power demand and supply for ESS

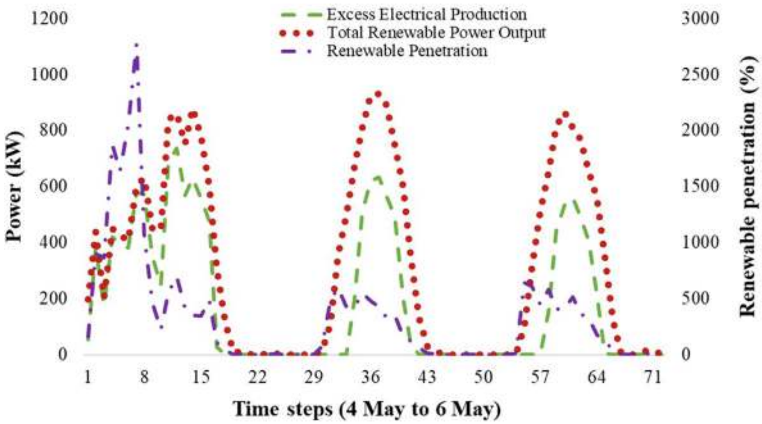

Fig. 4 Analysis of excess generation, RES power generation, and penetration

Figure 5 illustrates the energy produced by solar and wind sources and the EV load demand across different months of the year. The PV panels operate for 4412 h annually at a capacity factor of 158%, while the WT operates for 7421 h per year at a capacity factor of 111%. Among the various configurations fulfill the charging demand of EV, the ESS/PV/WT system generated the highest annual electricity output (3,098,788 kWh) from PV modules and WT. It is noted that PV contributes 60.2% to satisfying the EV load demand, while WT contributes 41.2%. Reduced electricity production from PV modules during summertime is attributed to increased rainfall and cloud cover, which reduce solar radiation availability. The analysis confirms that this energy system combination achieves a renewable fraction of one, indicating that all electricity generated comes from renewable sources. Consequently, the system operates without emitting CO_2, CO, particulate matter, SO_2, unburned hydrocarbons, or other harmful pollutants.

Figure 5 also depicts monthly electricity generation trends, highlighting that PV modules generate more power between June and September due to higher solar radiation and longer daylight hours, optimal for solar energy production. Conversely, PV output is lowest in December and January when solar irradiance is minimal. Similarly, wind power production peaks in June and July, corresponding to higher wind speeds, while September records the lowest wind power production. The solar energy source has a peak output power of 1071 kW and the aggregate generation of 209 kW, with a LCE of \$0.0772 per kilowatt-hour. On the other side, the wind generation has a maximum output power 538 kW with the aggregate of 139 kW, with the LCE of \$0.0389 per kilowatt-hour.

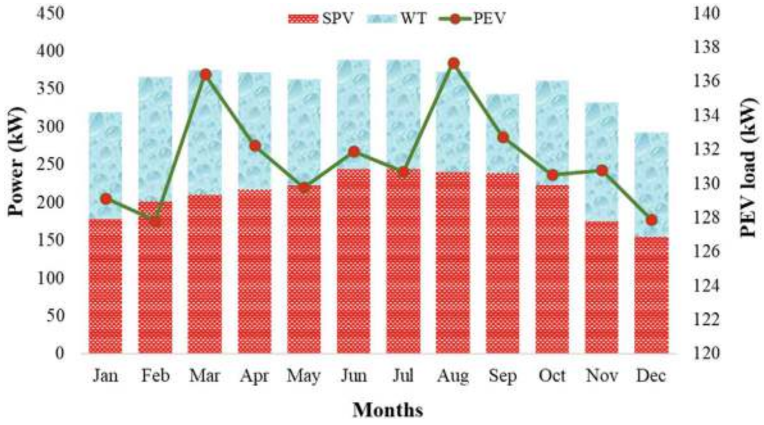

Fig. 5 EV charging demand and RES average power supplied

4.3 Cost Wise-Break up Analysis of Various System Component

Figure 6 illustrates the cost allocations of PV, WT, ESS, and converter components within the TNPC for different possible combinations: (a) ESS/PV, (b) ESS/WT, and (c) ESS/PV/WT. The TNPC for the ESS/PV/WT system, calculated using the proposed technique, amounts to $5,582,679.05. This is 34.7% and 57.3% lower than the TNPC for the ESS/PV and ESS/WT systems, respectively, estimated using the same technique. In the optimal configuration, ESS/PV/WT, the storage unit contributes the most to the NPC, trailed by the PV panels. Furthermore, the ESS and PV costs constitute 53.8% and 32.6% of the TNPC, respectively. Similarly, the WT represents an annualized cost of 12.2% of the TNPC. The combined initial capital cost of PV, WT, ESS, and converters ($4,198,446.25) accounts for the largest proportion, comprising 75.8% of the total NPC. The optimal ESS/PV/WT combination incurs an operating cost of $99,876.12, which is 7.3% and 71.05% less than the operating costs of the ESS/PV and ESS/WT systems, respectively.

4.4 Comparison Analysis of Grid-Connected and Off-Grid Design of EV Load

This study explores the techno-economic implications of grid-connected RESs. The proposed action plan involves using grid power when RESs are unable to satisfy the load demand. Excess energy generated by hybrid energy solutions is efficiently managed by selling it back to the grid, minimizing the need for extensive energy storage.

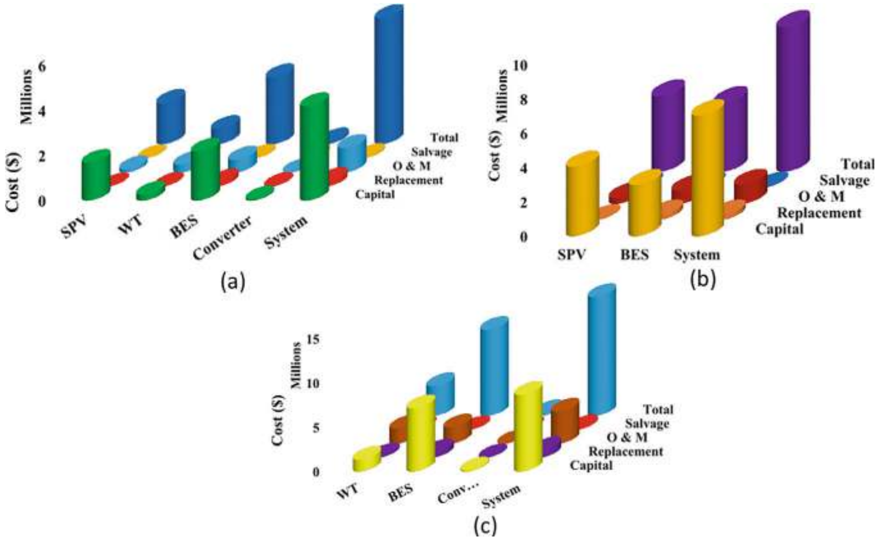

Fig. 6 Different types of cost: **a** ESS/PV, **b** ESS/WT, and **c** ESS/PV/WT

Figure 7 illustrates the electricity produced from various energy sources over three consecutive days in May. Due to the high solar irradiance during May, PV panels significantly contribute to meeting the EV load requirement. The remaining energy comes from wind turbines and the grid. Notably, PV, WT, and the grid contribute 64.5%, 6.2%, and 32.3%, respectively, to the total load demand.

Figure 8 illustrates the average monthly energy sales and purchases with the utility network. The system produces an excess of power even after fulfilling the EV demand, and this additional power is transferred to the utility. Annually, 515,123

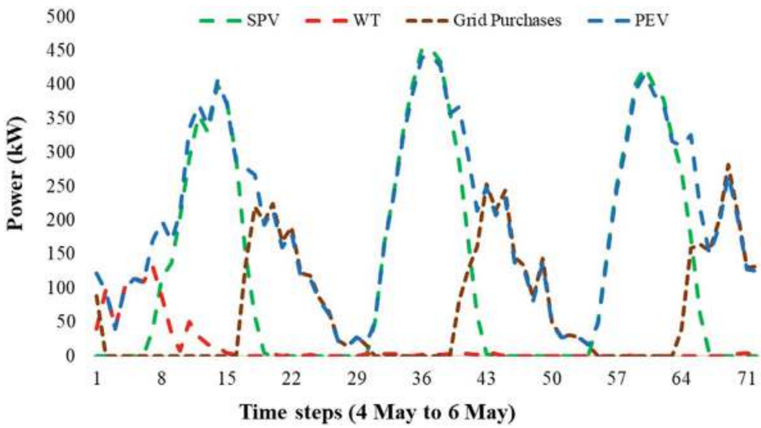

Fig. 7 Power supplied by WT, PV, and power grid for EV charging load

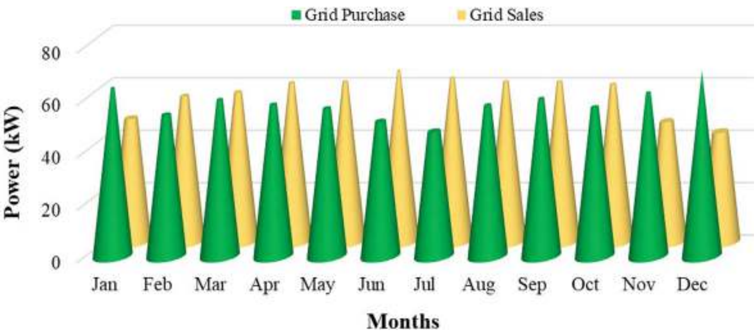

Fig. 8 Grid exchange power data for a year

energy units are taken from the power grid, while 489,956 energy units are sold back to grid. The highest amount of power is purchased from the utility during December and January because of the low solar and wind energy generation. Conversely, very less energy is taken from the distribution grid, when the energy produced by RESs is sufficient, predominantly in June and July.

5 Conclusion

This chapter explores a techno-economic analysis of utilizing PV panels, WT, and ESS for charging EVs in Noida, an industrial hub with a substantial presence of multinational companies. The proposed framework has been optimized using the Giza Pyramid Construction Algorithm, incorporating real datasets of solar irradiation and wind speed specific to the studied location. The outcomes consider various technical and economic factors. The optimization results indicate that ESS/PV/WT-based charging for EVs is the most efficient method for meeting EV demand in the specified region. Designing EV load based on ESS/PV/WT yields the lowest LCE compared to other potential frameworks, namely ESS/PV and ESS/WT. The TNPC for the optimal combination is 57.8% and 34.2% less than that of ESS/PV and ESS/WT, respectively. Similarly, the optimal configuration demonstrates a minimum LCE, which is 35.2% and 58.3% lower than the ESS/PV and ESS/WT combinations, respectively. In the studied area, PV and WT systems generate more electricity during June and July, respectively.

This work further examines the techno-economic analysis of a grid-connected design for EV load. In this study, power is acquired from the power grid at $0.12 per unit and sold back to the grid at $0.078 per unit. The analysis reveals that the grid-connected system is significantly less expensive than ESS/PV/WT-based charging stations. The grid-connected system yields a TNPC of $1,569,375 and an ideal LCE of $0.0846 per unit. Compared to the ESS/PV/WT system, the grid-connected system requires fewer PV and WT units—specifically, only 525 PV units and 133 WT units. Additionally, the study suggests that a hybrid system with comparable grid acquisition and sell-back prices can be an affordable option. This means that the price at which the system buys electricity from the grid is the same as the price at which it sells excess electricity back to the grid.

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Chapter 6
Smart Grid and Energy Management

Jigneshkumar P. Desai

Abstract A groundbreaking development in the energy industry, smart grid uses technology to advance the sustainability, dependability, and effectiveness of the power grid. In-depth study of smart grids' components and effects on energy management are covered in this chapter along with an examination of its many facets. Advanced Metering Infrastructure (AMI), Volt/VAR Management (VVM) systems, and Outage Management Systems (OMS) are important components of smart grid described in this chapter. Smart meters, communication networks, and data management are all integrated by AMI, allowing utilities and customers to communicate with each other in two directions. To expedite outage response, prioritization, and crew assignments, OMS integrates real-time network data with predictive capabilities. By adjusting voltage levels, VVM improves efficiency, reduces peak load, and promotes energy saving. The chapter also emphasizes the interdependence of smart grids, true online Uninterrupted Power Supply (UPS), and direct current (DC) schemes, as well as Power Quality Analyzers (PQAs), which are solutions for reducing voltage sag. These methods increase the grid's resistance to voltage drops, which is essential for maintaining power quality. The chapter provides extensive strategy for multi-energy management of smart home. In the end, pilot smart grid projects are discussed and challenges of smart grid are summarized.

Keywords Demand-side management · Energy management · Integration · Power quality · Peak load · Smart grid

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1 Introduction

An electric grid, also known as a power grid or electricity grid, is a complex network of infrastructure that facilitates the power generation, power transmission, and power distribution of electrical power from power plants to consumers and consumers to Low Voltage (LV) bus. Figure 1 shows the recent electric grid which is evolved as smart grid. As per the definition of Institute of Electrical and Electronics Engineer (IEEE), the smart grid can be conceptualized as a comprehensive "System of Systems," with each operational domain featuring three crucial layers: (i) the power and energy tier, (ii) the communication tier, and (iii) the IT/computer tier. The communication and IT/computer layers (ii) and (iii) act as integral infrastructure components, elevating the intelligence of the existing power and energy infrastructure, thereby making it more sophisticated and efficient. As per the National Institute of Standards and Technology (NIST) [1], an upgraded grid, fostering bidirectional power streams and leveraging two-way information sharing and regulator capabilities, is poised to introduce a diverse range of new functions and applications. Figure 1 shows the all three layers and cloud-based technology integrated smart grid structure. Smart grid operator manages the supply–demand using cloud-based server information and AI-driven decisions. Dotted blue line shows the communication using smart meters using common access point.

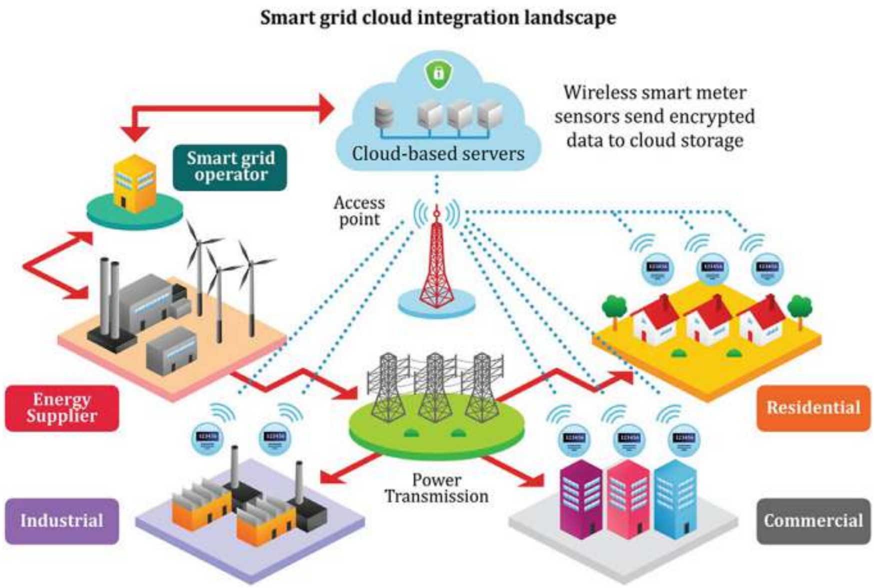

Fig. 1 Cloud-integrated smart grid design with bidirectional communication and power flow [2]

The chapter offers insights into cutting-edge technological advancements in the field of smart grids. It contributes by imparting knowledge on smart grid technologies, elucidating their impact, expansion, unused benefits, and interconnections. The inclusion of detailed pilot project descriptions and case studies on load growth adds depth to the exploration. Ultimately, the chapter concludes by presenting a comprehensive overview of multi-energy management solutions for smart homes within the context of a smart grid environment.

The chapter commences with an introduction that delves into the concept and evolution of smart grids, offering an extensive exploration of their development. Section 2 focuses on a thorough examination of smart grid technologies, while the core apparatuses of the smart grid are comprehensively addressed in the middle segment of the chapter. The latter part extensively delves into the intricacies of energy management systems. The chapter concludes by addressing the challenges associated with the implementation of smart grid systems.

1.1 Vertical Nature of Conventional Grid

The term "vertical" in the context of a conventional grid may refer to the hierarchical structure of the electric power system, where the system is divided into different levels or layers. This hierarchical structure is often described in terms of voltage levels and the functions performed at each level. Figure 2 shows the breakdown of the vertical nature of a conventional power grid: (1) Generation Level: At the bottom of the hierarchy is the generation level, where electricity is produced at power plants. These power plants can use various power sources, which include fossil fuels, nuclear, or renewable sources (solar, wind, hydro).

(2) Transmission Level: The next level is the transmission level, where the generated electricity is transmitted over long distances through high-voltage transmission lines. This level involves the bulk movement of electricity from power plants to various regions. (3) Substation Level: Along the transmission lines, there are substations that may step up or step down the voltage as needed. Substations play a vital part in maintaining the stability of the grid by controlling voltage levels and directing the flow of electricity.

(4) Distribution Level: Above the substation level is the distribution level, where the electricity is distributed to end-users. Distribution lines carry power from substations to homes, businesses, and other consumers. The voltage at this level is lower than that at the transmission level. (5) End-User Level: At the top of the hierarchy is the end-user level, where electricity is finally consumed by residential, commercial, and industrial customers. This level represents the destination of the electricity produced at the generation level.

This vertical structure shown in Fig. 3 allows for the efficient and organized flow of power from the point of power plants to the consumer. Each level serves a specific function in the inclusive action of the power grid. Note that this ordered

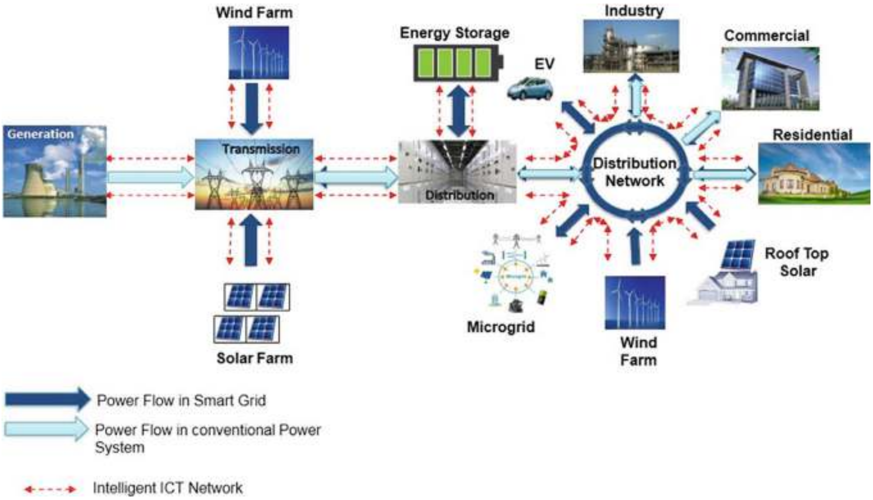

Fig. 2 Hybrid energy sources along with microgrid and electrical vehicle (EV) in smart grid

structure is a simplification, and modern electric grids are becoming more dynamic and interconnected, especially with the integration of smart grid technologies.

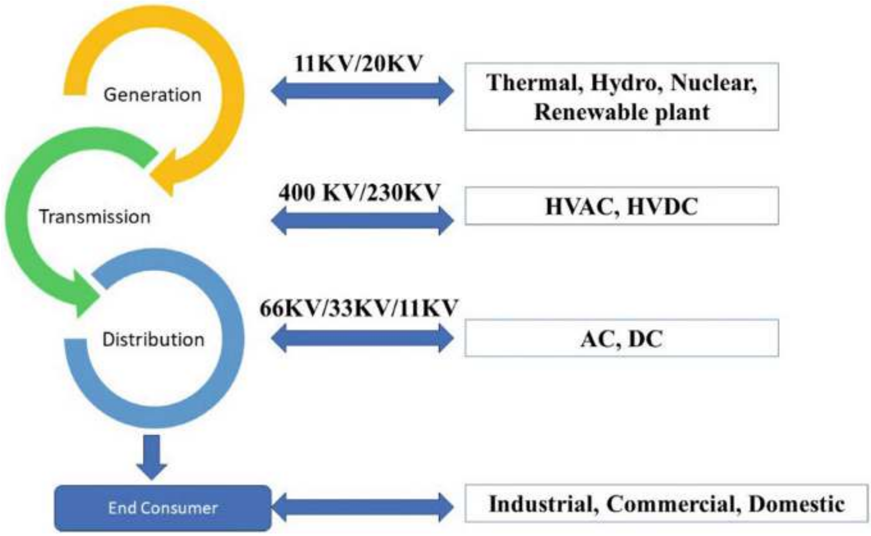

Fig. 3 Conventional grid's vertical structure

1.2 History of Grid

In the late nineteenth century, the rivalry between Thomas Edison and Nicola Tesla laid the foundation for the development of electrical distribution systems. Edison hailed as the father of DC distribution, and Tesla, recognized for his pioneering work in Alternating Current (AC) distribution, engaged in a competition that would shape the future of power transmission. Tesla's innovations in long-distance AC distribution posed a formidable challenge to Edison's short-distance DC distribution system. The battle between these two technologies culminated in the victory of AC due to its superior cost-effectiveness and efficiency in transmitting electricity over extended distances. As the world moved into the early 1960s, a pivotal era in grid management emerged. The concept of regional grid management took root, leading to the interconnection of state grids. In India, this marked the demarcation of the country into five distinct regions: Northern, Eastern, Western, North Eastern, and Southern.

In an Indian case study, the timeline of grid evolution unfolded further in subsequent decades. In October 1991, the North Eastern and Eastern grids were interconnected, setting a precedent for future integrations. By March 2003, the WR (Western Region) and ER-NER (Eastern Region—North Eastern Region) were linked, expanding the scope of the interconnected grid [3]. August 2006 witnessed a significant milestone as the North and East networks were unified, resulting in the formation of four regional grids—Northern, Eastern, Western, and North Eastern—all operating synchronously at a unified frequency. This marked a crucial step towards the establishment of a centralized grid system. The culmination of this process occurred on December 31, 2013, when the Southern Region seamlessly integrated into the Central Grid. This accomplishment, marked by the contracting of the 765 kV Raichur-Solapur Transmission line, symbolized the recognition of the vision: 'ONE NATION,' 'ONE GRID,' 'ONE FREQUENCY.' The interconnected and synchronized nature of the grids ushered in an era of unified power distribution across the nation.

1.3 Factor Affecting the Performance of Existing Grid

(1) Increasing Demand for Electricity: As the population grows and industries expand, the demand for electricity tends to increase. This can strain the existing grid infrastructure, leading to potential inefficiencies and reliability issues. For instance, A city experiences rapid urbanization, resulting in a higher demand for electricity due to the construction of new residential and commercial buildings. The existing grid may struggle to meet this increased demand, causing potential blackouts or voltage fluctuations. (2) Supply Shortfalls of Electricity: Inadequate generation capacity or disruptions in the power supply chain can lead to shortages, impacting the reliability of the grid. For instance, A region heavily relies on a specific power plant for its

electricity. If that power plant experiences a technical failure or fuel shortage, it can result in a supply shortfall, affecting the stability of the grid. (3) Need for Reducing Losses: Energy losses occur during the transmission and distribution of electricity. These losses can be due to factors such as resistance in power lines and transformers. For instance, upgrading aging infrastructure with more efficient equipment, such as high-capacity transmission lines or transformers with lower losses, can help reduce overall energy losses in the grid. (4) Peak Demand Management: Peak demand refers to the maximum amount of electricity required during a specific period. Effectively managing peak demand is crucial to ensure the grid can handle periods of high stress without failures. For instance, A utility implements smart grid technologies that allow for demand response programs. During peak periods, consumers are incentivized to reduce their electricity usage, helping to balance the grid load and prevent overloads. (5) Integration of Renewable Energy Generation Systems: Incorporating RES, such as solar PV and wind power, into the network introduces variability and challenges linked to the irregular nature of these sources [4]. For instance, A region invests heavily in wind power. Sudden changes in wind speed can lead to fluctuations in electricity generation. Grid operators need to implement advanced forecasting and storage solutions to manage the variability and ensure a stable power supply [5]. Addressing these factors requires a holistic approach involving technological advancements, policy frameworks, and strategic planning to build a resilient and efficient electrical grid. (6) Ageing Assets and Lack of Circuit Capacity: Over time, the components of a power grid, such as transformers, switchgear, and transmission lines, age and may become less efficient or reliable. Additionally, an increase in demand might exceed the capacity of existing circuits. For instance, an urban area experiences population growth and increased industrial activity, leading to a higher demand for electricity. The existing transmission lines and substations, designed decades ago, may not be equipped to handle the current load, resulting in overloads and increased risks of failures. (7) Power Network Designed Life in Need of Replacement: The infrastructure of a power network has a designed lifespan, and as it approaches the end of this lifespan, the risk of failures and inefficiencies increases. For instance, A set of transformers in a substation was designed with a lifespan of 30 years. As these transformers reach the end of their design life, the likelihood of breakdowns and maintenance requirements rises, necessitating the replacement of aging assets. (8) Capital Costs of Like-for-Like Replacement Will Be Very High: Simply replacing ageing assets with similar technology can be expensive. Capital costs may pose a challenge, especially if the replacement technology is more costly or if financial resources are limited. For instance, upgrading a substation's outdated switchgear with the latest technology may be financially burdensome, especially if the utility faces budget constraints. This can lead to a need for careful financial planning and possibly seeking alternative, cost-effective solutions. (9) Security of Supply: As critical loads, such as hospitals, data centers, and emergency services, become increasingly reliant on a stable power supply, ensuring the security of the electricity network becomes paramount. For instance, A city with a growing number of critical infrastructure facilities requires a power grid that is resilient to disruptions. Grid operators need to implement measures, such as redundancy and backup systems, to

Table 1 Contrast of conventional grid and smart grid

Feature	Conventional grid	Smart grid
Technology	Conventional relaying and one-way flow of electricity	Digital relaying and two-way flow of electricity and information
Power distribution	One-way supply from the main plant	Two-way power delivery and automation in substations
Power generation	Centralized. All power must be generated from a central location	Distributed. Power can be distributed from multiple plants and substations
Sensors	Few sensors, making it tough to pinpoint the place of a fault	Many sensors all over the grid
Monitoring	Limited monitoring competencies	Capable of monitoring actions of the grid-connected scheme, customer preferences of using power, and providing real-time information of all the events
Control	Limited internal regulation	Facilitates remote control and self-regulation

ensure the continuous and reliable supply of electricity to critical loads. (10) Thermal Constraints: Overloaded transmission and distribution lines can experience thermal constraints, leading to increased temperatures and a reduction in the life of the equipment. This can also contribute to a higher incidence of faults. For instance, during periods of high electricity demand, transmission lines may approach their thermal limits. This can result in overheating, reduces the lifespan of the equipment and increasing the likelihood of faults, such as line sagging or conductor failures.

1.4 Conventional Grid Versus Smart Grid

Table 1 clearly shows that smart grid has superior control and advanced monitoring which facilitates the user as compared to conventional grid. Moreover, it has a bidirectional power flow which requires complex control and protection design.

1.5 Smart Grid Enablers

The numerical expertise that permits two-way communication between the utility and its clients, and the detection along the power transmission lines is what kinds the network smart. For customers, if you previously manage actions such as private banking from your home-based computer, visualize management of your power in a similar way. For instance, customers will no longer need to await monthly statements to ascertain their electricity usage. Through the implementation of a more intelligent grid, they can gain a transparent and timely overview, facilitated by devices such as "smart meters." It can be perceived in what way much power you use, when you use it, and its price. Joint with real-time pricing, this will permit you to save money by means of less power when energy is most expensive. Smart Grid has the potential to help you save money by helping you to attain your power use and choose the premium periods to purchasing power. And you can accept even extra by producing your individual power.

2 SG Technologies

2.1 Advanced Metering Infrastructure (AMI)

In this section, we delve into the intricacies of the smart meter network, focusing on its core components and their interconnected functionalities. The foundation of the network shown in Fig. 4 lies in the Smart Meter with Powerline connection via Data Concentrator Unit (DCU), which employs a mobile network for seamless communication with the central system. Figure 4 shows the smart metering infrastructure schematic diagram.

The central system shown in Fig. 4 serves as the nerve center of the smart meter network, orchestrating various components to ensure efficient operations. The key elements of the Central System include: (1) Advanced Meter Management (AMM): Interfaces with the Head End System (HES) for efficient communication with smart meters. (2) HES Interface Adaptation: Facilitates communication between the AMM and smart meters, ensuring a streamlined exchange of information. (3) Advanced

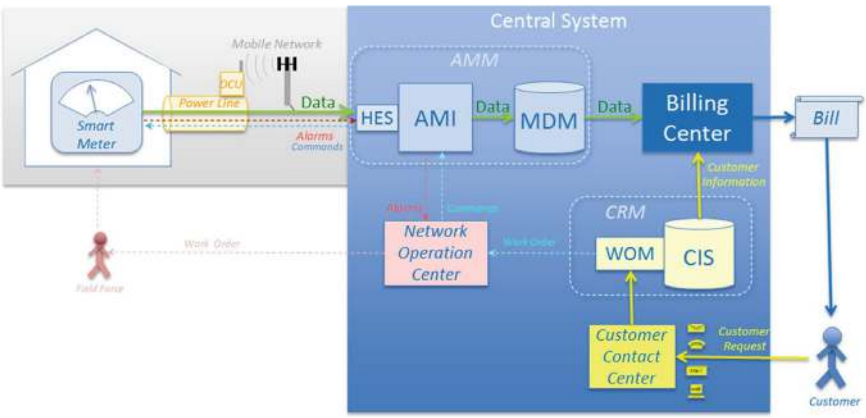

Fig. 4 Schematic block diagram of smart metering infrastructure

Metering Infrastructure (AMI): Controls the smart meters, forming an infrastructure that enhances metering capabilities. (4) Meter Data Management (MDM): Stores and manages the measured values obtained from smart meters, ensuring a reliable repository for crucial data. (5) Network Operation Center (NOC): Operates as the central hub for managing and overseeing the smart meter network, ensuring its seamless functionality [6]. (6) Field Force: Executes on-site activities essential for the proper functioning of the smart meter network. (7) Customer Relationship Management (CRM): Integrates with the Customer Information System (CIS) to store customer-related data for enhanced service provision. (8) CIS: Acts as a repository for customer-related data, providing essential information for service optimization. (9) Work Order Management System (WOM): Executes customer-related operations to ensure efficient workflow and service delivery. (10) Customer Contact Center (CCC): Manages customer requests and facilitates access to customer sites as needed. (11) Billing Center: Generates customer bills and invoices, ensuring accurate and timely financial transactions.

2.2 Power Quality Management

Power quality events can be classified into several categories: (1) Voltage Variation: This occurs when the voltage momentarily falls below or exceeds a definite limit, known as voltage sag or voltage swell. It also includes cases of complete voltage loss. (2) Frequency Variation: This happens when the system frequency momentarily exceeds or falls below a specified limit, often measured as a significant increase in volts per Hertz. (3) Voltage Unbalance Variations: When negative sequence currents accompany positive sequence currents, it leads to increased motor losses, reduced efficiency, torque fluctuations, and motor failures. Additionally, it contributes to higher cable losses and adversely affects the action of UPS, inverters, and Variable Frequency Drive (VFD). (4) Current Unbalance Variations: These result in voltage unbalance. (5) Waveform Alteration: This pertains to a persistent deviation from the ideal sinusoidal wave of power frequency in a steady state, which includes DC offset, harmonics, inter-harmonics, notching, and noise. Notching, characterized by periodic voltage disturbances resulting from the regular operation of power electronics devices during phase commutation, has the potential to cause mis-operation in control systems. (6) Noise: Interference that disrupts electronic devices, including microcomputers and programmable controllers, leading to communication issues, heating problems, and malfunctions in solid-state devices.

2.3 Power Quality Management in Smart Grid

VVM system is designed to control voltage profiles within permissible limits and minimalize the flow of reactive power in distribution systems. By improving voltage levels for customers along feeder power lines, this system offers substantial advantages in terms of conservation, efficiency, and peak reduction.

On the other hand, Distribution Automation (DA) systems take a proactive approach by addressing issues before they impact customers or mitigating their effects in the event of service interruptions.

2.4 Peak Load Management

Peak load, or peak demand, refers to the maximum power demand experienced by an electrical grid during a specified timeframe. In simpler terms, peaks occur when a substantial number of buildings within an electrical system simultaneously consume the highest amount of electricity or power, often concentrated in the afternoon hours, typically between 3 and 5 pm as shown Fig. 5.

The installation of a new coal plant presents a challenge in terms of load control by customers. However, leveraging an AC/DC microgrid can effectively manage and regulate loads. This technology offers a solution to control excessive reinforcement, ensuring more efficient and controlled energy consumption.

Figure 6 shows case study of Indian grid development, in which thermal power generation is 239.072 GW highest, followed by hydro-power of 46.85 GW, Nuclear 7.48 GW while non-conventional power generation like solar and wind has installed capacity of 72.01 GW and 44.29 GW, respectively. This shows that limiting peak demand impacts on reduction of thermal power future installation and has

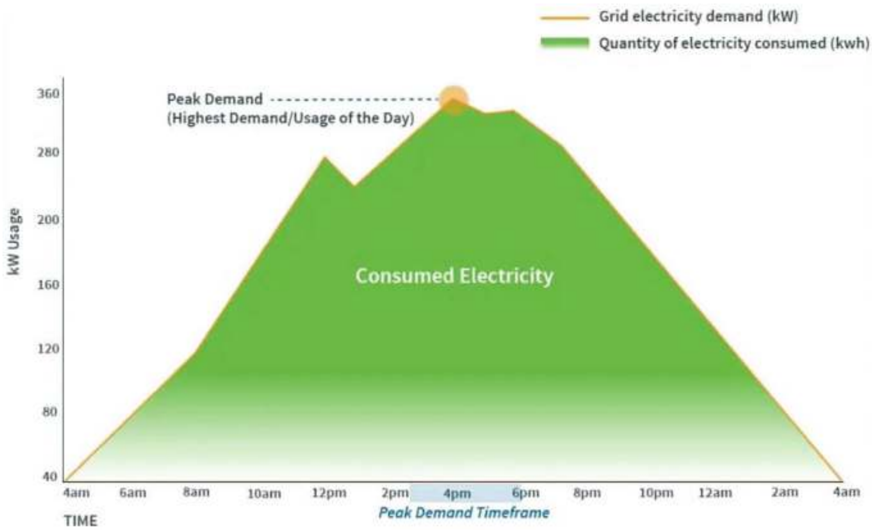

Fig. 5 Peak load demand during a day with consumed electricity

contributed to reduction of CO_2 emissions. As per data, there is shortage of 144 MW on 30.11.2023 on Indian grid as depicted in Fig. 7. This problem of shortage can be resolved using Demand-side management (DSM). DSM strategies encompass various approaches to influence and optimize energy consumption patterns. These strategies include: (1) Energy Efficiency Programs: Implementing initiatives to enhance the efficiency of energy use in buildings, appliances, and industrial processes. (2) Demand Response Agendas: Reassuring customers to adjust their electricity practice in reply to peak demand periods or other grid conditions. (3) Time-of-Use Pricing: Introducing variable electricity rates based on the time of day to incentivize consumers to shift their energy consumption to off-peak hours. (4) Incentive Programs: Providing financial incentives or rebates to consumers who adopt energy-efficient technologies or practices. (5) Smart Grid Technologies: Utilizing advanced technologies to enhance grid management, monitor consumption in real-time, and enable better communication between utilities and consumers. (6) Load Shedding and Peak Clipping: Temporarily reducing electricity consumption during peak demand periods to alleviate strain on the grid. (7) Energy Storage Solutions: Implementing storage technologies to store excess energy during low-demand ages for use during highest times. (8) Renewable Energy Integration: Promoting the acceptance of renewable energy sources to reduce reliance on conventional power generation and decrease environmental impact (9) Behavioral Change Programs: Educating and encouraging consumers to adopt energy-saving behaviors in their daily lives. (10) Electrification of Transportation: Promoting the use of electric vehicles and infrastructure to manage and optimize electricity demand.

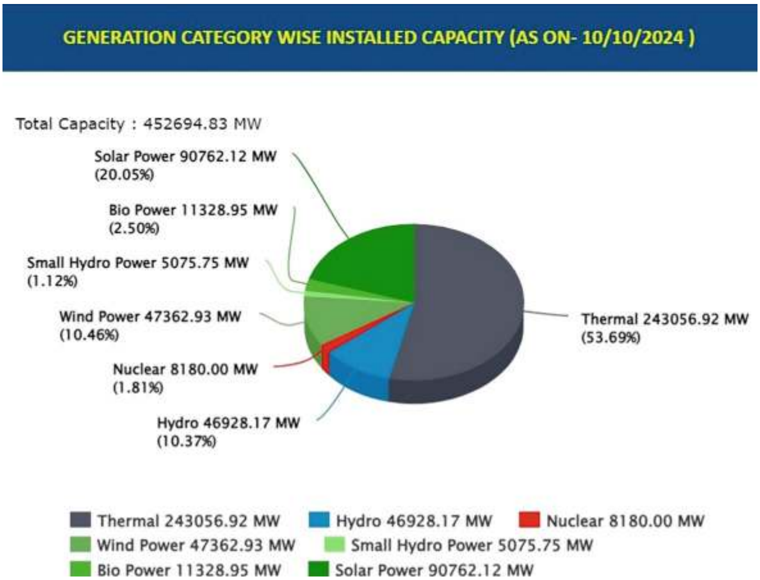

Fig. 6 Category-wise installed capacity in India [7]

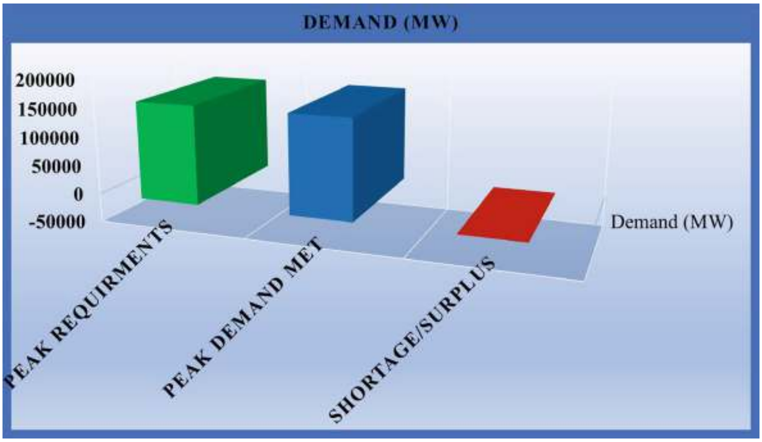

Fig. 7 Daily demand with peak load and shortage as on 30.11.2023 in India [7]

These DSM strategies aim to create a more flexible and sustainable energy landscape by actively involving consumers and optimizing the utilization of resources. Figure 8 shows different DSM strategies, each one is described below:

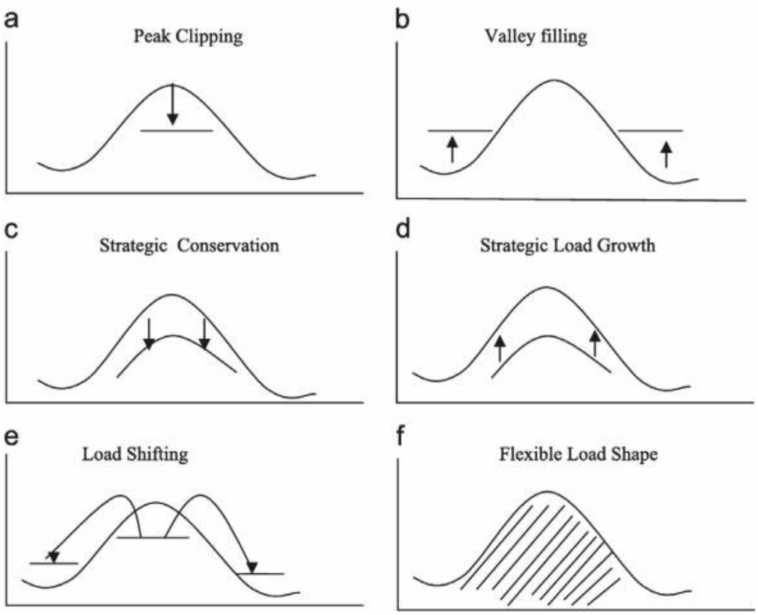

Fig. 8 DSM techniques [8]

(1) Peak Clipping: Peak clipping refers to the practice of reducing or "clipping" the peak electricity demand by employing strategies such as demand response, load shedding, or energy storage during periods of high demand. This helps prevent exceeding the maximum capacity of the electrical grid. (2) Valley Filling: Valley filling is the complementary concept to peak clipping. It involves filling in the low-demand periods, or "valleys," in the energy consumption pattern. This can be achieved by encouraging activities that consume more energy during off-peak hours or through load-shifting strategies. (3) Load Shifting: Load shifting involves adjusting the timing of energy ingesting from periods of high demand to periods of lower demand. This strategy aims to optimize energy use, reduce peak demand, and often involves encouraging consumers to use electricity during off-peak hours when rates may be lower. (4) Conservation: Conservation in the energy context refers to the practice of using less energy by adopting energy-efficient technologies, implementing energy-saving behaviors, and reducing unnecessary energy consumption. It is a fundamental strategy for sustainable energy management. (5) Load Growth: Load growth indicates an increase in the demand for electricity over time. This can result from factors such as population growth, economic development, or the expansion of industrial activities, leading to an increased need for electrical power. (6) Flexible Load: Flexible load refers to electricity-consuming processes or devices that can be adjusted or controlled to respond to changes in energy demand. These flexible loads can be dynamically managed to align with grid conditions, allowing for better integration of renewable energy sources and improved grid stability.

2.5 Outage Management

OMS leverages the latest network status and a sophisticated prediction engine to assist in anticipating and addressing outages with greater insight and efficiency. Presently, dispatchers have access to real-time network data, enabling precise assessments of outage impacts on customers. This facilitates prioritized responses, efficient crew assignments, and improved decisions regarding potential power back-feeding possibilities.

3 Energy Storage Application in Smart Grid

Energy storage plays a crucial role in the modern energy landscape, offering a range of applications that contribute to grid stability, reliability, and efficiency.

(1) Time Shifting of Electric Energy (Grid-Supplied): Involves charging the storage facility using affordable electric energy in periods of short demand and freeing it back to the grid during high-demand intervals. For instance, storing energy overnight when electricity rates are lower and releasing it during peak demand hours when rates are higher, thereby maximizing cost-effectiveness. (2) Electrical Source

Volume: Decreases or weakens the need to connect new generation sizes by providing stored energy during peak demand periods. For instance, using energy storage to meet high-demand periods, avoiding the need to build new power plants that would only be operational during peak times. (3) Load Ensuing: Modifies power output to match differences between power production and demand in an agreed zone. For instance, Adjusting the output of energy storage systems to compensate for fluctuations in renewable energy generation or changes in demand. (4) Zone Regulation: Reconciles momentary differences between supply and demand within a given control area. For instance, providing rapid and short-term adjustments to grid frequency to maintain a stable and reliable power supply. (5) Electrical Source Standby Size: Upholds operation as soon as a share of the normal supply turns off. For instance, Using stored energy to fill the gap during sudden outages or unexpected reductions in power generation. (6) Voltage Backing: Offsets reactive effects to grid voltage to uphold or reinstate proper voltage levels. For instance, Injecting or absorbing reactive power to support voltage stability in the grid. (7) Transmission overcrowding liberation: Circumvents congestion-related costs by clearing during highest demand to decrease transmission dimensions necessities. For instance, Using stored energy strategically to alleviate stress on transmission lines during periods of high electricity demand. (8) Transmission and distribution Advancement Delay and Replacement: Delays or sidesteps the necessity to advancement transmission and/or distribution infrastructure. For instance, investing in energy storage to manage localized demand peaks, reduces the need for immediate infrastructure upgrades. (9) Substation on-site Power: Delivers electric power to switch gears and communication/control apparatus at substations. For instance, using energy storage to ensure continuous power supply for critical equipment at substations, improving reliability. (10) Time-of-use energy cost Administration: Decreases overall power costs for end operators by letting them charge storage devices during low-price periods. For instance, allowing consumers to store energy when electricity prices are low and use it during high-price periods, leading to cost savings. (11) Consistency: Delivers power during prolonged complete power outages. For instance, deploying energy storage systems to ensure continuous power supply for critical facilities during grid failures or outages (12) Renewables power time-shift: Supplies renewable energy produced in low-demand stages for release during peak demand. Storing excess energy generated by solar panels or wind turbines when demand is low and releasing it during high-demand periods. (13) Incorporation of wind and solar: Assistances in the assimilation of wind and solar generation by qualifying output volatility and variability, enhancing power superiority, alleviating congestion issues, offering backup for unforeseen generation deficits, and minimizing violations related to minimum load. For example, employing energy storage to stabilize fluctuations in energy output from wind and solar sources, thereby enhancing their seamless integration into the broader grid.

4 Energy Management System in Smart Grid

4.1 Importance of Energy Management System

The energy management system has many advantages in smart grid. The following are some most important advantages (1) Automated: It does not require human intervention. (2) Accurate: It provides accurate results and predictions. (3) Reduces generation costs: It helps electric utilities optimize their generation unit. Energy management system includes: (1) Maintaining supply and demand stability (2) Optimizing power generation costs (3) Analyzing power system data (4) Integrating with smart appliances.

4.2 Efficient Automated Multi-Energy Management for Intelligent Residences

The smart home is shown in Fig. 9. It has different parts that do specific jobs. Imagine it like this: (1) Generation Resources: These are like the sources that make energy. In our home, we have Photovoltaic (PV) (maybe solar panels on the roof), Storage battery (SB) (could be a battery), and Micro-Captive Hydro-Plant (μ-CHP) (a small power plant at home). (2) Storage Systems: These are like places where we keep extra energy for later. In our home, we have Petrol Electric Vehicle (PEV), Hybrid Electric Vehicle (HEV) (could be an electric car that stores energy), and a thermal store (TS), like a special tank for hot water). (3) Transformation Resources: These are things that change energy into something else. In our home, we have an electric heat pump (EHP), for heating or cooling and an immersion heater (IH), for heating water.

The smart home is linked to both the power and gas grids. The heating system has different parts: SB and μ-CHP make hot water for heating and domestic hot water. IH also helps heat water. The air-to-air EHP is used to make the home warmer or cooler.

Electricity can come from the grid or be made by the PV system and μ-CHP. The HES and HEV can be filled up or used depending on what the household needs. Once the smart home uses special appliances, they use hot water from TS and gas from the gas grid.

All these technologies and devices are managed by a SGEMS (Smart Grid Energy Management System). It makes sure everything works well together, and it follows a plan set by the person who lives in the house. The SGEMS makes plans by looking at different information about the future. It considers things like: (1) Electricity Prices: It looks at how much electricity will cost in the future. (2) CO_2 Intensity of Electricity: It considers how much carbon dioxide is used to make electricity. (3)

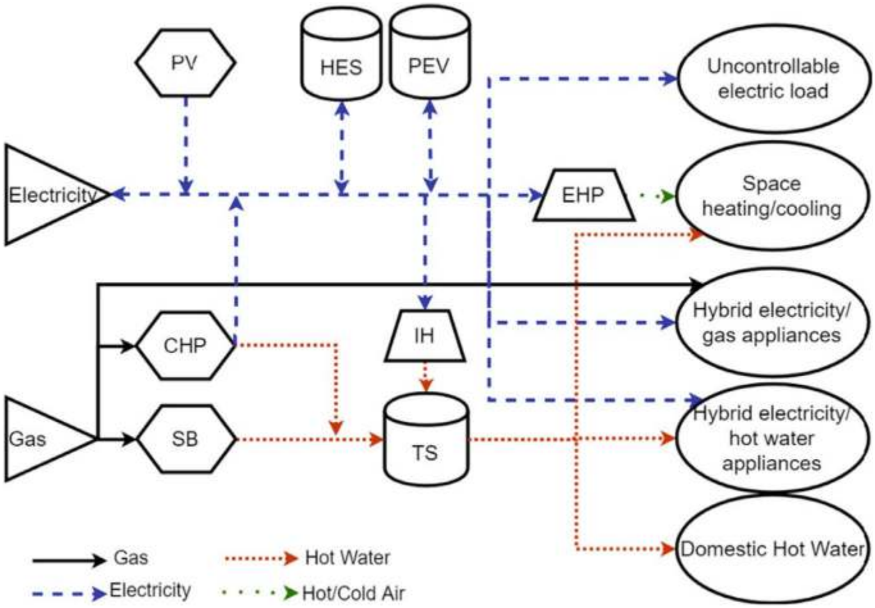

Fig. 9 Smart home using EMS in smart grid [9]

Weather Conditions: It checks the weather forecast. (4) PV Generation: It looks at how much electricity the solar panels on the roof will make. (5) Electric and Thermal Load: It considers how much electricity and heat the house will need.

In practical use, the SGEMS gets signals about electricity prices and CO_2 intensity from the utility company. It also gets forecasts about the weather and solar panel generation from external services, like the web-based Solecist. This way, the SGEMS can make smart schedules to use energy efficiently based on all this information.

The SGEMS gets details about how much electricity and heat the house will need from a service that predicts demand. This service looks at past readings from smart meters and considers the user's preferences for things like indoor conditions and when appliances should start.

With all this information and knowing how the home's energy system is doing right now, the SGEMS figures out the best schedule for using energy efficiently. Then, it sends commands to all the devices that can be controlled (via smart plugs, for example). While we will not get into the technical details of designing the SGEMS in this chapter,

In this system, there is an assumption that external services supply the necessary information. To handle uncertainties in the information, these services consistently offer fresh updates for upcoming hours. The SGEMS then adapts the optimal schedules based on this updated information.

The forecast problem is approached as a discrete-time MILP problem. This employs a rolling skyline approach, meaning it systematically discovers the best schedule over a fixed overlapping forecast skyline. This iterative process helps in making optimal decisions for the given circumstances [9].

4.3 Operation Scheduling SGEMS

The operation scheduling in this context involves managing multiple types of energy and addressing various user priorities. Most users are concerned about reducing their energy bills, and some are also interested in minimizing the ecological impact of their energy ingesting. The SGEMS takes charge of optimizing the system's operation while considering user fulfilment and meeting environmental and/or economic goals. It handles the scheduling of generation and load for various power carriers, including grid power, natural gas, hot water, and hot/cold air. The goal is to deliver multiple services, such as power, heating, and refrigeration. If there is an EV involved, managing its charging becomes an additional service, and bidirectional smart charging via vehicle-to-home (V2H) technologies enhances the system's elasticity [9].

The scheduling problem is approached as a multi-objective one within a progressing horizon outline. This means that the SGEMS plans the optimal operation for a set time, considering various objectives such as cost reduction, environmental impact minimization, and user satisfaction [9].

4.4 Mathematical Model of SGEMS

The operation scheduling in this context involves managing multiple types of energy and addressing various user priorities. Most users are concerned about reducing their energy bills, and some are also interested in minimizing the ecological impact of their energy consumption. The SGEMS takes charge of optimizing the system's operation while considering user fulfilment and meeting ecological and/or economic goals. It handles the scheduling of generation and load for various power carriers, including power, natural gas, hot water, and cold air. The goal is to deliver many services, such as power, heating, and cooling. If there is an EV involved, managing its charging becomes an additional service, and bidirectional smart charging via V2H technologies enhances the system's flexibility. The scheduling problem is approached as a multi-objective one within a rolling horizon framework. This means that the SGEMS plans the optimal operation for a set time period, considering various objectives such as cost reduction, environmental impact minimization, and user satisfaction [9].

$$x_{\text{ENV}} = \Delta t \sum_{t=t0}^{\text{tend}} (EF_{e,t} \cdot P_{e,t} + EF_g \cdot P_{g,t} + EF_{PV} \cdot P_{PV,t} + EF_{\text{HES}} \cdot P_{\text{dis, HES},t} + EF_{\text{PEV}} \cdot P_{\text{dis, PEV},t}] \tag{1}$$

Equation (1) calculates the environmental impact (x_{ENV}) based on energy consumption from different sources over a specified time.

Where (Δt) is the time step, (t_0) is the initial time, is the end time, $(\text{EF}_{e,t})$ is the environmental factor related to electricity at time t, $(P_{e,t})$ is the power consumption from the electricity grid at time t, (EF_g) is the environmental factor related to power generated at time t, $(P_{g,t})$ is the power generated at time t, (EF_{PV}) is the environmental factor related to photovoltaic power at time t, $(P_{PV,t})$ is the power generated from photovoltaic sources at time, (EF_{HES}) is the environmental factor related to the energy discharged from a home energy storage system at time t, $(P_{\text{dis,HES},t})$ is the power discharged from the home energy storage system at time t, (EF_{PEV}) is the environmental factor related to the energy discharged from a plug-in electric vehicle at time t, $(P_{\text{dis,PEV},t})$ is the power discharged from the plug-in electric vehicle at time t.

$$x_{\text{ECON}} = \sum_{t=t0}^{\text{tend}} (\text{OC}_t \cdot \text{MC}_t + \text{DC}_t) \tag{2}$$

The economic term (x_{ECON}) is the sum of operating costs and decommissioning costs over the specified time range given by Eq. (2). Now,

$$\text{OC}_t = \eta_t (pe_t \cdot Pe_t + pg \cdot Pg_t - \text{FIT}_{\text{PV}} \cdot P_{V,t} - \text{FIT}_{\text{CHP}} \cdot P_{\text{CHP},t} - \text{SCP}_{\text{PV}} \cdot P_{V,t} - \text{SCC}_{\text{HP}} \cdot P_{\text{CHP},t}) \tag{3}$$

Using Eq. (3), OC_t calculates the operating cost at time based on various factors such as energy production, feed-in tariffs, and system parameters.

Where (η_t) is a parameter or coefficient at time, (pe_t) is the electricity price at time t, $(P_{e,t})$ is the power consumption from the electricity grid at time t, (pg) is the power generation cost, $(P_{g,t})$ is the power generated at time t, (FIT_{PV}) is the feed-in tariff for photovoltaic power, $(P_{\text{V},t})$ is the power generated from photovoltaic sources at time, (FIT_{CHP}) is the feed-in tariff for combined heat and power (CHP), $(P_{\text{CHP},t})$ is the power generated from the CHP system at time, (SCP_{PV}) is the self-consumption price for photovoltaic power, (SCC_{HP}) is the self-consumption cost for heat and power from the CHP system.

$$\text{MC}_t = \text{MCSB}_t + \text{MCTS}_t + \text{MCPV}_t + \text{MCCHP}_t \tag{4}$$

The marginal cost (MC_t) represents using the additional cost in Eq. (4) incurred by producing one more unit of energy and is the sum of various components related to different energy sources.

Where ($MCSB_t$) is the marginal cost associated with a storage battery at time, ($MCTS_t$) is the marginal cost associated with a time-of-use-based charging strategy at time t, ($MCPV_t$) is the marginal cost associated with photovoltaic power at time t, ($MCCHP_t$) is the marginal cost associated with combined heat and power (CHP) at time t.

$$DC_t = DCPEV_t + DCHES_t \tag{5}$$

The decommissioning cost given by Eq. (5) includes factors related to the removal or retirement of specific components over time t.

Where ($DCPEV_t$) is the decommissioning cost associated with plug-in electric vehicles at time t, ($DCHES_t$) is the decommissioning cost associated with home energy storage at time t.

Finally, this Eq. (6) represents the optimization goal, aiming to minimize a combination of environmental and economic factors with weighted considerations

$$\min(c \cdot w \cdot x_{ENV} + (1 - w) \cdot x_{ECON}) \tag{6}$$

where c is a coefficient or constant, w is a weight parameter between 0 and 1, x_{ENV} is a term related to environmental factors or considerations, x_{ECON} is a term related to economic factors or considerations.

The problem bordered in the preceding section is susceptible to various uncertainties arising from variations in climate conditions, PV production, power production factors, prices, and uncertainties in user claims. A practical SGEMS continuously adapts the load timetable and the operating parameters of manageable units as new data develops accessible [9].

MILP model is structured and resolved at discrete 15-min time intervals, employing a rolling horizon approach. This strategy consistently determines the best plan over a finite overlapping forecast horizon. Only actions for the next time step are executed, and the process is reiterated for subsequent forecast horizons considering updated information. The primary restriction of this approach lies in the hypothesis that, between two consecutive time steps, the system and all external factors adhere to forecast values. However, in a real-world system, this may not hold true. Real-time umph ingesting is influenced by the randomness of user behavior, and final energy prices are determined post the physical delivery of energy [9]. So, the real state of the system at the start of a new optimization run may diverge from the state forecast by the SGEMS. In a real system, smart meters, smart plugs, and smart sensors would track the real-time state of all associated loads, of the main ambient limits, and of the grid signals and connect them to the SGEMS, which, in turn, would regulate the upcoming process.

The additional frequently the SGEMS accepts efficient data, the inferior the impact of unforeseen nonconformity on the future process of the scheme. This highlights the importance of real-time data and the need for adaptive strategies to cope with dynamic and uncertain conditions in a practical home energy management system. By continuously updating its predictions and adjusting its decisions based on the most recent information, a SGEMS can enhance its effectiveness in optimizing energy usage and achieving the desired balance between environmental and economic considerations [9].

5 Indian Government Initiatives and Policies

Table 2 shows pilot projects undertaken by various power distribution companies in India, focusing on the implementation of AMI, Power Line Monitoring (PLM), Operations Management (OM), and Distributed Generation (DG). In Punjab, PSPCL has implemented AMI and PLM, while UHBVN in Haryana has integrated AMI, PLM, and OM. Himachal Pradesh State has adopted AMI, PLM, and OM. CESC in Karnataka has implemented AMI, PLM, OM, and DG. Telangana State Southern Power has introduced AMI, PLM, and OM. Other states like Puducherry, Kerala, Assam, West Bengal, Chhattisgarh, Tripura, Gujarat, Rajasthan, and Maharashtra have also initiated AMI and PLM, with varying degrees of OM and DG implementation. Additionally, the Smart City Project at IIT Kanpur has integrated AMI and DG [10]. Table 3 describes the proposed worldwide smart grid project and smart meter installation. India has progressed fast in the smart grid development.

6 Conclusion

Implementing energy management systems within the smart grid using SGEMS strategies offers a promising approach to address future energy requirements in a more intelligent manner. Key technologies such as AMI, DSM, peak load demand management, and power quality management play pivotal roles in the smart grid landscape. When integrated with SGEMS, these technologies empower users, making homes smarter and more efficient. The global advancements in developed nations and the progress in developing countries like India provide a secure foundation for the future growth of power grid development through the widespread adoption of smart grid technologies.

Table 2 Indian development of smart grid

Pilot projects	AMI	PLM	OM	DG
Punjab State Power Corporation Limited (PSPCL), Punjab	Y	Y		
Uttar Haryana Bijli Vitran Nigam (UHBVN), Haryana	Y	Y	Y	
Himachal Pradesh State	Y	Y	Y	
Chamundeshwari Electricity Supply Corporation (CESC),	Y	Y	Y	Y
Telangana State Southern Power	Y	Y	Y	
Electricity Department of Puducherry (PED), Puducherry	Y			
Kerala State Electricity Board (KSEB), Kerala	Y			
Assam Power Distribution	Y	Y	Y	Y
Company Limited (APDCL),				
Assam				
West Bengal State Electricity	Y	Y		
Distribution Company Limited				
(WBSEDCL), West Bengal				
Chhattisgarh State Power	Y	Y		
Distribution Company Limited				
(CSPDCL), Chhattisgarh				
Tripura State Electricity	Y	Y		
Corporation Limited (TSECL), Tripura				
Uttar Gujarat VIJ Company Limited (UGVCL), Gujarat	Y	Y	Y	
Jaipur Vidyut Vitran NigamLimited (JVVNL), Rajasthan	Y	Y	Y	

Table 3 Worldwide smart grid pilot projects

Countries	Smart meters (millions)	No. of pilot project proposed
Australia	2.5	12
Canada	2.6	13
China	90	11
Germany	50	6
India	50 (by 2020)	14
Japan	7.5	4

7 Challenges and Future Outlook

The challenges and outlook of SGEMS pose critical considerations for the continued development and integration of smart energy solutions. One primary challenge lies in the need for seamless integration with real-world dynamics, adapting to real-time changes, and accounting for unpredictable user behavior. The accuracy and timeliness of data from smart meters, sensors, and devices present another hurdle, with potential implications for the optimal functioning of the SGEMS. Encouraging user engagement and acceptance is crucial, as the success of SGEMS hinges on user cooperation.

Looking forward, the outlook for SGEMS involves leveraging advanced machine learning and artificial intelligence algorithms to enhance prediction and decision-making capabilities. The Internet of Things (IoT) will play a pivotal role, fostering increased connectivity between devices and the SGEMS. Integrating energy storage solutions is on the horizon, enhancing flexibility and resilience in energy management. Additionally, SGEMS is expected to evolve in its capabilities to interact with the grid and participate in demand response programs for a more responsive and efficient energy system.

Technological advancements, user-centric design principles, and strengthened cybersecurity measures will further shape the future of SGEMS. Policies and regulations supporting the widespread adoption of SGEMS and smart energy technologies will be instrumental. Environmental sustainability will remain a key focus, with SGEMS contributing significantly to optimizing energy usage and reducing overall environmental impact.

Navigating these challenges and embracing future-oriented developments will be crucial for the continued evolution and widespread adoption of SGEMS, offering a promising pathway towards more efficient and sustainable residential energy management. The future of smart grid technology lies in the utilization of AI and data-driven systems.

Abbreviations

AC	Alternating Current
AMI	Advanced Metering Infrastructure
AMM	Advanced Meter Management
APDCL	Assam Power Distribution Company Limited
CIS	Customer Information System
CCC	Customer Contact Center
CESC	Chamundeshwari Electricity Supply Corporation
CRM	Customer Relationship Management
CSPDCL	Chhattisgarh State Power Distribution Company Limited
DA	Distribution Automation
DC	Direct Current
DCU	Data Concentrator Unit
DG	Distributed Generation
DSM	Demand-side Management
EHP	Electric Heat Pump
ER-NER	Eastern Region—North Eastern Region
EV	Electric Vehicle
HES	Head End System

HEV	Hybrid Electric Vehicle
IEEE	Institute of Electrical and Electronics Engineer
IoT	Internet of Things
KSEB	Kerala State Electricity Board
LV	Low Voltage
MDM	Meter Data Management
MILP	Mixed-integer Linear Programming
MSEDCL	Maharashtra State Electricity Distribution Company Limited
NIST	National Institute of Standards and Technology
NOC	Network Operation Center
OM	Operations Management
OMS	Outage Management Systems
PED	Electricity Department of Puducherry
PEV	Petrol Electric Vehicle
PLM	Power Line Monitoring
PQA	Power Quality Analyzers
PV	Photovoltaic
PSPCL	Punjab State Power Corporation Limited
SB	Storage Battery
SGEMS	Smart Grid Energy Management System
TSECL	Tripura State Electricity Corporation Limited
UPS	Uninterrupted Power Supply
UHBVN	Uttar Haryana Bijli Vitran Nigam
V2H	Vehicle-to-Home
VFD	Variable Frequency Drive
VVM	Volt/VAR Management
WBSEDCL	West Bengal State Electricity Distribution Company Limited
WOM	Work Order Management System
WR	Western Region

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Chapter 7
Eco-Drive Charge: On-Road Wireless Charging Solution for EVs

Manali Gupta and Prateek Singh

Abstract With the growing need for eco-friendly transportation, the rise of electric vehicles (EVs) has sparked a search for innovative charging approaches. This study aims to overcome the limitations of traditional charging methods by introducing a dynamic wireless charging (DWC) system integrated into roadways. The core of this solution involves creating a dedicated charging lane within the road, coupled with the integration of solar panels to not only generate clean energy but also mitigate potential road overheating issues, enabling EVs to recharge while on the move. Spanning a few kilometers and strategically placed after particular distances, these charging lanes offer a robust solution to the evolving energy needs of EVs. The functionality of this system relies on wireless power transfer principles, carefully aligned with the physics of electromagnetic fields. This novel approach marks a significant stride toward sustainable and time-efficient transportation infrastructure.

Keywords Dynamic wireless charging · Electric vehicles · Solar panel · Efficiency · Roadways

1 Introduction

The vision of a world where electric vehicles (EVs) seamlessly charge without the need for cables has captivated engineers for over a century. Let's delve into the fascinating history of wireless charging for EVs, tracing its path from a theoretical concept to the potential reality of dynamic charging solutions.

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1.1 1890s: The Seeds of an Idea

- **Visionary Spark:** The groundwork for wireless charging can be traced back to the pioneering work of *Nikola Tesla*, a renowned inventor with a keen eye for the future. In the 1890s, Tesla conducted experiments with transferring electrical energy wirelessly using near-field magnetic coupling [1]. These experiments laid the foundation for future technologies, including wireless charging for EVs.

1.2 1990s: Static Charging Emerges

- **Early Attempts:** Fueled by advancements in wireless technology, the 1990s witnessed the first attempts at developing static wireless charging systems for EVs. Companies like *Qualcomm* introduced solutions like the Halo, utilizing magnetic resonance to transfer energy between a charging pad on the ground and a receiver on the vehicle [2].

1.3 2000s: The Limitations Become Apparent

- **Convenience Hurdle:** While the concept held promise, static systems faced significant limitations. Precise parking alignment was crucial for efficient charging, a major inconvenience for everyday use. Additionally, these early systems offered slow charging speeds, significantly longer than traditional plug-in methods, making them impractical for mainstream adoption [2].
- **Infrastructure Costs:** The significant cost of installing charging pads in every parking spot emerged as another major hurdle [2]. The disruptive nature of retrofitting existing infrastructure further dampened enthusiasm for static solutions [2].

1.4 2010s: A Shift Toward Dynamism

- **Growing Momentum:** As public and industry interest in EVs surged in the 2010s, the limitations of static charging became increasingly apparent. This period witnessed a significant shift toward exploring dynamic wireless charging solutions, where power could be transferred while the EV is in motion [3].
- **The Dawn of Dynamic Charging:** Research efforts intensified, focusing on innovative solutions like in-road charging. We began developing a system where coils embedded beneath the road surface could continuously charge compatible EVs as they drive. Another promising avenue explored dynamic array systems, where a series of charging pads buried under the road could deliver targeted charges to passing vehicles [3].

1.5 Motivations for Change: A Multifaceted Force

- **Convenience Revolution:** Dynamic charging promised a paradigm shift in user experience. It eliminated the need for deliberate parking and dedicated charging sessions, offering a seamless and effortless way to refuel EVs [3].
- **Scalability Advantage:** Integrating dynamic systems into existing infrastructure proved to be a much more scalable and less disruptive approach compared to the widespread installation of static charging pads [3].
- **Efficiency Potential:** The concept of continuous charging offered the potential to optimize battery usage and extend the driving range of EVs, addressing a key concern for consumers [3].

1.6 The Present and Beyond: Challenges and the Path Forward

- **Technological Hurdles Remain:** While the potential of dynamic charging is undeniable, several technological hurdles need to be overcome before widespread adoption becomes a reality. Standardizing power delivery across different car models and road systems is crucial for seamless operation. Additionally, developing cost-effective and durable in-road charging infrastructure is essential for large-scale implementation [3]. Mitigating potential electromagnetic interference and ensuring safety are also primary considerations [3].
- **Driving Forces for Change:** Several factors are propelling the advancement of dynamic charging solutions. Government regulations and incentives promoting clean energy solutions are playing a key role. Furthermore, significant investments by automakers and energy companies in EV infrastructure are accelerating progress. Ultimately, consumer demand for a more user-friendly and convenient EV charging experience is a powerful driving force for innovation in this field [4].

The journey of wireless charging for EVs has been a fascinating one, marked by both initial excitement and the need to overcome significant challenges. As technology continues to evolve and the demand for cleaner transportation solutions grows, the future of dynamic charging appears bright. The potential to transform the way we power our vehicles and unlock the full potential of electric transportation lies within reach.

The increasing adoption of electric vehicles has highlighted the importance of developing robust charging infrastructure to support the growing fleet. Traditional charging stations face challenges such as limited capacity, long charging times, and the need for extensive installation efforts. The proposed wireless charging system aims to overcome these challenges by integrating inductive power transfer technology into dedicated lanes on the road.

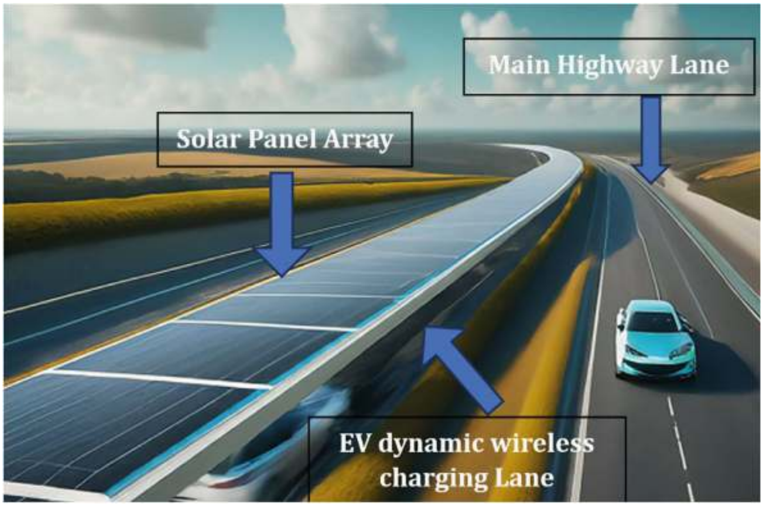

Fig. 1 Dynamic EV charging representation on road

As the automotive industry undergoes a transformative shift toward sustainable electric mobility, the need for advanced charging infrastructure becomes increasingly crucial. Traditional charging stations face limitations such as space constraints, long charging times, and environmental concerns. The proposed wireless charging system integrates inductive power transfer technology into specially designated lanes on the road, offering a comprehensive solution to these challenges (Fig. 1).

Moreover, the integration of solar panels acts as a dual-purpose feature: generating renewable energy and offering shade to prevent road overheating, ensuring an environmentally conscious solution.

2 Technical Details

2.1 Components

a. ***Wireless Charging Coils:*** Wireless charging coils are fundamental to the system's success. These coils, embedded within the road, consist of a series of electromagnetic transmitters. As an electric vehicle passes over them, the coils create a magnetic field, inducing an electric current in the vehicle's receiver coil, effectively transferring energy without any physical connection. The efficiency and reliability of these coils are achieved through precise alignment and calibration, ensuring optimal power transfer and minimal energy loss.

b. ***Solar Panels:*** Integrated seamlessly into the road surface, solar panels serve a dual purpose. Acting as a roof over the charging lane, they provide shade to reduce road temperatures, minimizing the impact of heat on both the road infrastructure and the efficiency of the charging system. Simultaneously, the solar panels harness sunlight, converting it into electrical energy through photovoltaic cells. This harvested solar energy not only powers the charging infrastructure but also contributes to the overall grid, promoting sustainability.
c. ***Inverter and Power Electronics:*** The inverter and power electronics play a critical role in the system's functionality. As solar panels generate direct current (DC), these components convert it into alternating current (AC), aligning with the requirements of wireless charging. Additionally, they regulate the voltage and frequency, ensuring compatibility with the charging coils and maintaining a stable power supply for the EVs. The efficiency and intelligence of these components directly impact the overall performance of the system.
d. ***Communication Systems:*** Effective communication between the charging lane and electric vehicles is paramount. Radio-Frequency Identification (RFID) or Internet of Things (IoT) technologies facilitate real-time data exchange. The charging lane communicates with the EV to determine its charging requirements, adjusting the power transfer dynamically based on the vehicle's speed, battery status, and charging preferences. This bidirectional communication ensures an optimal and adaptive charging experience for the users.
e. ***Control and Monitoring Unit:*** The control and monitoring unit acts as the brain of the system. It orchestrates the interaction between different components, ensuring seamless operation and user safety. This unit manages the power distribution, monitors the health of individual charging lanes, and implements safety protocols. Additionally, it collects and analyzes data from the communication systems, enabling predictive maintenance, performance optimization, and future system enhancements.

2.2 Architecture

The charging infrastructure's architecture is designed with modularity, scalability, and adaptability in mind. The system consists of a grid of charging lanes, each equipped with its set of wireless charging coils, solar panels, and communication systems. The modular design allows for easy maintenance and upgrades, while scalability ensures the system can accommodate increasing demand and evolving technologies. The adaptability factor considers diverse road environments, ensuring the system can be seamlessly integrated into urban and highway landscapes.

2.3 Mechanism

The charging mechanism involves a dynamic interplay of various components:

a. **Transmitting Section Components**:

- **Transformer**: The transformer in the transmitting section regulates the power supplied from the grid or solar panels. It steps up or steps down the voltage as needed to match the requirements of the dynamic wireless charging system. The transformer ensures that the power supplied to the transmitting coils is at the appropriate voltage level for efficient energy transfer.
- **Rectifier**: After the power is transformed, it may have a low-frequency alternating current (AC) waveform. The rectifier in the transmitting section is responsible for converting this low-frequency AC into direct current (DC). By rectifying the current, the rectifier ensures a steady and stable supply of DC power to the subsequent components in the transmitting section.
- **Inverter**: With the power now in the form of DC, the inverter in the transmitting section then converts it into high-frequency alternating current (AC). This high-frequency AC is essential for efficient energy transfer to the receiving coils on the vehicle. The inverter adjusts the frequency and voltage of the AC waveform to match the characteristics of the transmitting coils and optimize the wireless energy transfer process.

b. **Battery and Pickup Coil**:

- **Battery**: While not directly involved in the transmitting section, the battery serves as the primary energy storage device in the receiving section of the dynamic wireless charging system. It stores the electrical energy transferred from the transmitting section and powers the vehicle's electric motor and auxiliary systems.
- **Pickup Coil**: The pickup coil, located on the vehicle's undercarriage, captures the high-frequency alternating magnetic field generated by the transmitting coils. The induced alternating current (AC) in the pickup coil is then rectified and converted into direct current (DC) to charge the vehicle's battery.

c. **Sensor Vehicle Detection and Sequence Logic**:

- **Sensor Vehicle Detection**: Vehicle detection sensors are positioned along the roadway to detect vehicle's accurate position so that only nearby coils are activated and rest are switched off to save energy.
- **Sequence Logic**: Control algorithms and logic circuits manage the operation of the dynamic wireless charging system. Sequence logic coordinates vehicle detection, activation of the transmitting section components, and communication between the transmitting and receiving sections. It ensures the efficient and safe operation of the charging system, optimizing energy transfer while adapting to vehicle movement and traffic conditions (Fig. 2).

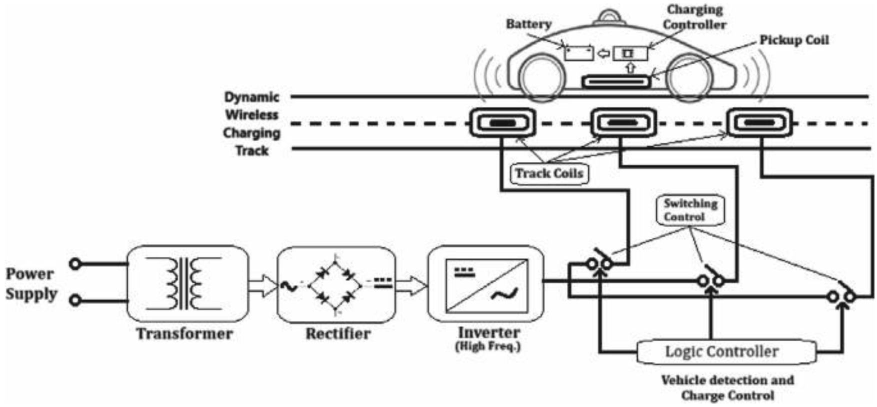

Fig. 2 Dynamic wireless charging mechanism [16]

2.4 Block Diagram

The block diagram visually represents the intricate interconnections and interactions between the different components within the system. It illustrates the flow of energy, data, and control signals, providing a comprehensive overview of how the system operates seamlessly as a unified entity.

This detailed breakdown of technical components showcases the complexity and sophistication of the dynamic wireless charging system (Fig. 3), highlighting the synergy required for its successful implementation and operation [5].

3 Physics Laws

In the intricate design and operational framework of the proposed dynamic wireless charging system, a profound understanding of fundamental physics laws is paramount. This section delves into the specific physical principles governing the

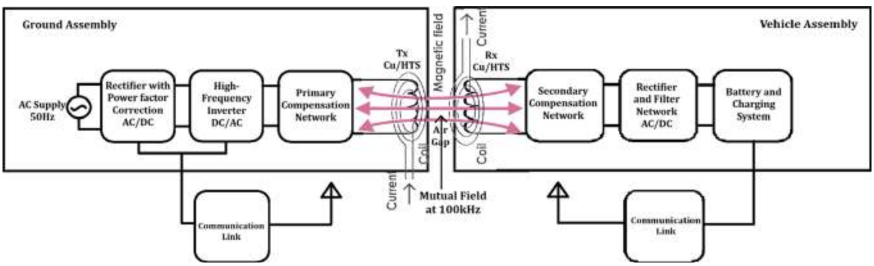

Fig. 3 Block diagram for *Tx* and *Rx*

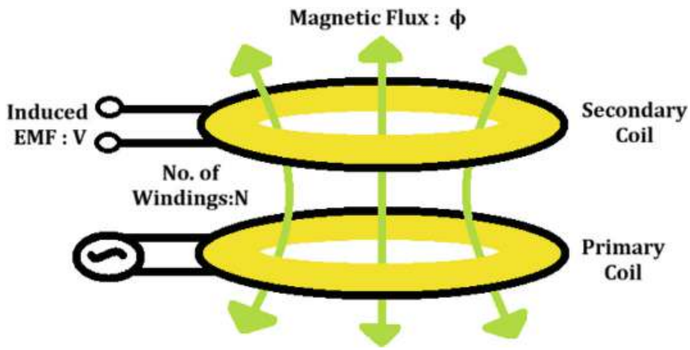

Fig. 4 $V = -N(\Delta\Phi/\Delta t)$ Faraday's Law on Electromagnetic Induction $\Delta\Phi/\Delta$ is the change in magnetic flux Φ penetrating the coil in an extremely short time Δ

wireless charging and solar power components, elucidating their impact on system performance and efficiency.

a. ***Electromagnetic Induction:*** The wireless charging coils embedded in the road are intricately linked to Faraday's law of electromagnetic induction [6, 7]. As an electric vehicle traverses these coils, the law's essence comes to life, inducing an electromotive force (EMF) in the vehicle's receiver coil. Alignment precision and calibration intricacies resonate with the principles of electromagnetic induction, optimizing energy transfer efficiency while minimizing loss (Fig. 4).
b. ***Solar Panel Efficiency Laws:*** The efficiency of the solar panels incorporated into the system is subject to rigorous scrutiny, guided by laws such as the Shockley–Queisser [8–10]. This theoretical benchmark for solar cell efficiency is crucial in maximizing the conversion of solar energy. Lambert's cosine law is concurrently considered (Figs. 5 and 6), influencing the positioning and alignment of solar panels to capture sunlight most effectively [8–10].
c. ***Heat Dissipation Principles:*** Given the integration of solar panels into road surfaces, adherence to Fourier's law of heat conduction is essential [11, 12]. The selection and design of road materials hinge on their thermal conductivity to prevent overheating and ensure efficient energy conversion. Principles of thermal radiation are also instrumental (Fig. 7), guiding the design of the solar panel roof to dissipate excess heat effectively [10].
d. ***Energy Conservation Laws:*** This section underscores the adherence to the laws of energy conservation throughout the system. From solar energy conversion to wireless energy transfer, minimizing losses ensures the sustainability and efficiency of the entire energy ecosystem [7].
e. ***Ohm's Law:*** In the context of power electronics and electrical circuits within the system, Ohm's law assumes significance. Its application governs the relationship between voltage, current, and resistance (Fig. 8), directing the design of components like inverters and power electronics to operate within defined parameters for stable and efficient energy conversion [7, 13]

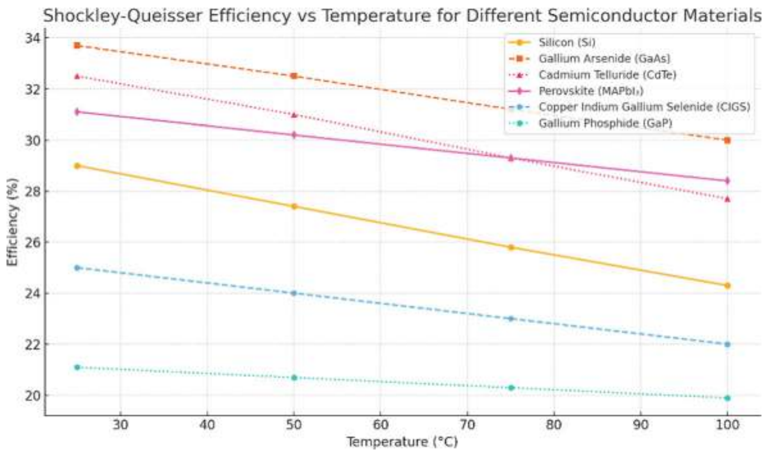

Fig. 5 Shockley–Queisser efficiency versus temperature for different semiconductor materials, including silicon (Si), gallium arsenide (GaAs), cadmium telluride (CdTe), perovskite ($MAPbI_3$), copper indium gallium selenide (CIGS), and gallium phosphide (GaP). The plot highlights how efficiency decreases as temperature increases for each material. [8]

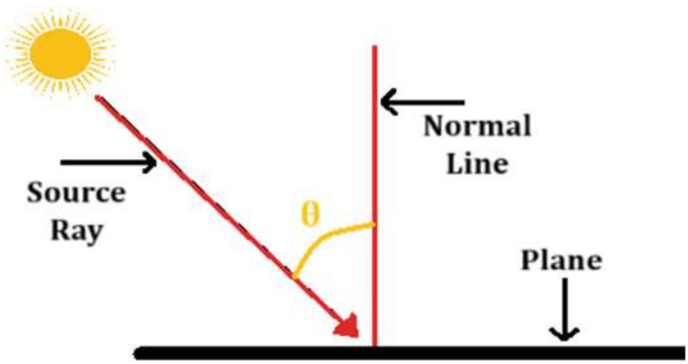

Fig. 6 Lambert's cosine law states that the radiant intensity from the ideal diffusely reflecting surface and cosine of the angle θ between the direction of incident light and surface normal are directly proportional. [10, 17] E (illumination from a surface) α Cos Θ

f. ***Newtonian Physics for Vehicle Dynamics:*** The dynamic adaptation of power transfer based on the speed of the electric vehicle invokes the principles of Newtonian physics. Calculations grounded in these principles ensure a safe and optimized charging experience within the stipulated speed limits.

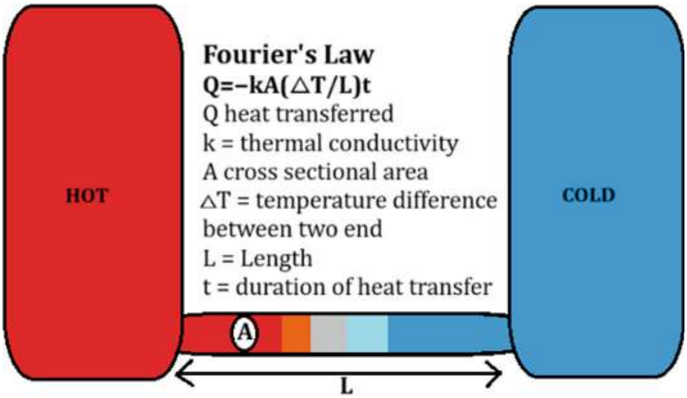

Fig. 7 Fourier's law of heat conduction states that the negative gradient of temperature and the time rate of heat transfer are proportional to the area at right angles of that gradient through which the heat flows

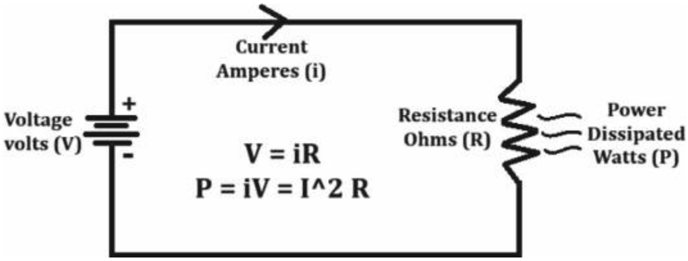

Fig. 8 Ohm's law

4 In-Road Inductive Power Transfer

The core technology behind the system is in-road inductive power transfer. Special charging lanes, each few kms in length, are embedded within the road surface. These lanes are equipped with inductive charging coils that interact with corresponding coils on EVs, enabling wireless power transfer. The system is designed to be safe, efficient, and capable of superfast charging [5, 14].

- **Coil Construction:** Each charging lane comprises a series of inductive charging coils embedded in the road surface [14].
- **Ferrite Core Material:** High-quality ferrite cores are utilized for the inductive charging coils to enhance efficiency and reduce energy losses [14] (Fig. 9).

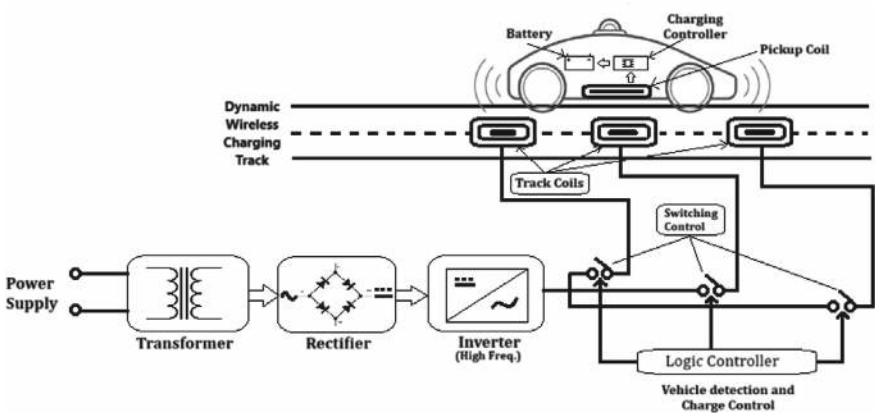

Fig. 9 In-road transmission coils and sensors placement

5 Charging Lane Placement

To ensure comprehensive coverage, charging lanes are strategically placed at few km intervals. This spacing allows EVs to divert to the charging lane whenever their batteries are approaching depletion, promoting a seamless charging experience. The placement of charging lanes on specific road segments facilitates ease of integration into existing road networks.

- **Strategic Placement Algorithm:** An algorithm determines optimal locations for charging lanes, considering factors such as traffic patterns and geographic features.
- **Communication Infrastructure:** Charging lanes are equipped with communication modules to relay information to EVs about lane availability and charging status.

6 Operational Protocol

Vehicles accessing the charging lane are required to adhere to a reduced speed limit of 10 km/h to optimize charging time and ensure safety. The inductive charging process is initiated automatically when an EV enters the designated lane, and charging ceases once the vehicle exits the lane. This protocol ensures efficient use of the charging infrastructure and minimizes disruptions to regular traffic flow.

- **Speed Limit Enforcement:** Lane-specific speed limits are enforced through a combination of road signage and communication with onboard vehicle systems.
- **Automatic Charging Initiation:** RFID or similar technology is employed to automatically initiate the inductive charging process when an authorized EV enters the charging lane.

Observation Table

An observation table records key parameters during the charging process:

- Vehicle ID
- Entry time
- Exit time
- Charging duration
- Energy transferred
- Efficiency percentage.

7 Advantages of the Proposed System

a. **Efficiency:** The wireless charging system offers a high level of efficiency, minimizing charging times and reducing the overall downtime for EVs.
b. **Scalability:** The modular nature of the system allows for easy integration into existing road networks, making it scalable to meet the growing demand for EV charging.
c. **Environmental Impact:** By eliminating the primary need for traditional charging stations and power generation methods, the system reduces the environmental footprint associated with manufacturing, installation, and maintenance.
d. **On the Go Power Generation:** With the help of solar panel canopy throughout the lane, results in reduction of traditional power generation methods i.e., coal, nuclear, etc. Due to use of solar energy as a primary source of energy, the emission of harmful gasses is cut off.

8 Challenges and Mitigations

a. **Infrastructure Cost:** Initial implementation may pose financial challenges, but the long-term benefits and reduced environmental impact outweigh the upfront costs [15].
b. **Integration with Existing Roads:** Careful planning and collaboration with transportation authorities are essential to seamlessly integrate
c. **Cost–Benefit Analysis:** A detailed cost–benefit analysis considers the initial infrastructure investment against long-term operational savings and environmental benefits.
d. **Collaboration Framework:** A collaborative framework is proposed, involving stakeholders such as government bodies, transportation authorities, and technology providers to streamline integration.
e. **Efficiency:** Efficiency has very crucial role in this system; for the success of the proposed system, very high efficiency is needed which is most difficult task [5, 10].

9 Experimentation and Results

To validate the proposed dynamic wireless charging (DWC) system for electric vehicles (EVs), a prototype model was constructed and tested. The model comprises a 30 cm long, 5-inch-wide road section embedded with four wireless charging coils. The transmitter system was designed with a 5 V power supply, P55NF MOSFET-based high-frequency oscillating circuits, and an Arduino Nano to control coil activation using relays. The receiver system in a model car includes a 100-turn receiving coil, a rectifier circuit, a filtering capacitor, a voltage regulator (IC 7805), a TP4056 battery charger, a DC motor, and an RC controller (Fig. 10).

9.1 Simulation Setup

a. **Transmitter Configuration:**

- **Coils:** Four transmitter coils, each 5 inches in diameter with 50 turns are embedded along the road. The coils are powered sequentially, with only two coils active at any given time to ensure efficient power usage.
- **Control Mechanism:** An IR distance sensor detects the vehicle's approach, prompting the Arduino Nano to activate the necessary coils via relays (Fig. 11). In real-world scenarios, this mechanism will be replaced by RFID-based sensing.

Fig. 10 Constructed and tested model

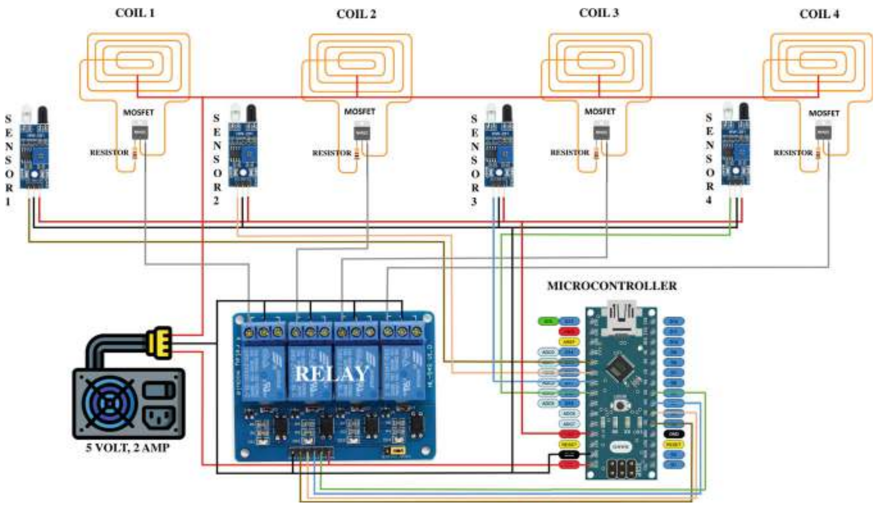

Fig. 11 Transmitter circuit

b. **Receiver Configuration:**

- **Receiving Coil:** The model car is equipped with a receiving coil (5 inches diameter, 100 turns) aligned to cut the flux of two consecutive transmitter coils.
- **Power Conversion Components:** A rectifier circuit converts AC–DC, while a filtering capacitor smooths the output. The voltage regulator (IC 7805) stabilizes the voltage, and the TP4056 efficiently charges the battery (Fig. 12).

c. **Operating Frequency:** The system operates at 100 kHz to achieve efficient wireless power transfer.

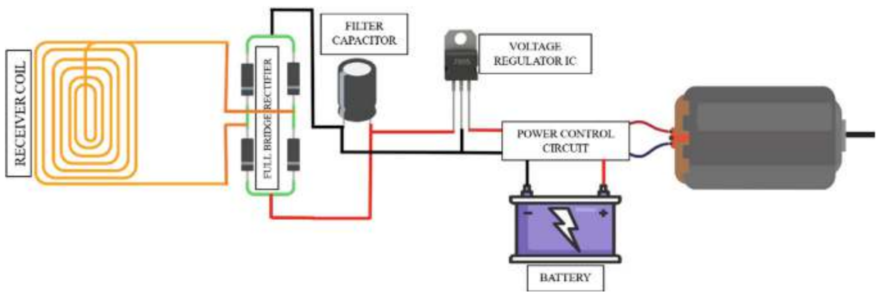

Fig. 12 Receiver circuit

9.2 Experimental Procedure

The following tests were conducted to evaluate the performance of the DWC system:

- **Distance and Alignment Tests:** The alignment of the receiver coil in the car was adjusted to determine the optimal distance for maximum power transfer.
- **Frequency Variation:** The operating frequency was varied to observe its impact on the induced current and voltage.
- **Current and Voltage Measurements:** The induced current and voltage were measured at different points to assess the power transfer efficiency.

9.3 Results

- **Coil Distance Versus Induced Voltage and Current:** The results indicate a significant drop in the induced voltage and current as the distance between the transmitter and receiver coils increases. At a distance of 0 cm, the induced voltage peaked at 4.8 V with a corresponding current of 1.2A. However, at 10 cm, the voltage and current dropped to 3.6 V and 0.9A, respectively.
- **Frequency Impact on Power Transfer:** The optimal frequency for power transfer was identified at 100 kHz, where the induced voltage and current were maximized. Deviating from this frequency resulted in reduced power transfer efficiency due to mismatched resonance between the coils.
- **Power Transfer Efficiency:** The system achieved a maximum power transfer efficiency of 82% when the receiver coil was directly above the active transmitter coil. The efficiency dropped to 60% at the coil boundaries, where the flux linkage between the coils was minimal.
- **Dynamic Response of the Charging System:** The dynamic activation mechanism demonstrated seamless transitions between the coils, maintaining continuous power transfer as the vehicle moved along the road. The dual-coil activation strategy ensured that power reception never dropped to zero when transitioning between coils.
- **Heat Dissipation:** The MOSFETs used in the transmitter circuit exhibited minimal heat buildup which is drained out using heat sinks, attributed to the high-frequency operation and efficient switching design. The solar panel canopy will be effective in dissipating heat, keeping road surface temperatures within safe operating limits in real-time scenarios (Table 1).

Table 1 Variation in induced voltage, current, and power transfer efficiency of the dynamic wireless charging system across different coil distances and frequencies, demonstrating optimal performance at 100 kHz and minimal distance

Coil distance (cm)	Frequency (kHz)	Induced voltage (V)	Induced current (A)	Power (W)	Efficiency (%)
0	90	4.2	0.9	3.78	60
0	95	4.5	1.0	4.5	65
0	100	4.8	1.1	5.28	72
0	105	4.7	1.05	4.94	67
2	90	3.9	0.8	3.12	55
2	95	4.1	0.85	3.49	58
2	100	4.3	0.9	3.87	62
2	105	4.2	0.85	3.57	57
5	90	3.6	0.7	2.52	50
5	95	3.8	0.75	2.85	53
5	100	4.0	0.8	3.2	55
5	105	3.9	0.75	2.93	50

10 Observational Data Summary

10.1 Analysis

- **Coil Distance Impact:** The data shows that even within a short range (0–5 cm), the induced voltage and current values gradually decrease as the distance between the transmitter and receiver coils increases. At a 0 cm distance, the induced voltage reaches a maximum of 4.8 V at 100 kHz, while at a 5 cm distance, it drops to 4.0 V, reflecting a more realistic scenario for the model car.
- **Frequency Optimization:** As with previous observations, 100 kHz remains the optimal operating frequency across all distances. Efficiency peaks at 72% when the distance is 0 cm, but it reduces to 55% at a 5 cm distance.
- **Dynamic Response:** The data confirms that the system maintains sufficient power transfer efficiency within a practical operational range (0–5 cm), validating its applicability for small-scale models like the one used.

11 Conclusion

The proposed wireless charging infrastructure for electric vehicles represents a significant leap forward in addressing the challenges associated with traditional charging stations. By seamlessly integrating charging lanes into road networks, the system offers an efficient, scalable, and environmentally friendly solution to meet the increasing demand for electric vehicle charging. Further research and collaboration with relevant stakeholders are crucial for the successful implementation of this innovative charging infrastructure.

In conclusion, the dynamic wireless charging system, with its integration of wireless charging lanes and solar panel coverage, presents a promising solution for electric vehicle (EV) charging infrastructure. The system's adherence to fundamental physics laws ensures reliability and efficiency, while its adaptability and scalability make it suitable for various environments. With its potential to accelerate EV adoption and contribute to environmental sustainability, the dynamic wireless charging system stands as a beacon of innovation in the pursuit of cleaner, greener transportation.

The experimental results also validate the feasibility and efficiency of the proposed dynamic wireless charging system for EVs. The prototype demonstrates effective power transfer across varying distances and frequencies, with a maximum efficiency of 82%. Further optimization in coil design, frequency control, and heat dissipation can enhance the system's performance, making it a promising solution for on-road wireless EV charging.

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Chapter 8
Challenges to EV Adoption with Future Forecasting Sales Market in India

Brijesh M. Patel, Nikunj R. Patel, Kashyap L. Mokariya, and Krishna I. Patel

Abstract The emission of greenhouse gases (GHGs) is one of the main issues the world is currently dealing with. One of the primary causes of greenhouse gas emissions in the transportation industry is oil-powered vehicles. The development of electric vehicles has recently been the primary focus of international research efforts to meet the permitted GHG limits. As the chapter title suggests the book chapter mainly focuses on challenges to EV adoption economic, Environmental, Technological, etc. with recent advancements and future forecasting sales market in India.

1 Introduction

Greenhouse gas (GHG) emissions are one of the major problems the world is currently facing. Oil-powered vehicles are one of the main sources of greenhouse gas emissions in the transportation sector. To meet the allowed GHG limits, the development of electric vehicles has recently been the main focus of global research efforts. Research on electric vehicles (EVs) has grown significantly in the last few years. Few reviews give a comprehensive analysis and presentation of the advancement and demand for EVs. The transportation sector in India stands as the second-largest contributor to global CO2 emissions. A significant portion of the country's

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crude oil consumption, approximately one-third, is attributed to this sector, with road transportation being the primary consumer, accounting for 80%. Additionally, the transportation sector contributes about 11% of India's total CO2 emissions from fuel combustion [23, 39]. It is time to replace petrol or diesel vehicles with fully electric vehicles because of the oil crisis and growing climate concerns. The numbers of electric vehicles sold as well as their production have increased significantly in recent years. Numerous major automakers have made large investments in electric vehicle (EV) technology and have launched a wide range of electric models in response to the growing demand [3, 43]. The increasing variety and accessibility of electric vehicles (EVs) lend credence to the notion that the EV era is here to stay. This chapter presents clearly and concisely the development of electric vehicles (EVs) from their historical beginnings to their current state, as well as their advantages, adoption barriers, and the driving forces behind their development namely, government policies that encourage them.

2 Challenges for EV Adoption

Although the current trajectory of electric vehicles (EVs) appears promising, it is essential to acknowledge that they come with their own set of challenges. Here, we will delve into three major obstacles within the EV landscape, examining the various types of challenges hindering their widespread adoption.

2.1 Economic Challenges

High Initial Cost

Over time, the cost of conventional internal combustion engine vehicles has decreased, particularly when compared to the electrified vehicle technology that is still advancing [14]. The initial cost of purchasing an electric vehicle is higher than that of a conventional vehicle. Due to their high initial cost, which prevents many potential buyers from affording them, EVs have limited demand. The primary reason for this cost difference is the expensive battery technology utilized in EVs. More research and development is required before electric vehicles can be produced on a large scale and made widely available [5].

Negative Impact on Some Sectors

In many different industries and economic sectors, EVs can have a substantial, sometimes even detrimental, economic impact. This is especially true for nations that produce oil and heavily rely on the money generated by these sectors [5, 7]. The government's abrupt adoptions of EVs and strong support for them have the potential to upset the delicate economic balance. According to the IEA, transportation accounts for roughly 60% of global oil demand, of which 10% is accounted for by the USA alone. This percentage should decrease because, by 2030, the IEA projects that EVs will have eliminated about 5 million barrels of daily global oil demand [6, 26].

High Infrastructure Charging Station Cost

The cost of the infrastructure for EV charging can vary greatly depending on the location and type of charging station. Three primary categories can be used to group charge stations: Level 1, Level 2, and Level 3 (DC fast charging) [35]. Level 1 charging stations are the slowest, they can only charge a car up to 4 miles per hour. Vehicles can be charged at up to 25 miles per hour using faster Level 2 chargers. DC charging stations are the fastest; depending on the model, they can refuel a car with up to 200 miles of range in just 30 min.

Level 1 charging stations range in price from $200 to $1000 for the actual charging equipment, making them the most basic and least expensive. Although Level 2 charging stations are substantially faster than Level 1, they are more expensive, with the equipment alone costing anywhere from $1,500 to $5,000. The price of installing the electrical vehicle supply equipment (EVSE) will not be the only expense to take into account. These expenses include the cost of running electrical wiring to the charging station, labor costs associated with installation and construction, grid updates, permits, and compliance fees. Grid access, the distance from the electrical panel, site preparation, and inspections are the factors that will determine how much these additional costs will cost.

Installing a Level 2 EV charging station can cost as much as $10,000 total when including the cost of the EVSE and installation, not to mention the equipment's ongoing and routine maintenance. Level 3 EVSEs start at around $20,000, and the equipment alone can cost up to $100,000, or more for models with more sophisticated features like multiple charging ports or integrated energy storage Jerome [25].

2.2 Technological Challenges

Technological challenges posted by the vehicle

The electric motors supplying the EVs cannot yet generate great power, instantaneous torque, or top speeds like IC engine cars can.

Technological Challenges Posted by the EV Batteries

The limitations of battery technology are one of the main obstacles to the widespread adoption of electric vehicles (EVs). The driving range of the car is limited by the low energy density of the current EV battery design. EV electric car battery efficiency is still a big problem [41]. Because batteries are expensive, bulky, and require frequent charging, they are less useful for daily use. Scientists are working hard to advance battery technology, which will decrease weight, boost driving range, cut expenses, and speed up charging times, to address these issues. Ultimately, the commercial success or failure of electric cars will depend on advancements in battery technology. The term "range anxiety" describes how far a battery can go on a single charge [30, 37].

Technological Challenges Posted by Charging Infrastructures

Electric vehicles draw their energy from the grid, and as a result, charging costs vary depending on the time of day. Peak hours, typically in the afternoon and early evening, often incur higher charging prices, making it less optimal to charge a large vehicle during these times. However, this issue can be mitigated by charging during non-peak hours, although it necessitates more deliberate planning compared to simply refueling a gas tank when it is nearly empty [27, 54].

Even though the infrastructure for charging has recently improved, it is still not as accessible or convenient as traditional gas stations. As a result, EV drivers may find it challenging to locate charging stations when necessary, especially in distant or long-distance areas. Another hazy technological feature is how quickly batteries recharge. Because they can charge quickly and securely, electric vehicles are expected to eventually replace individually built vehicles [27].

Various national standards, voltage, frequency, and other factors affect how charging infrastructures are configured and designed in different countries. European standards currently rule the field when it comes to EV charging infrastructures. Because they make it easier to use compatible plugs and charging systems, these standards are essential to the expansion of the electric vehicle market [27, 54].

Integration of electric vehicles into smart cities: Smart city transportation systems are anticipated to heavily rely on electric vehicles. Governments, business stakeholders, and residents must work together to integrate them into these cities, though. This entails creating infrastructure for charging, supporting renewable energy sources, and boosting public transportation.

3 Advanced Technological Development in the EV Industry

This section includes some advanced technological developments in EV Industries.

3.1 Advance Battery Technology for EV

The primary barrier to the high acceptance of EVs at this time is the limitations of batteries. There is a cost associated with electric vehicles (EVs) because their batteries deteriorate over time, reducing their lifespan and decreasing customer satisfaction. Interesting battery-related facts are provided in this section, including global production growth, cost reductions, key features, and the various technologies used in the manufacturing process.

Better, more accessible, and larger capacity batteries—which consumers see as a competitive substitute for internal combustion engine vehicles—will lead to an improvement in vehicle autonomy. Electric vehicle (EV) batteries are essential, so more and more manufacturers are devoting resources to developing more efficient and better batteries.

Industry and consumer interest stems from the battery's key performance indicators (KPIs), which include (i) energy, (ii) power, (iii) lifetime, (iv) safety, and (v) cost [53]. These key performance indicators can be further broken down into the following categories: (i) charge acceptance (fast charging), (ii) specific power (W kg − 1), power density (W L − 1), and specific energy (Wh kg − 1), (iii) cycle and calendar life; (iv) mechanical, electrical, and thermal safety; and (v) cost per energy content [53].

While EV is charged Significant increase in battery temperature can increase the temperature that puts some concerns about safety, such as thermal runaway, electrolyte fire, swelling, and explosions. This presents another difficulty for the sector. Lithium-ion batteries have a much shorter operating life than traditional cars, which are made to tolerate extended high-temperature engine operation. Electrolytes go through a self-destruction process at temperatures higher than 150 °C. This may cause the battery's performance to rapidly decline and, in certain situations, even raise security issues.(for instance, make it burst into flames, or explode) [11, 12].

State-of-the-Art Batteries

In this section, we go through the oldest to the latest battery types as shown in Fig. 1. Recent advancements in battery technology bring forth a spectrum of enhancements compared to traditional technologies, including enhanced specific energy and energy density, signifying increased energy storage per unit volume, or weight [45, 51]. Table 1 represents the life cycle, advantages, disadvantages, and the EV in which the battery is implemented.

Super-Capacitor Battery

An ultra-capacitor (UC) is an energy storage device that stores electro-statically, instead of chemical reaction like in batteries with faster charging and discharging cycles. It has much higher capacitance means it can store more energy than a regular capacitor. Ultra-capacitors have lower energy density compared to battery means cannot store much energy for a long time, so it is very ideal for applications where a quick amount of power is required like regenerative braking and power mode during acceleration of the vehicle. Expansion of the use of UC for electric vehicles more than power boosters is an ongoing research area. In recent years, developed super-capacitor batteries in which the electrode is mixed capacitor materials with lithium-ion battery materials [21]. Super-capacitor battery has high energy density and then lithium-ion batteries and possible fast charging and discharge.

Key features

High Power Density: Very useful for applications to deliver more power in a short duration, like regenerative breaking in EV and Hybrid vehicles [21].

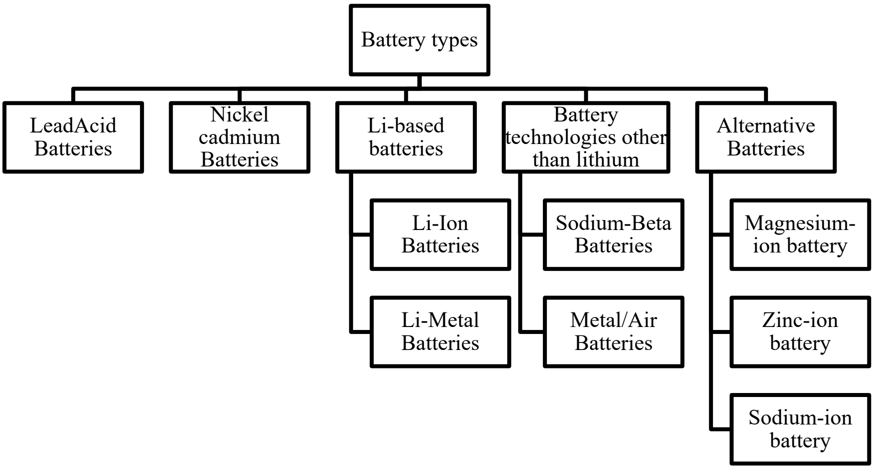

Fig. 1 Types of batteries: oldest to the latest development [51]

Long Life: It is possible thousands of discharges and charging cycles, are very high compared to battery technology.

Thermal Capacity: It is very high and can operate in a range of − 30 °C to + 55 °C.

Pollution-Free: It does not contain any hazardous materials or chemicals and also recycling of used material is possible at the end of life.

A newer approach gaining attention is direct recycling, enhancing efficiency by preserving the material structure of the cathode instead of breaking it down into elements. This method retains both energy and economic value during cathode processing, eliminating the necessity to generate new materials from raw resources. Direct recycling is particularly effective for cathodes with fewer valuable metals, such as LFP. However, it comes with limitations, requiring customization for each cathode type, and the recycled cathodes can only be used to manufacture the same battery type. Researchers are actively developing methods to convert recycled materials into different battery types, like transforming NMC333 into NMC811 [36].

3.2 Advanced Battery Charging Technology and Revised Standards for EV

The landscape of fast charging technology for lithium-ion batteries in EV applications is poised for continual growth and innovation [9, 34]. Several promising avenues are emerging:

a) Ultra-fast charging: Researchers are actively exploring ultra-fast charging possibilities, aiming to reduce charging times to mere minutes. Significant challenges

Table 1 Pros and cons of different batteries with vehicle application [38]

Types	Specific energy (Wh kg^{-1})	Specific power (W kg^{-1})	Life cycle	Pros	Cons	Examples and vehicle applications
Lead–acid	30~50	150~200	400~800	Good performances at a low cost	Low specific energy, low energy efficiency, and memory effect	VRLA: Ford Ranger, Chrysler Voyager, Suzuki Alto
Nickel-based	35~80	150~450	800~2000	High specific power at a low cost	Low specific energy and low energy efficiency	Ni–MH: Toyota RAV4L, Honda EV Plus, Peugeot 106
Ambient temperature lithium-ion	120~300	200~450	600~ > 3000	Extended life cycle, high specific power, and high energy efficiency	High (moderate) cost and fire risk (reliability)	Li-Ion: Tesla 3, BMW i3, Nissan Leaf
Sodium-beta	115~200	120~250	800~2000	High energy efficiency, high specific energy	elevated working temperature, risk to safety, and high expense	Na/NiCl2: BMW AG, Mercedes-Benz Vito
High-temperature lithium	130~180	240~400	1000~1200	–		
Metal/air	75~250	100~200	300~800	Reasonably priced, highly specific energy, and easily refueled	Expensive, low specific power, and limited temperature range of operation	Zn/Air: Mercedes-Benz MB410, GM-Opel Corsa Combo
Zinc/halogen	65~75	60~110	200~400	Liquid fuel, inexpensive	High cost, low specific energy and power, and frequency maintenance	Zn/Br2: Fiat Panda, Hotzenblitz EV, Toyota EV-30

such as managing extreme heat generated during rapid charging persist, but progress is anticipated.

b) Solid-state batteries: Solid-state batteries are attracting significant attention for their potential to revolutionize fast charging in EVs. These batteries replace traditional liquid electrolytes with solid alternatives, offering increased energy density and faster charging capabilities. Continued research and development efforts are dedicated to advancing solid-state battery technology.
c) Wireless fast charging: Wireless charging technology for EVs is advancing swiftly. High-power wireless charging systems are under development to provide convenient, fast charging without physical connectors. This technology has the potential to redefine the EV charging experience.
d) Grid integration: As fast charging becomes more widespread, effective integration into the electrical grid will be crucial. Smart grid solutions and demand response programs will play vital roles in optimizing the use of fast charging stations, reducing peak power demand, and enhancing grid stability.

Globally, there are primarily three levels of EV charging: Level 1, Level 2, and Level 3. Jerome [25] These levels are characterized by higher levels producing higher power output from the charger and faster EV charging.

Three categories are used by the US Department of Energy to categorize EV charging: Level 1 represents standard charging with a power output of less than 5 kW; Level 2 represents fast charging with a power output of 5 kW to 50 kW; and Level 3 represents super-fast charging with a power output greater than 50 kW.

The development of electric vehicle standards by governments and subject matter experts (SMEs) guarantees a stable EV market with fewer risks and hazards. One of the many deciding elements that assist businesses in prioritizing safety and ensuring the dependability of their products will be EV standards. To safely advance modern transportation, the industry needs to maintain compliance with EV standards, especially as these EV systems become more complex. International organizations like the Society of Automotive Engineers (SAEs) and the International Electrotechnical Commission (IEC) play a crucial role in establishing charging standards. By convening manufacturers, government bodies, and technical specialists, these groups establish widely accepted standards within the automotive sector.

IEC 61,851–1, IEC 61,851–23, and IEC 62,196 stand as pivotal standards offering technical specifications for charging connectors, communication protocols, and other integral components of EV charging systems.

IEC 61,851–1 serves as the standard for AC charging, delineating the physical connection between the EV and the charging station, along with the communication protocols facilitating interaction between the two.

IEC 61,851–23, meanwhile, is the standard for DC fast charging. Like its AC counterpart, it encompasses the physical connection between the EV and the charging station, as well as the requisite communication protocols.

IEC 62,196 represents a comprehensive standard covering both AC and DC charging. It defines the specifications for the charging connector and associated communication protocols, ensuring compatibility across a range of charging scenarios.

The new standards introduce several modifications, which include:

- Adding temperature sensors to send alerts and prevent thermal incidents.
- Incorporating battery-level safety checks.
- Enhancing ingress protection or insulation.
- Providing adequate spacing between individual cells within a battery pack.
- Conducting a propagation test to ensure thermal runaway in one battery does not affect others.
- Implementing a more intelligent battery management system.

4 Roll of IoT and AI in EV Technology

There are obstacles to EV adoption, in contrast to conventional ICE vehicles, which include energy management, predictive analytics, route optimization, grid interface, charging infrastructure optimization, range anxiety, and charging times for EVs. Using artificial intelligence (AI) and the Internet of Things (IoT), manufacturers are overcoming these challenges. The top 7 IoT and AI applications are displayed in Fig. 2 [13].

The Internet of Things (IoT) and artificial intelligence (AI) work together to improve the functionality, efficiency, and overall performance of electric vehicles (EVs). Table 2 lists several important ways that IoT and AI contribute to the development and operation of electric vehicles Kavitha [28].

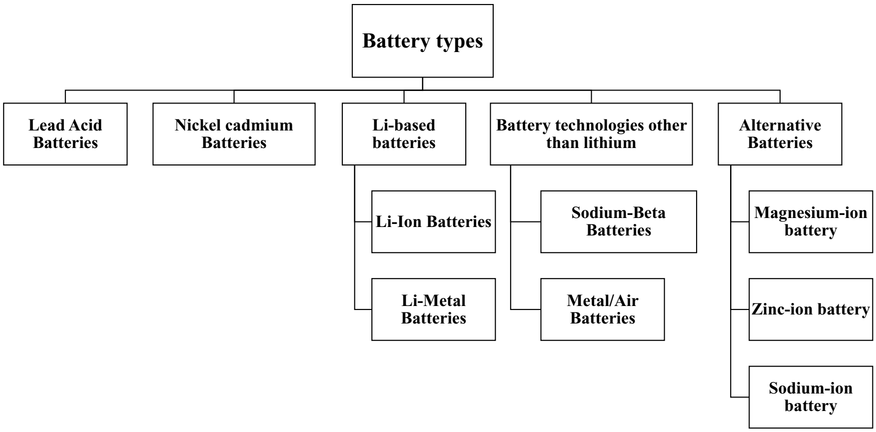

Fig. 2 Applications of IoT in EV [13]

Table 2 Role of IoT and AI as per various key aspects of EV Kavitha Kumari et al. [28]

Key aspects	Role of IoT	Role of AI
Vehicle connectivity	EVs can connect to the Internet because they have sensors and communication devices installed. Real-time data exchange between the car and external systems is made possible by this connectivity	The data gathered from IoT sensors can be analyzed by machine learning algorithms to reveal information about the performance, health, and usage patterns of vehicles. Models for predictive maintenance can be created to foresee possible problems and take action before they get out of hand
Range optimization	Sensors in EVs can monitor battery levels, energy consumption, and charging status. Additionally, IoT-enabled infrastructure, such as smart charging stations, can provide data on charging availability and rates	AI algorithms can analyze historical data, weather conditions, traffic patterns, and individual driving habits to optimize the vehicle's energy management system. This helps in maximizing the range of the electric vehicle and improving overall efficiency
Autonomous driving	Connected vehicles have the capability to communicate both among themselves and with infrastructure components such as traffic lights and road sensors	AI technologies, particularly machine learning and computer vision, play a crucial role in autonomous driving. These systems process and interpret data from sensors to make real-time decisions, navigate the vehicle, and ensure safety
Charging infrastructure management	Smart grids and IoT-connected charging stations can monitor energy demand, manage charging schedules, and balance the load on the electric grid	AI algorithms can optimize charging strategies based on electricity prices, demand fluctuations, and grid conditions. This helps in efficient energy utilization and reduces the overall impact on the power grid
User experience and personalization	In-vehicle IoT devices can gather data on driver preferences, behavior, and comfort settings	AI can analyze this data to personalize the driving experience, such as adjusting climate control, seat positions, and infotainment options. Natural language processing can also enable voice-activated controls for various vehicle functions
Security and safety	Security protocols within the IoT infrastructure ensure secure communication between the vehicle, cloud services, and other connected devices	By identifying abnormalities in data patterns, AI algorithms can assist in identifying possible threats to cyber security. Additionally, through functions like collision avoidance, lane-keeping assistance, and emergency braking, artificial intelligence (AI) supports advanced driver-assistance systems (ADASs) for increased safety

5 Battery Management System (BMS) with IoT &AI

An autonomous or electric car's battery management system, or BMS, is a crucial component. But what connection does the battery have to artificial intelligence (AI) or the Internet of Things? Let's look at how BMS works in an EV and how adding AI and IoT to BMS can help us progress technology even further [15, 47].

Figure 3 depicts the general layout of a BMS integration with AI and IoT. An EV's BMS is equipped with a number of sensors to track temperature, voltage, current, and vibration/acoustics. Every second, these parameters are gathered. An edge intelligence system is used in EVs and intelligent cars, which lessens reliance on the cloud [15].

In most electric vehicles (EVs), state estimation functions, like State of Charge (SOC), State of Available Power (SOAP), and State of Health (SOH), are core operations carried out automatically by embedded computing systems. These systems operate in real-time. Through edge intelligence actions, anomalies such as excessive temperature can be mitigated by reducing the motor's power consumption. While this might lead to a slight decrease in vehicle speed, it prevents the motor from consuming excessive energy and heating the battery. Furthermore, to optimize the State of Health, edge intelligence can also effectively manage the State of Charge.

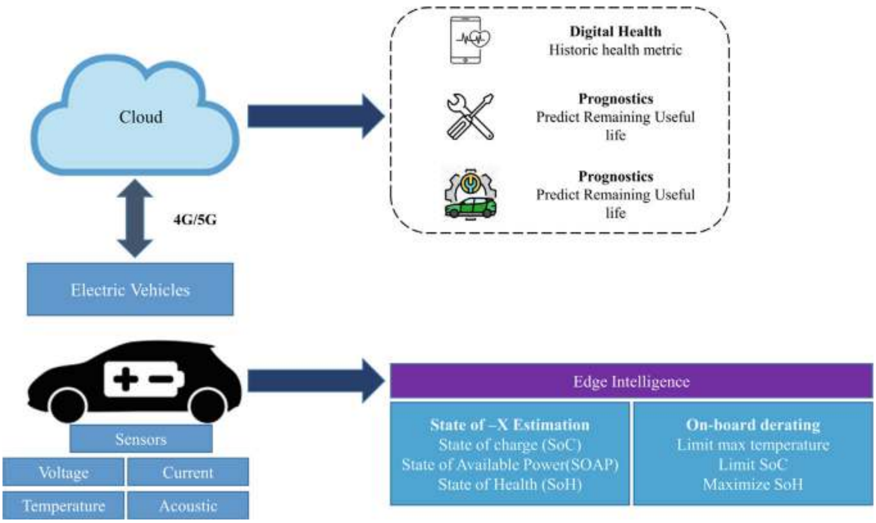

Fig. 3 Integration of BMS with IoT and AI

Leveraging 4G/5G connectivity, data can be seamlessly transmitted to the cloud. In the cloud, Graphic Processing Units (GPUs) equipped with substantial computing capabilities can perform digital health assessments and forecast the remaining useful life. In the event of an anomaly detected in the battery management system (BMS), notifications are promptly dispatched to the registered mobile device or any installed dashboard application within the electric vehicle (EV).

6 IoT's Drawbacks for Monitoring and Managing Electric Vehicles

(1) Cyber-Attack Risk

Due to the large number of devices that we now have connected to the Internet, data that is transferred over a network in large quantities is more susceptible to data theft and cyber-attacks. Hackers could get access to the system, take personal data, and use it for malicious purposes [31]. Thus, it is necessary to fortify and increase the hacker-proofness of the Internet of Things devices that are connected to the EV and gather all of the data.

(2) Exorbitant Price of Electric Cars

Since IoT systems for electric vehicles are highly sophisticated and expensive to install and operate, EVs are more expensive overall. More R&D in this field may soon make it possible to lower overall costs [31].

(3) Intricacy of Technology

The complex technology in the IoT system is challenging to design, develop, maintain, and enable, which makes managing the overall EV design more challenging [32].

(4) Connectivity and Power Dependence

To operate and deliver real-time data correctly, Internet of Things (IoT) devices used in electric vehicles (EVs) require constant power and Internet access. The device and everything connected to it will both go down when one of them fails (Fig. 4). Thus, it will also have an impact on EVs' overall performance [32].

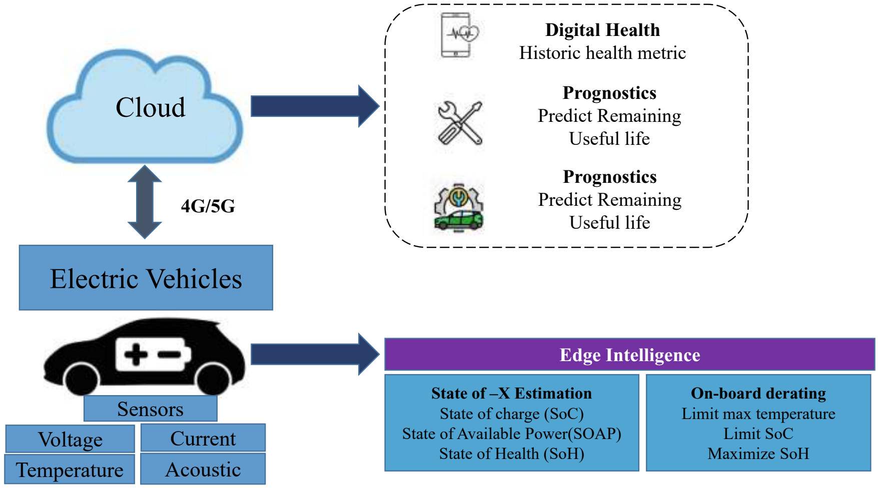

Fig. 4 Integration of BMS with IoT and AI [18]

7 Analysis of Vehicle Sales Trends in India

Figure 5 from the Ministry of Road Transport & Highways shows the number of cars sold in India from 2014 to 2022. According to the data, there has been a noticeable increase in sales of electric battery-operated vehicles (BOV) starting in 2016, which suggests that people are becoming more interested in environmentally friendly transportation options. Vehicles with gasoline/CNG and gasoline/hybrid powertrains also demonstrated a rising sales trend. The overall market share of electric vehicles in India during this period was lower than that of conventional fuel-powered vehicles [17, 33].

7.1 Gross National Income (GNI) Per Capita of India and Its Impact

Between 2014 and 2022, India's car sales grew significantly, which is consistent with the country's economic expansion as indicated by the rise in GNI per capita. India's GNI per capita grew steadily over these eight years, rising from $1,550 in 2014 to $2,380 in 2022 (Fig. 6).

This increase implies that more people were able to buy cars as the gross national income (GNI) per capita rose, which in turn raised people's disposable incomes and contributed to the spike in sales. By 2030, the Indian government hopes to grow its current budget of $4,000 by 70% from its current levels of $2,450 [19, 24, 52].

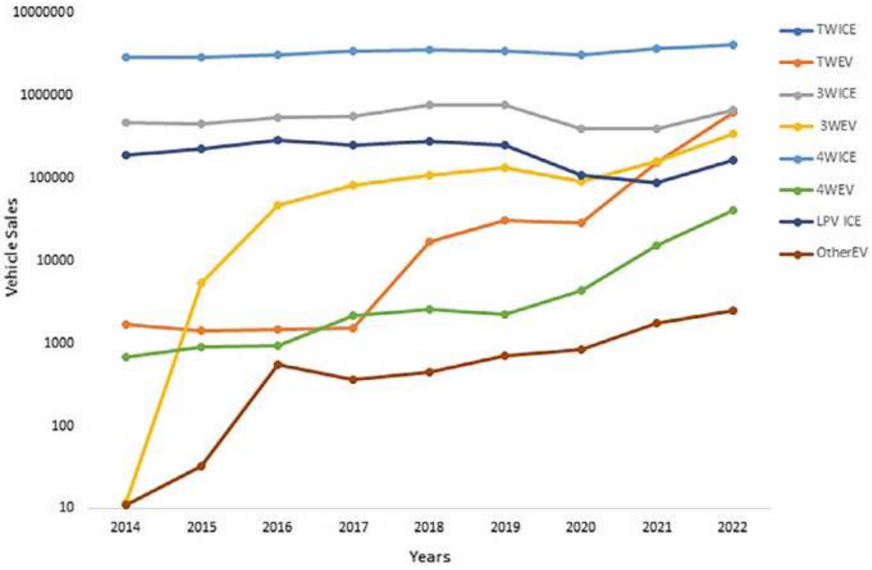

Fig. 5 Vehicle category trends over the years (Government of India, "Vahan and Sarathi Portal," https://vahan.parivahan.gov.in/vahan4dashboard/, Aug-2023, n.d.)

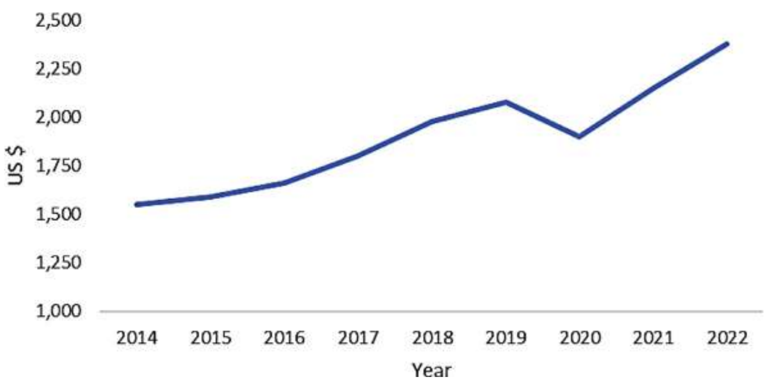

Fig. 6 GNI per capita of India (US $) [52]

7.2 *Electric Vehicle Sales Market at Present*

Sales of electrical vehicles have been rising steadily because of the government's incentive program and the continuous rise in crude oil prices, which have encouraged consumers to convert from internal combustion engines (ICEs) to electrical vehicles. The ongoing decline in EV prices and the development of battery and controller technology, which increases EV range, are additional influencing factors. A study found that while EV sales in the country decreased in 2020 due to the pandemic (Fig. 7), they sharply increased in 2022 Gujarathi et al. [20, 50].

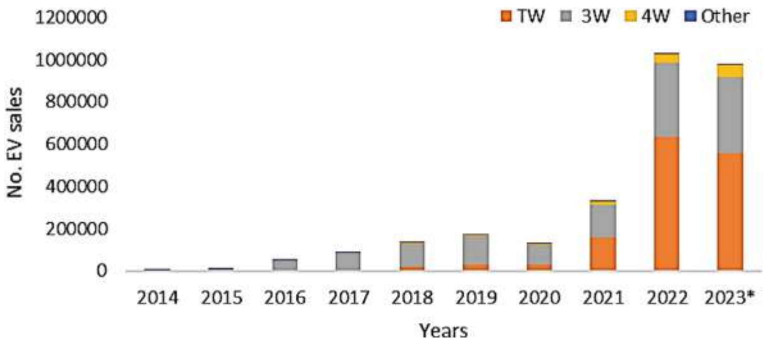

Fig. 7 Electric vehicle sales growth in India (Government of India, "Vahan and Sarathi Portal," https://vahan.parivahan.gov.in/vahan4dashboard/, Aug-2023, n.d.)

These figures demonstrate the notable shift in recent years toward environmentally friendly and sustainable transportation options as well as the growing acceptance and popularity of electric vehicles (Fig. 8). (Government of India, "Vahan and Sarathi Portal," https://vahan.parivahan.gov.in/vahan4dashboard/, Aug-2023, n.d.; Gujarathi et al., [20, 29].

In 2022 and 2023, two-wheelers are predicted to account for the majority of sales of electric vehicles. However, the increase in three- and four-wheelers in 2023 indicates that the electric vehicle market has undergone significant diversification [19, 48].

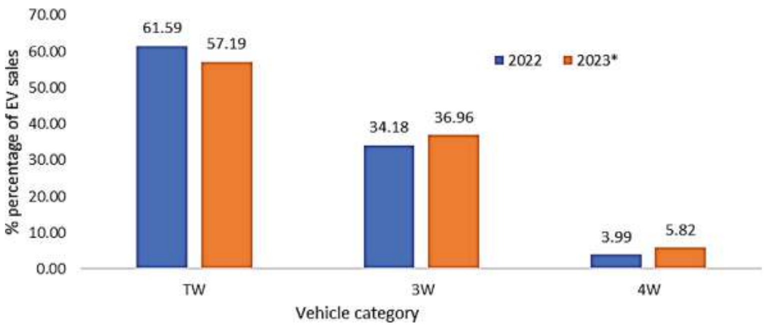

Fig. 8 Electric vehicle sales growth year 2022–2023 [50]

8 Forecasting the Future

Time series forecasting is a branch of predictive analytics that forecasts a variable's future values based on its historical observations or measurements. A time series' goal is to predict future values by collecting and logging data points over a long period of time. This approach is applied in a wide range of fields, such as economics, finance, stock market research, meteorology, and energy consumption forecasting.

Simple Moving Average (SMA) is a simple classical time series prediction technique that shows trends smoothly over time by averaging a predefined number of recent data points. The Exponential Moving Average (EMA) allows the forecast to respond to changes more quickly than the SMA because it assigns greater weight to more recent observations. The Autoregressive Integrated Moving Average (ARIMA) model consists of three components: moving averages (MAs) to account for past forecast errors, autoregression (AR), and differencing (I) to make the data stationary [49].

8.1 Regression-Based Methods:

- Linear Regression: Examines the relationship between variables by drawing a straight line.
- Polynomial Regression: An extension of linear regression is the fitting of a polynomial function to represent non-linear relationships.
- Time Series Decomposition: A time series is dissected into its component parts, such as trend, seasonality, and residuals, in order to improve forecasting accuracy. Important elements of time series forecasting consist of:
- Time Series Data: A collection of data points, such as daily stock prices, hourly temperature readings, and monthly sales statistics, that are indexed chronologically.
- Trend: Extended changes in the data over time, like values that rise or fall.
- Seasonality: Repeating cycles or patterns that arise on a regular basis, often due to the days of the week, holidays, or seasons.
- Noise: Variations or anomalies in the data that are not consistent with a predefined pattern.

9 Future Forecasting of Electric Vehicle Sales in India

One effective machine learning technique for sales forecasting is regression analysis. It generates accurate forecasts by projecting future sales trends using a time series of historical data. An analysis of the sales of electric vehicles (EVs) in India has been carried out specifically using this historical data. The ultimate objective is to forecast the trajectory of EV sales for the ensuing few years [1, 40].

Table 3 Yearly electric vehicle sales in India [50]

Years	EV sales
2014	2389
2015	7801
2016	49,848
2017	87,420
2018	130,253
2019	166,823
2020	124,647
2021	331,463
2022	1,025,795

Table 4 Forecasting result of electric vehicle sales in

Years	Linear regression EV sales prediction	Polynomial regression EV sales prediction
2023	654,738	1,107,374
2024	742,898	1,467,116
2025	831,058	1,876,236
2026	919,219	2,334,735
2027	1,007,379	2,842,612
2028	1,095,539	3,399,868
2029	1,183,699	4,006,502
2030	1,271,859	4,662,514

9.1 Linear Regression Analysis for Future Forecasting

A dependent variable (often shortened to "Y") and one or more independent variables (often shortened to "X") are modeled using the statistical technique of linear regression. The aim of simple linear regression, which is based on the equation $Y = M*X + C$, is to find the best-fitting straight line to represent the relationship between Y and X [10, 40, 46].

We looked into projecting future sales of electric vehicles (EVs) using historical data and a linear regression model. The basic idea behind linear regression is that there is a linear relationship between the target variable, in this case EV sales, and the predictor variable, in this case the years. The actual annual registered sales data for electric vehicles in India are shown in Table 3. We fit a linear regression model to actual annual sales data for EVs. The result is shown in Table 4. Although linear regression offers simplicity and results that are easy to understand, polynomial regression is better at capturing nonlinear growth patterns.

9.2 Polynomial Regression Analysis for Future Forecasting

Polynomial regression builds upon the ideas of linear regression and allows for more flexible curve fitting by incorporating polynomial terms. The dependent variable (y) and one or more independent variables (x) are still present in polynomial regression; however, a polynomial curve is fitted as opposed to a straight line. The general form of a polynomial regression equation with one independent variable (x) is shown in equation [14].

$$Y = b_0 + b_1 * X_1 + b_2 * X_2 + b_3 * X_3 + \ldots + b_n * X_n$$

We projected sales of electric vehicles (EVs) for the next few years using historical data. Our dataset included EV sales data from 2014 to 2022. The actual yearly EV sales data was fitted to a polynomial regression model that was prepared. Table 4 displays the resulting projections for the following years [42, 46].

9.3 Seasonal ARIMA Methodology for Future Forecasting

Both SARIMA and ARIMA forecasting techniques are used. Autoregressive, moving average (ARIMA) bases its predictions of future values on historical data. Similar to SARIMA, seasonality trends and historical values are taken into account. SARIMA is far more accurate at forecasting than ARIMA [16].

The remaining components of the model are still the ARIMAs, p-moving average (MA) [44], d-integrated (I), and q-autoregressive (AR) components. The SARIMA model is made more robust by adding seasonality (P, D, and ARIMA (p, d, q)(P, D, Q) Q). It seems to be below.

A. **Testing the Stationarity of Time Series EV Sales Data:**

A time series data set's stationarity is ascertained through statistical tests. These tests consist of checking for stationarity in time series data for an enhanced ARIMA forecasting model and the Augmented Dickey-Fuller (ADF) test. A key idea in time series analysis is stationarity [44]. The results of an Augmented Dickey-Fuller (ADF) test run on the set of EV sales time series data are as follows.

$$\text{ADF Test Statistic}: -2.9851906417801892$$
$$\text{p} - \text{value}: 0.036300744473384425$$

In the context of the ADF test, it establishes the minimum difference in the data that is necessary to make it stationary. For the EV sales data in our instance, the test statistic is approximately -2.9852. The negative ADF test statistic provides additional evidence in favor of stationarity. The p-value (0.0363) is less than the commonly accepted significance level of 0.05 (5%). If the p-value is less than the significance threshold, reject the null hypothesis. Because our data series does not have a unit root, there is strong evidence that the data is stationary.

B. **Autoregressive (AR) Models for Time Series EV Sales Data Analysis and Forecasting:**

Autocorrection analysis testing is crucial if we plan to use an ARIMA model for forecasting since it will enable us to determine the autoregression (AR) and moving average (MA) parameters required by the model [16].

$$Y^t = \alpha_1 * Y_{t-1} + \ldots + \alpha_p * Y_{t-p}$$

We assume that in this AR model, the current value (y^t) depends on the values that came before it ($y^t - 1$, $y^t - 2$, $y^t - 3$,...). and to use the partial autocorrelation function (PACF) to determine the order of an AR model (p) for a given input set of data, in this case, EV sales data.

C. **Moving Average (MA) Model for Time Series EV Sales Data Analysis and Forecasting:**

The moving average model is a key component of time series analysis. It focuses on capturing the short-term fluctuations in data by examining the moving average of data points over a predefined period of time. According to [16], it gives an approximation of the quantity of historical observations needed to calculate the moving average.

$$Y^t = \in_t + \beta_1 \in_{t-1} + \ldots + \beta_q \in_{t-q}$$

For given input data, in this case EV sales data, the order of an MA model (q) is determined using the autocorrelation function (ACF). The MA model postulates that the error terms, such as the current error (ϵ_t, $\epsilon_t - 1$, $\epsilon_t - 2$, $\epsilon_t - 3$,...), determine the current value (y^t).

A crucial element in the modeling of EV sales time series is lag 1 (AR (1)). There are notable spikes in the autocorrelation function (ACF) plot at lags 1, 2, 3, and 4, with lag 1's spike being the most significant [8, 22].

The partial autocorrelation function plot is shown in Fig. 9. The number of autoregressive terms, or the optimal value of p, was found. We can decide to set the p's order to 1 in this case since the first lag in PACF is obviously outside of the range.

D. **SARIMA Model Testing and Validation:**

In order to test and validate our train model, we will make sure that the actual data and the predicted values follow the same pattern in order to assess the forecast accuracy of our model. Additionally, we might consider splitting our data into training and testing sets in order to evaluate how well the model generalizes to new data. Plotting the actual EV sales data (EV sales) against the forecasted values (forecast) is the final step in determining how well your ARIMA model fits the data and how accurate its predictions are. This is shown in Fig. 10 Andrew [2].

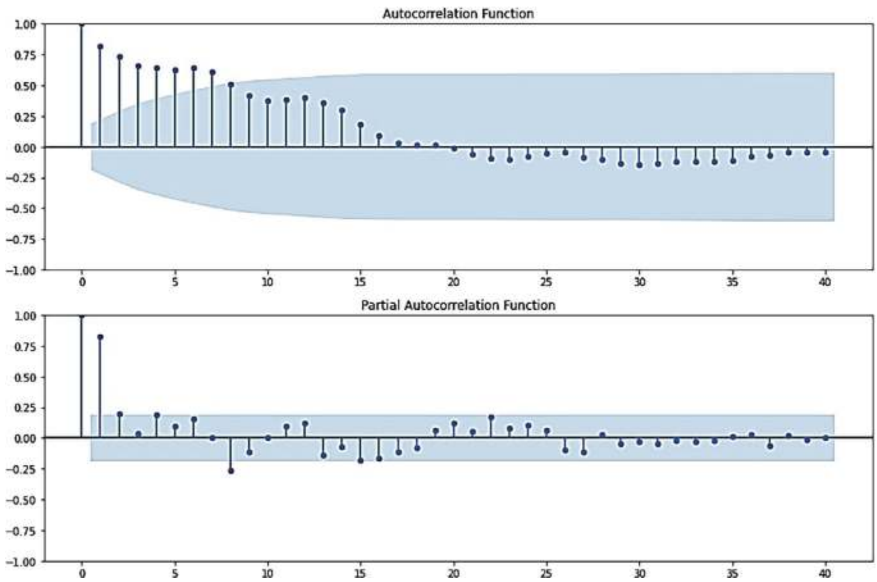

Fig. 9 Autocorrelation function and partial autocorrelation function test

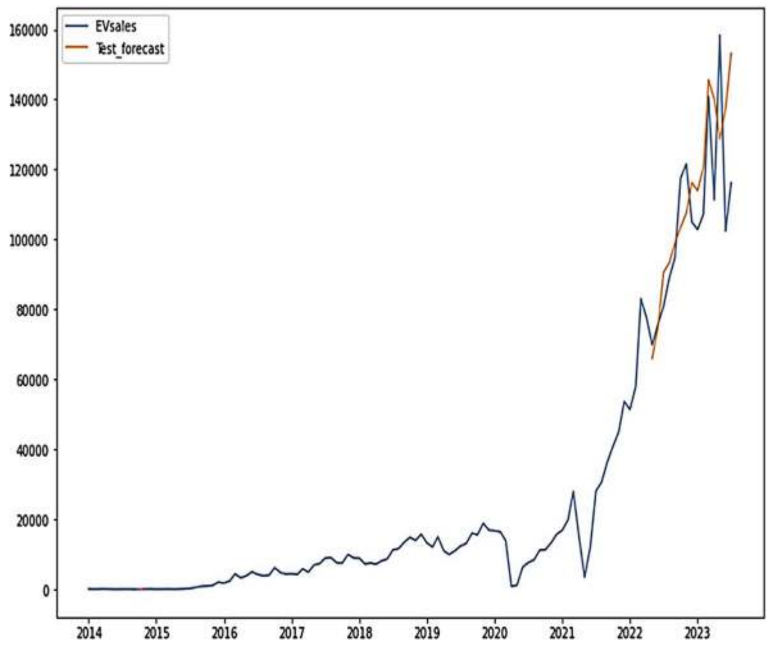

Fig. 10 Actual EV sales versus test forecasted EV sales

Table 5 Forecasting result of electric vehicle sales in India with SARIMA model

Year	SARIMA model EV sales prediction
2023	1,543,586
2024	1,966,934
2025	2,390,282
2026	2,813,630
2027	3,236,978
2028	3,660,326
2029	4,083,674
2030	4,507,022

E. **SARIMA Model for Future Forecasting of EV Sales:**

The Seasonal Autoregressive Integrated Moving Average, or SARIMA, model is a helpful tool for forecasting EV sales data when past trends are significant. A pre-trained SARIMA model allows us to make data-driven predictions for an extended period of time, which aids in future strategic planning and better decision-making Andrew [2, 4].

The SARIMA model is a powerful tool for time series forecasting. We employ a pre-trained SARIMA model in this context to forecast sales of electric vehicles (EVs). Table 5 shows the EV sales data for the years 2023 through 2030.

Based on data from the SARIMA model, the market for electric vehicles is expected to grow steadily and more quickly through 2030. By 2030, it is projected that EV sales will total 45,07,022 units per year. This could be explained by advancements in battery technology, increased consumer choice in EV models, and developments in infrastructure. This significant achievement for the electric vehicle (EV) sector is in line with the goals set forth by governments and automakers to promote the transition to electric vehicles.

10 Conclusion

Electric vehicles are becoming more widely introduced and used, both in developed and developing nations. The government is driving the drive for the next generation of environmentally friendly cars in developed nations. Along with traditional automakers, other businesses, both large and small, have ventured into the EV market as new business opportunities. The execution of multiple pilot projects and EV-related events is consistent with the high expectations that the general public has for EVs. The writers of this book's chapters have concentrated on challenges to the adoption of EVs and future sales forecasting sales techniques of EV.

What challenges will EV technology present at the same time and place for global researchers and industry participants to work? The chapter effectively highlights several aspects of the book, encouraging readers to read the entire work and benefit from it. These include developments in EV smart manufacturing technologies, smart charging infrastructure and grid, battery and battery technology advancements, battery management systems, EV communication and protocols, artificial intelligence, blockchain, and IoT technology. This chapter will motivate readers toward EV future in India.

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Chapter 9
Integration of Renewable Energy Sources (RES) into Electric Vehicle (EV) Charging Infrastructure: State-of-the-Art Review

Pooja Jain, Ankush Tandon, and Ramesh Chand Bansal

Abstract This chapter presents a comprehensive review of the integration of renewable energy sources (RES) into electric vehicle (EV) charging infrastructure, addressing the critical challenges of carbon emissions reduction and reducing dependence on fossil fuels in the transportation sector. It begins with an overview of RES, including their types, characteristics, and current utilization in the energy sector. Subsequently, the chapter delves into the intricacies of EV charging infrastructure, discussing various station types and associated challenges. It then explores the integration of RES into EV charging systems, highlighting the benefits such as emissions reduction and considerations like grid stability. Technological advancements and case studies are presented to illustrate successful implementations of RES-EV charging systems. Additionally, the chapter examines the challenges and opportunities in this domain, including technical solutions, economic viability, policy frameworks, and grid integration strategies. Furthermore, future trends and research directions are discussed to promote sustainability and resilience in the transportation sector. The chapter underscores the significance of RES-EV integration in achieving environmental goals and concludes with recommendations for stakeholders and policymakers to advance this integration further.

Keywords RES · EV

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1 Introduction

1.1 Background and Significance of RES and EV Charging Infrastructure

Over the course of the last decade, there has been a gradual but noticeable increase in the adoption of electric vehicles (EVs). This surge in popularity can be attributed to significant advancements in technology and a notable expansion in the variety of purchasing options available to consumers. As a result of these developments, drivers now have access to EV models that offer enhanced range capabilities and a broader selection of features, thereby contributing to the growing appeal and acceptance of electric vehicles in the automotive market [1]. EVs have become the pathway toward carbon-free transportation, contributing to the reduction of greenhouse gas emissions. However, the development of a nationwide EV charging station network remains a significant barrier to the widespread adoption of EVs. In this article, we will explore the current state of EV charging infrastructure, the challenges it faces, and the initiatives being taken to build a sustainable network.

Over the last decade, the infrastructure for charging electric vehicles has seen significant growth. Presently, there exist over 115,000 charging stations, and this figure is anticipated to rise further as additional funding is directed toward expanding the network. Specifically, in 2021, the Bipartisan Infrastructure Law allocated $ 7.5 billion toward establishing a nationwide EV charging station network, with the objective of deploying 500,000 chargers by the year 2030.

Merely increasing the quantity of chargers may not adequately address the escalating demand. It's imperative to ensure a diverse array of charging stations within the infrastructure network. Presently, fast chargers, capable of adding 100–200 miles of range in just 30 min of charging, comprise only about 20% of the available charging stations. In contrast, Level 2 chargers, constituting over 78% of the current network, offer approximately 25 miles of range per hour of charging. This slower charging rate is deemed insufficient for extended road journeys [2].

Although numerous EV owners charge their vehicles at home, the expansion of public charging stations is paramount. These stations not only facilitate longer journeys with greater ease but also enhance accessibility for individuals lacking at-home charging facilities. Presently, California boasts the highest count of electric vehicle charging stations, trailed by New York State. However, when considering state size, Vermont emerges as the leader with the most EV chargers per capita [3].

Recognizing the need for a robust and widespread EV charging network, the Biden administration has taken significant steps to support the development of charging infrastructure. The Bipartisan Infrastructure Law includes. $ 7.5 billion in funding for a national EV charging station network, with $ 1.5 billion already approved for states to begin deployment. This funding will help expand access to charging stations, particularly in rural areas where charging infrastructure is lacking [4].

To assist rural communities in leveraging federal funding for EV charging stations, the U.S. Department of Transportation has released a toolkit called "Charging

Forward: A Toolkit for Planning and Funding Rural Electric Mobility Infrastructure [5].” This resource provides guidance on planning EV charging networks and navigating federal funding and financing options. Additionally, the Department will be conducting workshops to help rural communities effectively utilize the toolkit and accelerate the deployment of EV charging infrastructure.

As the number of EVs on the road increases, understanding the impact of charging demand on emissions and grid capacity is crucial. A model developed by researchers examines the consequences of EV charging demand on various factors, including emissions, grid capacity, costs, storage, and renewable integration [6]. The study considers scenarios for controlled charging and changes in access to home and workplace charging. By simulating the use of fossil fuel generators and considering future levels of renewable generation and grid storage, the model calculates the grid dispatch and associated emissions for different charging scenarios [7].

While progress has been made in expanding EV charging infrastructure, several challenges remain. One of the significant barriers is the slow development of a nationwide charging network. The availability of charging stations is not uniform across the country, with certain regions having a higher concentration of chargers than others. This disparity can hinder long-distance travel for EV owners and deter potential buyers who rely on public charging infrastructure [8].

To address these challenges, it is crucial to continue investing in the expansion of fast-charging stations, particularly along highways and major travel routes [9]. Fast chargers that can provide a significant range in a short amount of time are essential for facilitating long-distance travel and reducing range anxiety. Additionally, incentives and policies that promote the installation of charging stations in residential areas, workplaces, and public destinations can further enhance the accessibility and convenience of charging for EV owners.

The future of EV charging infrastructure looks promising, with increased funding and initiatives aimed at building a sustainable network. The expansion of charging stations, particularly fast chargers, will play a vital role in supporting the growth of EV adoption. As technology continues to improve, the charging process will become more efficient and convenient, further incentivizing the transition to electric vehicles [10].

Additionally, advancements in renewable energy generation and grid storage will contribute to the integration of EV charging into the electricity grid. The electrification of transportation can complement the growth of renewable energy sources, reducing reliance on fossil fuels and decreasing greenhouse gas emissions.

Establishing a comprehensive EV charging infrastructure is vital for the ongoing expansion of electric vehicles. Although strides have been taken, efforts must persist to guarantee a smooth charging experience for EV owners. Through investments in diverse charging stations, rural accessibility enhancements, and solutions for charging demand and grid capacity challenges, we can construct a sustainable network fostering widespread EV adoption and advancing environmental sustainability.

1.2 Motivation for Integrating RES into EV Charging Infrastructure

Integrating renewable energy sources (RES) into electric vehicle (EV) charging infrastructure offers several motivations and benefits which are as follows:

1. Environmental Sustainability:
   (a) Reduced carbon footprint: RES, such as solar and wind power, generate electricity with minimal to no greenhouse gas emissions. By integrating RES into EV charging infrastructure, the overall carbon footprint of the transportation sector can be significantly reduced. EVs charged with renewable energy contribute to a cleaner and greener transportation system, helping combat climate change [11].
   (b) Synergy between clean technologies: EVs and RES are complementary clean technologies. By combining them, we can create a synergistic effect, where renewable energy powers the charging of electric vehicles, leading to a holistic and sustainable transportation solution [12].
2. Energy Grid Optimization:
   (a) Load balancing and peak shaving: EV charging infrastructure integrated with RES can optimize energy demand by intelligently managing charging patterns. Smart charging algorithms can leverage RES availability and variations in electricity prices to distribute charging load, reducing peak demands and grid stress. This results in more efficient use of energy resources and a smoother demand profile [13].
   (b) Grid stability and flexibility: RES, such as solar and wind, are intermittent energy sources. By integrating them with EV charging infrastructure, excess renewable energy generated during peak periods can be stored in EV batteries or used for charging [14]. This energy can then be released back into the grid during high-demand periods, enhancing grid stability and providing flexibility in managing electricity supply and demand.
3. Renewable Energy Integration:
   (a) Grid balancing and demand response: EVs connected to charging infrastructure can act as distributed energy storage systems. During periods of high renewable energy generation and low demand, excess electricity can be stored in EV batteries [15]. This stored energy can be discharged back into the grid during peak demand or when renewable energy generation is low, supporting grid balancing and demand response programs.
   (b) Increased renewable energy utilization: By integrating RES with EV charging infrastructure, the demand for renewable energy increases. This encourages the development of additional renewable energy generation

capacity and helps overcome barriers related to intermittency and variability. It promotes the efficient utilization of renewable energy resources and strengthens the business case for expanding RES installations [16].

4. Public Perception and Consumer Appeal:
   (a) Environmental consciousness: Consumers are increasingly concerned about their environmental impact and are attracted to sustainable solutions. EV charging infrastructure powered by RES aligns with these values, offering an environmentally conscious choice for EV owners [17]. It enhances the perception of EVs as a truly green and responsible mode of transportation.
   (b) Positive branding and marketing: Integrating RES into EV charging infrastructure provides a unique selling proposition for charging network operators and EV manufacturers [18]. They can showcase their commitment to sustainability, renewable energy, and carbon neutrality, enhancing their brand image and attracting environmentally conscious customers.

Overall, integrating RES into EV charging infrastructure creates a virtuous cycle, driving the adoption of both clean technologies and accelerating the transition to a low-carbon and sustainable energy system. It offers environmental benefits, optimizes energy grid operations, supports renewable energy integration, and appeals to environmentally conscious consumers.

1.3 Research Objective and Scope

The research scope of this chapter is to explore the benefits, challenges, and opportunities associated with the integration of renewable energy sources (RES) into electric vehicle (EV) charging infrastructure. Here are some specific research questions that the research chapter addresses:

1. What are the potential benefits of integrating RES into EV charging infrastructure?
2. What are the key considerations involved in integrating RES into EV charging infrastructure?
3. What are the challenges and opportunities associated with RES-EV integration?
4. What are the future trends and research directions in RES-EV charging integration?
5. What are the recommendations for future research and implementation?

The objectives of the research are to:

1. Provide an overview of RES and EV charging infrastructure.
2. Discuss the potential benefits and key considerations involved in the integration of RES into EV charging infrastructure.
3. Explore the challenges and opportunities associated with RES-EV integration.

4. Identify future trends and research directions in RES-EV charging integration.
5. Provide recommendations for future research and implementation.

The chapter provides a comprehensive overview of the state-of-the-art in RES-EV integration research. The research is relevant to stakeholders and policymakers who are interested in advancing the integration of RES into EV charging infrastructure. The findings of the research can help to inform decision-making and guide the development of future policies and regulations.

1.4 Outline of the Chapter

The chapter is organized in a clear and logical way, with each section building on the previous one. The first section introduction provides the background and significance of RES and EV charging infrastructure, as well as the motivation for integrating RES into EV charging infrastructure. It also includes the research objective and scope, as well as an outline of the chapter. The second section defines and describes the different types of RES, as well as their characteristics and benefits. It also discusses the current utilization of RES in the energy sector. The next section provides an overview of EV charging infrastructure, including the different types of EV charging stations and the challenges and limitations of existing EV charging infrastructure. The fourth section discusses the benefits and potential of RES integration as well as the key considerations for RES integration (grid stability, power management, etc.). It also discusses technological advancements in RES-EV charging integration and case studies of successful implementations of RES-EV charging systems. The technical challenges and solutions, economic considerations and cost-effectiveness, policy and regulatory frameworks for RES-EV integration, and grid integration and infrastructure requirements are discussed in the fifth section. While the literature review provides a comprehensive overview of the state-of-the-art in RES-EV integration research. The next section discusses emerging technologies and innovations, scalability and replicability of RES-EV charging systems, research gaps, and areas for further exploration. The conclusion section summarizes the key findings from the state-of-the-art review, discusses the implications and benefits of RES-EV charging integration, and provides recommendations for future research and implementation.

2 Overview of Renewable Energy Sources (RES)

2.1 Definition and Types of RES (Solar, Wind, Hydro, Etc.)

India has made significant strides in deploying renewable energy sources (RES) to address its energy needs and reduce its carbon footprint. The remarkable growth of renewable energy in the electricity sector has ushered in a new era of clean and sustainable power generation, paving the way for a greener and more resilient future. As of today, all India generation capacity available from various renewable energy sources is shown in Fig. 1. Renewable energy sources (RES) are forms of energy that are naturally replenished and have a minimal impact on the environment. They are considered sustainable alternatives to fossil fuels, which are finite and contribute to climate [19]. Renewable energy sources (RES) also play a significant role in the context of electric vehicles (EVs). EVs are vehicles that use electric motors powered by rechargeable batteries instead of internal combustion engines. Here's an overview of the renewable energy sources commonly associated with electric vehicles:

1. Grid Electricity: Most EVs are charged using electricity from the grid. While the grid mix varies by region, it increasingly includes renewable energy sources such as solar, wind, and hydropower. Charging an EV with grid electricity can be considered renewable if the power comes from renewable sources [20].
2. Solar Charging: Solar energy can directly power EVs through solar panels installed on rooftops or carports. Solar charging stations capture sunlight and convert it into electricity to charge EV batteries. Solar power generation can be an environmentally friendly option that reduces dependence on the grid and utilizes a clean and renewable energy source [21].
3. Wind Charging: Similar to solar energy, wind power can be harnessed to charge EVs. Small wind turbines or wind farms can generate electricity that is then used to charge EV batteries. This approach promotes the use of renewable energy and reduces greenhouse gas emissions associated with traditional fossil fuel-based charging [21].

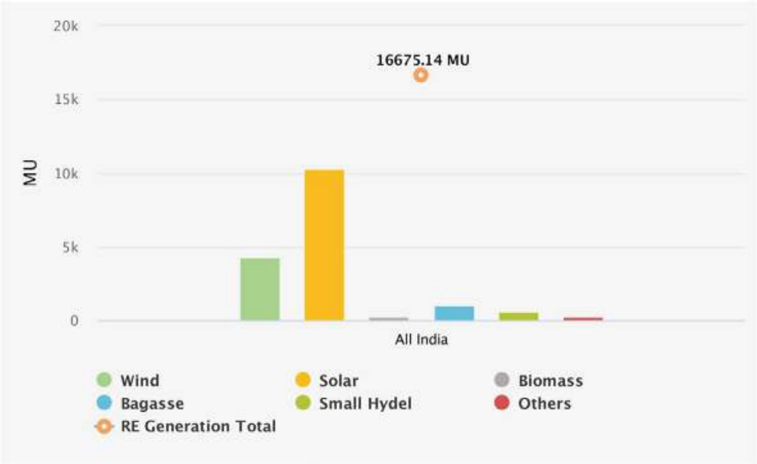

Fig. 1 All India RES generation capacity

4. Hydropower: Hydropower uses the energy of moving water to generate electricity. It is generated by harnessing the force of falling or flowing water, typically through the use of dams and turbines. Hydropower can be derived from rivers, streams, or tidal movements [21].
5. Biomass Energy: Biomass energy is obtained from organic materials such as plants, agricultural waste, or wood. It can be used directly as fuel or converted into biofuels, such as ethanol and biodiesel. Biomass can also be burned to produce heat or electricity through processes like combustion or gasification [22].
6. Vehicle-to-Grid (V2G) Technology: V2G technology facilitates two-way energy exchange between EVs and the power grid. It empowers electric vehicles to feed stored energy back into the grid during peak demand or low renewable energy generation. Serving as mobile energy storage, EVs aid in grid balancing and enhancing the incorporation of renewable energy [23].

Renewable energy sources provide numerous advantages, such as lowering greenhouse gas emissions, lessening dependence on fossil fuels, and bolstering energy security. They are pivotal in combating climate change and transitioning toward a more sustainable energy landscape. However, each source comes with distinct considerations and constraints, with their utilization contingent on factors like geographical location, resource availability, and technological progress. Highlighting the significance of EVs being powered by electricity from renewable energy sources is crucial. This combination optimizes environmental benefits by minimizing greenhouse gas emissions, reducing reliance on fossil fuels, and fostering a cleaner, more sustainable transportation system. Moreover, continual progress in battery technology and renewable energy production is facilitating the fusion of renewable energy sources with EVs. This symbiotic relationship is pivotal for realizing a decarbonized transportation industry and advancing toward a more sustainable energy paradigm.

2.2 Current Utilization of Renewable Energy Sources in Electric Vehicles

Renewable energy sources can play a significant role in the electrification of vehicles, offering several key characteristics that are beneficial for electric vehicles (EVs). Here are some of the characteristics of renewable energy sources in the context of electric vehicles:

1. Emission Reduction: Renewable energy sources like solar and wind power, employed for charging electric vehicles, exhibit markedly lower or zero greenhouse gas emissions in contrast to fossil fuels. Leveraging renewable energy for charging purposes enables EVs to play a pivotal role in curbing carbon dioxide and other pollutant emissions, thereby fostering better air quality and aiding in the fight against climate change [24].
2. Energy Efficiency: Renewable energy sources have high energy conversion efficiencies compared to traditional energy sources. This efficiency advantage

extends to EV charging as well. When EVs are charged with electricity generated from renewable sources, the overall energy efficiency of the vehicle is increased, reducing energy waste and minimizing the overall environmental impact [25].

3. Renewable Charging Infrastructure: Integrating renewable energy sources with EV charging infrastructure allows for sustainable and decentralized charging options. By installing solar panels or wind turbines at charging stations, the energy used for EV charging can be sourced directly from renewable sources on-site, reducing dependence on the grid and supporting energy independence [26].
4. Scalability and Flexibility: Renewable energy sources offer scalability and flexibility, which is particularly valuable in the context of EV charging. They can be deployed at various scales, from individual charging stations with solar canopies to large-scale charging networks powered by wind or solar farms. This scalability facilitates the expansion of EV charging infrastructure and accommodates different charging needs and locations [27].
5. Time-of-Use Charging: Renewable energy sources can enable time-of-use charging strategies for EVs. This means that EV owners can take advantage of off-peak periods when renewable energy generation is typically higher, leading to lower electricity costs and a reduced strain on the grid during peak demand. This can be achieved through smart charging systems and grid integration, ensuring the optimal utilization of renewable energy resources [28].
6. Environmental Synergies: Charging EVs with renewable energy sources presents environmental synergies. For instance, EVs can function as energy storage units, storing surplus renewable energy produced during peak production periods in their batteries. This stored energy can later be discharged back to the grid or utilized for other energy applications as required. This innovative approach, referred to as vehicle-to-grid (V2G) technology, aids in mitigating the intermittent nature of renewable energy sources and elevates the grid's overall stability and reliability [29].
7. Sustainable Mobility Solution: The integration of renewable energy sources with electric vehicles offers a sustainable mobility solution that diminishes reliance on fossil fuels and mitigates environmental effects. Embracing renewable energy for EV charging facilitates the realization of a sustainable transportation sector, fostering cleaner air, diminished greenhouse gas emissions, and enduring energy security [30].

It's crucial to recognize that the advantages of renewable energy sources in electric vehicles can vary based on factors like renewable resource availability, charging infrastructure integration, and EV technology efficiency. However, the fusion of renewable energy and electric vehicles holds significant promise in reshaping the transportation sector toward a sustainable, low-carbon future.

3 Electric Vehicle (EV) Charging Infrastructure

3.1 Overview of EV Charging Infrastructure

Electric vehicles (EVs) can be charged through various methods, depending on their location and specific requirements. This necessitates a range of EV charging infrastructure types, each designed for different applications.

The standards and specifications for EV chargers, known as electric vehicle supply equipment (EVSE), differ from country to country. These variations arise from differences in the EV models available in each region and the unique characteristics of local electricity grids.

Electric vehicle supply equipment (EVSE) is a critical component of EV charging infrastructure, as noted in [31]. It connects to the local electricity grid using a control system and a wired connection to safely charge EVs. The EVSE control system enables essential functions such as user authentication, charging authorization, network management, data recording and exchange, and ensuring data privacy and security. It is recommended to use EVSEs with basic control and management capabilities for all charging needs.

Conductive charging, also known as plug-in or wired charging, is the predominant technology for EV charging. The specific requirements for EVSE in conductive charging depend on factors such as vehicle type, battery capacity, charging methods, and power ratings. This section aims to explain the technical details of electric vehicle charging infrastructure, emphasizing the importance of considering the local context when planning and implementing EV charging networks.

3.2 Detailed Overview of EV Charging Infrastructure

3.2.1 Types of Charging Stations [32]

1. Level 1 Charging: This is the slowest charging method and typically uses a standard household outlet (120 V). Level 1 chargers are relatively inexpensive and convenient for overnight charging at home. They provide a charging rate of around 2–5 miles of range per hour.
2. Level 2 Charging: This charging method utilizes a 240 V power supply, offering faster charging than Level 1. Level 2 chargers, typically found in residential, commercial, and public locations, provide a charging rate of approximately 10–30 miles of range per hour.
3. DC Fast Charging (Level 3 Charging): DC fast chargers provide high-power charging, allowing for rapid charging of EVs. They use direct current (DC) instead of alternating current (AC) power and can deliver 60–80 miles of range

Table 1 Different types of charging stations

Type	Power supply	Charging rate	Typical locations
Level 1	120 V	2–5 miles per hour	Home, workplace
Level 2	240 V	10–30 miles per hour	Public, workplace
DC fast charging	480 V +	60–80 miles per hour	Highways, rest stops, urban areas

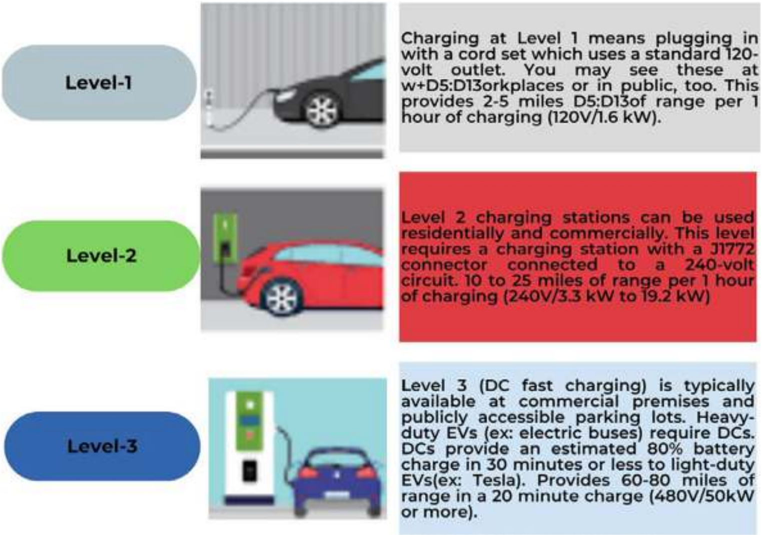

Fig. 2 Different types of chargers

in approximately 20 min of charging. DC fast chargers are typically installed along highways, at rest stops, and in urban areas to support long-distance travel and quick top-ups.

All the specifications of these various chargers are represented in Table 1. Graphically these chargers are shown in Fig. 2.

3.2.2 Charging Infrastructure Components

1. Charging Stations: These physical units supply electricity to charge electric vehicles. Charging stations vary in design and capabilities, from basic Level 1 chargers to advanced Level 3 DC fast chargers.
2. Charging Cables and Connectors: EVs are equipped with specific charging ports that require compatible cables and connectors to connect to the charging station. Different regions may have different standard connectors, such as the Type 1 (J1772) connector commonly used in North America or the Type 2 (Mennekes) connector used in Europe.

3. Network Connectivity: Many charging stations are connected to a central network, allowing for remote monitoring, control, and payment processing. This connectivity enables EV owners to locate available charging stations, monitor charging progress, and make payments using various methods, such as mobile apps or RFID cards.
4. Energy Management Systems: These systems help manage the energy flow and distribution within the charging infrastructure. They optimize charging schedules, balance the power load, and integrate with the electrical grid to maximize efficiency and reduce strain on the grid.

3.2.3 Charging Station Deployment

1. Residential Charging: Homeowners can install charging stations at their residences, allowing for convenient overnight charging. Home charging stations are typically Level 1 or Level 2 chargers and can be connected to the existing electrical infrastructure of the property.
2. Workplace Charging: Employers can provide charging infrastructure at workplaces to support employee EV charging needs. Workplace charging stations encourage EV adoption, particularly for employees who have limited access to charging options at home.
3. Public Charging: Public charging stations are installed in various locations such as parking lots, shopping centers, restaurants, and public areas. They provide accessible charging options for EV owners while they are away from home or work. Public charging stations can offer Level 2 chargers or DC fast chargers.
4. Fast-Charging Corridors: Fast-charging corridors are networks of charging stations strategically placed along highways or major travel routes. These corridors provide fast-charging options for long-distance travel, reducing range anxiety and enabling EV owners to undertake intercity journeys.

3.2.4 Charging Infrastructure Providers

Various companies and organizations are involved in the deployment and management of EV charging infrastructure. These include:

1. Charging Network Operators: These companies build and operate charging networks, providing access to a network of charging stations and related services. Examples include ChargePoint [33], EVgo [34], Electrify America [35], and Tesla Supercharger Network [36].
2. Utilities: Electric utilities often play a role in deploying charging infrastructure, leveraging their expertise in managing the electrical grid and ensuring reliable power supply to charging stations.
3. Government Entities: Governments at various levels, including local, regional, and national, can support the development of charging infrastructure through regulations, incentives, grants, and partnerships.

4. Private Businesses: Private businesses, such as retail establishments or parking operators, may install charging stations as a service to their customers or to attract EV owners to their premises.

The growth and advancement of EV charging infrastructure are crucial to support the transition to electric mobility. It requires collaboration among stakeholders, ongoing investment, technological innovation, and supportive policies to overcome challenges and provide a comprehensive and user-friendly charging network for EV owners.

3.3 Challenges and Limitations of Existing EV Charging Infrastructure

While EV charging infrastructure has made significant progress, there are still several challenges and limitations [37] that need to be addressed. Some of these include:

1. Limited Availability: In some regions, the availability of charging stations is limited, particularly in rural areas or regions with lower EV adoption rates. This can create range anxiety for EV owners and deter potential buyers from switching to electric vehicles.
2. Charging Speed and Time: Although DC fast chargers offer rapid charging, Level 1 and Level 2 chargers are relatively slower. Level 1 chargers, in particular, provide a low charging rate, which can be inconvenient for EV owners who rely on them for daily charging. Faster charging speeds and reduced charging times are desired to improve the overall user experience.
3. Infrastructure Scalability: As the population of EVs on the road steadily increases, there arises a necessity to proportionately expand the charging infrastructure. This entails substantial investment in augmenting the quantity of charging stations, enhancing the capacity of current stations, and upgrading electrical grids to accommodate the heightened demand.
4. Interoperability and Standardization: There are different charging connectors and communication protocols used by different charging station manufacturers and EV models. Lack of interoperability and standardization can make it challenging for EV owners to find compatible charging stations and may require multiple access cards or apps to use different networks. Universal standards and interoperability are crucial to providing seamless charging experiences.
5. Cost of Installation: Installing charging infrastructure can be expensive, especially for public fast chargers or high-capacity stations. Costs involve electrical upgrades, equipment installation, and site preparation. These high upfront costs can deter private businesses or public entities from investing in charging infrastructure.
6. Grid Constraints and Power Demand: Rapid charging of multiple EVs in a specific area can strain the local power grid. It requires careful planning to avoid overloading the electrical infrastructure and potential blackouts. Grid management

and optimization technologies are needed to balance power demand and prevent strain on the grid.

7. Equity and Access: Ensuring equitable access to charging infrastructure is crucial. Low-income communities and multi-unit dwellings may face challenges in accessing charging stations due to limited installation options or higher costs. Efforts should be made to ensure that charging infrastructure is accessible and affordable for all, regardless of socioeconomic status.
8. Long-Distance Travel Infrastructure: While there has been progress in deploying fast-charging stations along highways, some regions still lack sufficient charging infrastructure for long-distance travel. Expanding the charging network in remote areas and improving coverage along major travel routes is essential for facilitating long-distance EV travel.
9. Maintenance and Reliability: Charging stations require regular maintenance to ensure optimal performance and reliability. Issues such as faulty equipment, connectivity problems, or out-of-service stations can cause inconvenience for EV owners. Prompt maintenance and reliable charging station networks are critical to avoid downtime and provide a seamless charging experience.

Addressing these challenges and limitations will require collaboration among governments, charging infrastructure providers, utilities, and other stakeholders. Continued investment, technological advancements, and supportive policies are necessary to overcome these obstacles and create a robust and user-friendly EV charging infrastructure.

4 Integration of RES into EV Charging Infrastructure

Amidst urgent environmental concerns such as climate change, there's a rising acknowledgment of the imperative to mitigate our environmental footprint by embracing pioneering technologies. Securing a sustainable and eco-friendly energy blend is paramount not only for upholding energy security but also for safeguarding the well-being of our environment. The transportation sector plays a substantial role in emitting greenhouse gases, which are responsible for climate change. Hence, to enhance the competitiveness of electric vehicles compared to gasoline-powered vehicles, it is crucial to implement solutions that address concerns and improve the overall convenience of electric vehicles. Additionally, the source of electricity used to charge the vehicle's battery is another important factor to consider. Transitioning to renewable power sources, which are sustainable and not depleted when utilized, is the most effective approach to achieve this objective. These sources of energy do not generate emissions, resulting in a significant reduction in emissions by addressing both the transportation and electricity sectors. However, there are certain factors to consider when it comes to renewable energy. Renewable energy sources generate power intermittently since they rely on natural forces. Consequently, there is a possibility that the generated energy may not always meet the demands of consumers.

Therefore, it is imperative to seek alternative energy sources for vehicles in order to decrease our reliance on fossil fuels. Electric vehicles are often considered an ideal solution since they do not emit emissions directly and rely on electricity for power. The integration of RES into EV charging infrastructure is a complex issue, but it is one that is essential to the future of sustainable transportation. As the number of EVs on the road increases, the need for RES-powered EV charging stations will also increase. By addressing the challenges and developing solutions, we can ensure that the integration of RES into EV charging infrastructure is a success.

4.1 Benefits and Potential of RES Integration

Integrating renewable energy sources (RES) into EV charging infrastructure offers several benefits [38] and holds significant potential. Here are some key benefits and potential advantages of RES integration in EV charging:

1. Clean and Sustainable Charging: Integrating renewable energy sources (RES) ensures that the electricity used to charge electric vehicles is derived from renewable sources, such as solar or wind. This integration helps reduce carbon emissions from transportation, promoting cleaner and more sustainable mobility.
2. Environmental Synergy: EV charging infrastructure can be designed to complement RES generation. For example, solar carports or rooftop solar installations can provide shade and simultaneously generate electricity to power EV charging stations. This synergy maximizes the use of renewable energy and reduces strain on the grid.
3. Grid Stability and Load Management: The amalgamation of EV charging infrastructure with renewable energy source (RES) integration holds potential to stabilize the electrical grid. Through the utilization of intelligent charging systems, EVs can adapt their charging schedules in accordance with the availability of renewable energy. This capacity for load management facilitates the assimilation of intermittent renewable sources, smooths out demand peaks, and alleviates strain on the grid infrastructure.
4. Renewable Energy Storage Optimization: EVs can serve as portable energy storage units, adept at storing surplus renewable energy during periods of heightened generation. Subsequently, this stored energy can be discharged back into the grid or utilized for charging during periods of diminished renewable generation. Such time-shifting capabilities bolster the flexibility and dependability of RES integration.
5. Cost Savings: Integrating RES into EV charging infrastructure can lead to cost savings. When EVs are charged with renewable energy, owners can benefit from lower electricity costs, particularly during times of high renewable generation. Additionally, utilizing existing RES installations for EV charging optimizes the use of renewable energy assets and reduces the need for additional infrastructure investments.

6. Energy Independence: Integrating renewable energy sources (RES) with EV charging infrastructure fosters energy independence. By utilizing locally generated renewable energy, communities and regions can reduce their reliance on imported fossil fuels, thereby enhancing energy security and resilience.
7. Promoting Renewable Energy Adoption: EV charging infrastructure connected to RES generation can serve as a visible demonstration of the feasibility and benefits of renewable energy. This integration can increase public awareness and acceptance of renewables, leading to wider adoption of renewable energy technologies in other sectors as well.
8. Symbiotic Evolution of EVs and RES: The fusion of EV charging infrastructure and renewable energy sources (RES) engenders a symbiotic relationship. With the rise in EV adoption, there emerges a supplementary demand for renewable energy, thereby incentivizing investments in RES installations. Concurrently, the proliferation of renewable energy installations facilitates the expansion of EV charging infrastructure, furnishing clean energy for the burgeoning population of electric vehicles.
9. Green Branding and Corporate Social Responsibility: For businesses and organizations, integrating RES into EV charging infrastructure can enhance their green branding and demonstrate their commitment to sustainability and corporate social responsibility. It can attract environmentally conscious customers and stakeholders and align with their values.

The integration of renewable energy sources (RES) into EV charging infrastructure has significant potential to expedite the transition to a clean, sustainable, and low-carbon transportation system. This integration not only encourages the adoption of renewable energy but also establishes a virtuous cycle of sustainable mobility and the expansion of renewable energy.

Here are some specific examples of the benefits of RES integration:

In Denmark, the integration of wind power has helped to reduce greenhouse gas emissions by 40% [37]. In Germany, the integration of solar power has helped to reduce electricity prices by 20% [37]. In California, the integration of RES has helped to improve grid reliability by 50% [37]. These are just a few examples of the many benefits of RES integration. As the cost of RES continues to decline, it is expected that these benefits will become even more pronounced in the future.

4.2 Key Considerations for RES Integration (Grid Stability, Power Management, Etc.)

When integrating renewable energy sources (RES) into the energy system, there are several key considerations to ensure effective and reliable integration [39]:

1. Grid Stability: RES integration can impact grid stability due to the intermittent nature of renewable energy generation. Fluctuations in renewable energy supply must be managed to maintain a stable grid. This can be addressed through

advanced grid management techniques, energy storage systems, and demand response mechanisms.

2. Power Management and Balancing: Effective power management is crucial for RES integration. It involves balancing electricity supply and demand in real time to match fluctuations in renewable energy generation. Advanced forecasting, grid monitoring, and control systems are essential for efficient power management.
3. Grid Infrastructure and Interconnection: Upgrading and strengthening grid infrastructure is necessary to accommodate increased RES integration. Enhancing transmission and distribution networks, implementing smart grid technologies, and ensuring seamless interconnection between renewable energy sources and the grid are vital for efficient integration.
4. Energy Storage: Energy storage technologies play a significant role in RES integration by storing excess renewable energy for later use during periods of low generation. Battery storage systems, pumped hydrostorage, and other storage technologies help address intermittency and provide grid stability.
5. Flexibility and Demand Response: Incorporating flexibility and demand response measures allows the grid to adjust electricity consumption based on the availability of renewable energy. This includes incentivizing consumers to shift their electricity usage to align with periods of high renewable energy generation.
6. Grid Planning and System Flexibility: Effective grid planning is crucial to accommodate the integration of RES. Assessing grid capacity, identifying potential bottlenecks, and designing flexible grid architectures enable efficient RES integration while ensuring system reliability and stability.
7. Regulatory Structure and Market Framework: A conducive regulatory environment and well-designed market structures are imperative for the seamless integration of renewable energy sources (RES). Transparent policies, incentivization measures, and market mechanisms foster investment in renewable energy ventures and streamline their assimilation into the energy marketplace.
8. Grid Resilience and Backup Systems: Maintaining grid resilience is critical to handle unforeseen events or renewable energy supply disruptions. Backup systems, such as conventional power plants or energy storage, can provide a backup power supply during periods of low renewable energy availability.
9. Grid Monitoring and Control Systems: Advanced grid monitoring and control systems enable real-time monitoring of grid conditions, renewable energy generation, and electricity demand. This information helps optimize RES integration and ensures grid stability.
10. Cybersecurity and Data Management: As the energy system becomes more digitalized, ensuring robust cybersecurity measures and effective data management practices are essential to protect critical infrastructure, maintain data privacy, and prevent potential disruptions.

By addressing these factors in RES integration, grid stability, efficient power management, and reliable energy supply are ensured, thereby supporting the seamless integration of renewable energy sources into the energy system.

4.3 Advantages and Challenges of Local Versus Centralized Renewable Energy Production for EV Charging

4.3.1 Local Renewable Energy Production

The advantages associated with local renewable energy production are as follows:

1. Energy Autonomy: Implementation of solar panels at residential or commercial sites empowers energy autonomy, enabling EV owners to locally generate their electricity. This diminishes dependence on centralized grid infrastructure and mitigates the repercussions of grid outages or disturbances.
2. Financial Efficiency: In the long run, allocating resources to rooftop solar panels can yield substantial financial gains on electricity expenditures, particularly with the ongoing decline in solar technology costs. EV owners can capitalize on diminished charging expenses through the utilization of self-produced solar energy.
3. Reduced Grid Congestion: Local renewable energy production, through on-site electricity generation, lessens the burden on centralized grid infrastructure, particularly during peak demand periods. This can mitigate grid congestion and enhance overall grid reliability.
4. Environmental Benefits: Generating electricity from rooftop solar panels reduces carbon emissions associated with electricity generation, contributing to climate change mitigation efforts. It also helps reduce air and water pollution compared to fossil fuel-based electricity generation.

The challenges associated with local renewable energy production are as follows:

1. Initial Investment: The upfront capital outlay necessary for the installation of solar panels and related equipment may pose a barrier for numerous homeowners and businesses, constraining the broad adoption of decentralized renewable energy generation.
2. Space Limitations: Rooftop solar installations require adequate space and favorable orientation to maximize energy generation. For densely populated urban areas or buildings with limited roof space, installing sufficient solar capacity may be challenging.
3. Intermittency and Storage Challenges: Solar energy generation is subject to intermittency and influenced by weather patterns, resulting in fluctuations in electricity output. In the absence of efficient energy storage solutions, EV owners might still necessitate grid electricity during instances of limited solar generation.
4. Maintenance and Performance Monitoring: Solar panels require regular maintenance to maintain optimal performance and durability. This includes tasks such as cleaning, inspections, and potential repairs, which may increase the overall cost and complexity of decentralized renewable energy systems.

4.3.2 Centralized Renewable Energy Production

The pros of centralized renewable energy production are as follows:

1. Economies of Scale: Large-scale solar farms benefit from economies of scale, allowing for more efficient energy production and lower per-unit costs compared to distributed rooftop solar installations.
2. Land Use Efficiency: Solar farms can be situated in locations with abundant sunlight and available land, maximizing energy generation potential without competing for space with urban development or other land uses.
3. Grid Integration: Centralized renewable energy facilities can be strategically located near existing grid infrastructure, facilitating easier integration into the electricity grid and minimizing transmission losses.
4. Professional Maintenance and Operations: Solar farms are typically managed by professional operators who handle maintenance, performance monitoring, and repairs, ensuring optimal system performance and reliability.

The challenges associated with centralized renewable energy production are as follows:

1. Transmission and Distribution Infrastructure: Delivering electricity from centralized renewable energy facilities to EV charging stations may require significant investments in transmission and distribution infrastructure, particularly in remote or underserved areas.
2. Use and Environmental Concerns: Large-scale solar farms may encounter opposition due to concerns about land use, habitat disruption, and visual impact, especially in ecologically sensitive or densely populated regions.
3. Permitting and Regulatory Hurdles: Developing centralized renewable energy projects often involves navigating complex permitting processes, regulatory requirements, and community engagement, which can delay project timelines and increase costs.
4. Vulnerability to Disruptions: Centralized renewable energy facilities are vulnerable to disruptions caused by extreme weather events, natural disasters, or technical failures, which can affect electricity generation and supply reliability.

In conclusion, both local and centralized renewable energy production have their advantages and challenges when it comes to powering EV charging infrastructure. The optimal approach depends on various factors, including site characteristics, economic considerations, regulatory frameworks, and stakeholder preferences. A balanced strategy that leverages the strengths of both approaches may offer the most effective and resilient solution for transitioning to a sustainable energy future.

4.4 Technological Advancements in RES-EV Charging Integration

Technological advancements have played a crucial role in advancing the integration of renewable energy sources (RES) with electric vehicle (EV) charging infrastructure [40]. Here are some key technological advancements in RES-EV charging integration:

1. Smart Charging and Vehicle-to-Grid (V2G) Integration: Smart charging systems facilitate coordinated EV charging and RES generation, optimizing charging based on renewable energy availability, grid demand, and electricity tariffs. V2G technology facilitates bidirectional power transfer between EVs and the grid, enabling EVs to provide electricity during peak demand or bolster grid stability.
2. Advanced Energy Management Systems: Energy management systems integrate RES generation, energy storage, and EV charging to optimize energy flow. Using advanced algorithms and real-time data, these systems balance energy supply and demand, ensure grid stability, and maximize renewable energy utilization.
3. Vehicle-to-Home (V2H) and Vehicle-to-Building (V2B) Integration: V2H and V2B systems leverage EVs as portable energy storage, enabling homeowners to power their homes or buildings during outages or peak demand periods. This integration enhances grid resilience and promotes energy self-sufficiency.
4. Bidirectional Charging and Vehicle-to-Load (V2L) Integration: Bidirectional charging allows EVs to discharge power back to the grid or other electrical loads, serving as a decentralized energy resource for homes, businesses, or specific loads.
5. Vehicle-to-Grid Aggregators: These platforms aggregate the charging and discharging capabilities of multiple EVs, enabling grid operators to access distributed energy resources to support grid stability and integrate renewable energy.
6. Dynamic Demand Response: Dynamic demand response systems adjust EV charging patterns in real time based on grid conditions and renewable energy availability, optimizing energy consumption, reducing peak demand, and enhancing grid stability.
7. Advanced Metering and Monitoring: Real-time visibility into EV charging, RES generation, and grid conditions enables better grid management, load forecasting, and optimization of RES-EV charging integration.
8. Wireless and Inductive Charging Technologies: Wireless charging, such as inductive charging, offers convenient EV charging without physical cable connections, facilitating seamless integration with RES installations.
9. Blockchain and Decentralized Energy Management: Blockchain technology enables secure and transparent peer-to-peer transactions, allowing EV owners to trade electricity directly with RES producers or other consumers, promoting energy sharing and grid resilience.

10. Artificial Intelligence and Machine Learning: Artificial intelligence (AI) and machine learning (ML) algorithms are instrumental in analyzing EV charging patterns, renewable energy source (RES) generation, and grid conditions. By leveraging these technologies, energy flows are optimized, load balancing is achieved, and demand response mechanisms are enhanced, ultimately improving the efficiency of integrating RES with EV charging.

These technological advancements are driving the evolution of RES-EV charging integration, enabling a more sustainable, efficient, and flexible energy ecosystem. They facilitate the transition to clean transportation and renewable energy systems, ultimately contributing to a low-carbon future. Here are some specific examples of technological advancements in RES-EV charging integration:

1. The University of Delaware has developed a smart charging system that uses artificial intelligence to optimize the charging of EVs based on the availability of RES [41].
2. Enel X has devised a Vehicle-to-Grid (V2G) system enabling electric vehicles (EVs) to feed surplus electricity back into the grid during periods of peak demand [42].
3. The company Tesla has developed a battery storage system that can be used to store RES energy and then discharge it to power EVs [36].
4. The company Sunverge has developed a microgrid system that can be powered by RES [43].

These are just a few examples of the many technological advancements that are being made in the field of RES-EV charging integration. As these technologies mature, they will make it easier and more efficient to charge EVs with RES. This will help to reduce greenhouse gas emissions, improve grid reliability, and create a more sustainable transportation system.

4.5 Key Parameters Involved

4.5.1 Consumer Adoption

1. Perceived Benefits: Understanding consumers' perceptions of the benefits of RES-integrated EV charging infrastructure is crucial. Highlighting advantages such as cost savings, environmental benefits, and energy independence can encourage adoption.
2. Barriers to Adoption: Identifying and addressing barriers to consumer adoption is essential. Factors such as upfront costs, limited awareness, concerns about reliability, and lack of incentives can hinder adoption and need to be mitigated through targeted interventions.
3. Education and Outreach: Implementing educational campaigns to inform consumers about the benefits of RES-integrated EV charging infrastructure can

increase awareness and drive adoption. Providing clear and accessible information about installation, operation, and maintenance can help build trust and confidence among consumers.
4. Financial Incentives and Rebates: Providing monetary incentives like subsidies, tax credits, or rebates can enhance the affordability and appeal of RES-integrated EV charging infrastructure for consumers. These incentives serve to mitigate initial expenses and expedite the adoption of such systems.

4.5.2 Policy Frameworks

1. Regulatory Support: Establishing supportive regulatory frameworks is critical for promoting the integration of RES into EV charging infrastructure. This includes streamlining permitting processes, setting technical standards, and ensuring grid compatibility.
2. Incentive Mechanisms: Implementing policies such as feed-in tariffs, net metering, and renewable energy mandates can incentivize investment in RES and encourage their integration into EV charging infrastructure.
3. Research and Development Funding: Allocating funding for research and development initiatives can spur innovation in RES technologies and drive down costs, making them more competitive with conventional energy sources.
4. Collaborative Governance: Engaging stakeholders from government, industry, academia, and civil society in policy development processes can ensure that policies are well-informed, balanced, and effectively implemented.

4.5.3 Environmental Impact Assessment

1. Life Cycle Analysis: Conducting comprehensive life cycle assessments (LCAs) of RES-integrated EV charging infrastructure is essential for understanding their environmental impact across the entire lifecycle, from production to disposal.
2. Emissions Reduction Potential: Assessing the potential emissions reductions associated with RES integration can quantify the environmental benefits and inform decision-making processes.
3. Resource Use and Land Use: Evaluating resource use, land use requirements, and ecosystem impacts of RES technologies can identify potential trade-offs and inform sustainable siting and deployment strategies.
4. Mitigation Strategies: Developing mitigation strategies to address environmental concerns, such as habitat conservation, water management, and waste recycling, can minimize negative impacts and enhance the sustainability of RES-integrated EV charging infrastructure.

4.5.4 Public Awareness and Education

1. Information Dissemination: Utilizing various communication channels, including media campaigns, workshops, and educational materials, to disseminate information about RES-integrated EV charging infrastructure to the public can raise awareness and foster understanding.
2. Stakeholder Engagement: Engaging stakeholders, including communities, businesses, NGOs, and policymakers, in dialogue and decision-making processes can build support and consensus around RES integration initiatives.
3. Training and Capacity Building: Providing training programs and capacity-building initiatives to equip stakeholders with the knowledge and skills needed to participate in RES integration efforts can enhance implementation effectiveness and sustainability.
4. Demonstration Projects: Showcasing successful RES-integrated EV charging infrastructure projects through demonstration sites and case studies can provide tangible examples and inspire replication in other contexts.

4.6 Challenges Faced in Integrating Solar Power with EV Charging Infrastructure, Particularly in the Context of Grid Management and Energy Storage Solutions

4.6.1 Grid Management Challenges

1. Intermittency and Variability: Solar power generation is inherently intermittent and variable due to factors such as weather conditions and time of day. Matching the timing of solar generation with EV charging demand can be challenging, requiring sophisticated grid management strategies.
2. Grid Stability and Reliability: Integrating large amounts of variable solar generation into the grid can affect grid stability and reliability, particularly during periods of high solar penetration or rapid fluctuations in generation. Grid operators must ensure adequate reserve capacity and ancillary services to maintain system stability.
3. Voltage and Frequency Regulation: Fluctuations in solar generation can impact voltage and frequency levels on the grid, requiring active regulation to maintain within acceptable limits. Grid management tools such as voltage regulators and frequency control mechanisms are essential for maintaining grid stability.
4. Congestion Management: Solar power generation may be concentrated in specific geographic areas or times of day, leading to congestion on transmission and distribution networks. Grid management strategies such as demand response, grid modernization, and flexible charging schedules can help alleviate congestion and optimize grid operations.

4.6.2 Energy Storage Solutions

1. Solar Power Integration: Energy storage solutions such as batteries can help smooth out fluctuations in solar power generation and provide dispatchable energy when needed. By storing excess solar energy during periods of high generation and discharging it during times of low generation or high demand, energy storage systems can enhance the reliability and flexibility of solar-integrated EV charging infrastructure.
2. Cost and Scalability: Despite significant cost reductions in recent years, energy storage technologies such as lithium-ion batteries still face challenges related to cost and scalability. Lowering the cost of storage systems through technological advancements, economies of scale, and supportive policies is essential for widespread deployment.
3. Technical Performance and Durability: Energy storage systems must meet rigorous performance and durability requirements to ensure reliable operation over their lifespan. Factors such as cycle life, degradation rates, safety, and efficiency are critical considerations for evaluating storage technology options.
4. Integration with Charging Infrastructure: Integrating energy storage systems with EV charging infrastructure requires careful planning and coordination to optimize system performance and maximize benefits. This includes selecting appropriate storage capacity, configuring charging profiles, and implementing smart charging algorithms.
5. Regulatory and Policy Barriers: Regulatory and policy barriers, such as permitting requirements, grid interconnection standards, and market structures, can hinder the deployment of energy storage solutions. Streamlining regulatory processes and providing incentives for energy storage deployment can accelerate adoption and integration with solar-powered EV charging infrastructure.

Addressing these challenges necessitates a collaborative effort involving policymakers, grid operators, utilities, technology developers, and various stakeholders. Through the implementation of advanced grid management strategies and the deployment of cost-effective energy storage solutions, the integration of solar power with EV charging infrastructure can play a pivotal role in fostering a more sustainable and resilient energy system.

4.7 Economic Analysis

Some information on the economic analysis, focusing on the cost of setup, maintenance, and potential government incentives or subsidies are as follows:

1. Setup Costs: The setup costs for integrating solar power with EV charging infrastructure include the purchase and installation of solar panels, inverters, charging stations, and associated equipment. These costs can vary depending on factors such as system size, location, equipment specifications, and installation

complexity. On average, the setup costs for a residential solar PV system with EV charging capabilities range from several thousand to tens of thousands of dollars, depending on the size of the solar array and the charging infrastructure requirements.

2. Maintenance Costs: Maintenance costs for solar power and EV charging infrastructure typically include periodic inspections, cleaning, equipment servicing, and potential repairs. Solar panels generally require minimal maintenance, with estimated costs ranging from 0.5 to 1% of the initial setup costs annually. EV charging stations may require more frequent maintenance, including software updates, equipment calibration, and hardware replacements. Maintenance costs for EV charging infrastructure can vary widely depending on usage patterns, equipment reliability, and warranty coverage.
3. Government Incentives and Subsidies: Many governments offer incentives and subsidies to promote the adoption of solar power and EV charging infrastructure. These incentives can include:
   (a) Tax Credits: Tax credits for residential and commercial solar installations can offset a percentage of setup costs, reducing the upfront investment for consumers and businesses.
   (b) Rebates and Grants: Rebate programs and grant funding provided by governments or utilities can further reduce the cost of solar PV systems and EV charging infrastructure, making them more financially accessible.
   (c) Feed-in Tariffs (FiTs): FiTs guarantee payments for solar electricity generated by residential or commercial systems, providing a steady income stream and improving the economic viability of solar installations.
   (d) Low-Interest Loans: Government-sponsored low-interest loan programs can help finance solar and EV charging projects, offering favorable terms and repayment options to borrowers.
   (e) Net Metering: Net metering policies allow solar PV system owners to offset their electricity bills by exporting excess energy to the grid, effectively reducing the payback period for their investment.
   (f) Return on Investment (ROI): The economic viability of solar-integrated EV charging infrastructure depends on various factors, including setup costs, maintenance expenses, electricity prices, solar resource availability, and incentive programs. Calculating the return on investment (ROI) for solar PV systems with EV charging capabilities involves comparing the upfront costs and ongoing expenses with the anticipated savings in electricity bills, potential revenue from energy sales, and any financial incentives or subsidies received. In many cases, solar-integrated EV charging infrastructure can offer favorable returns on investment, particularly in regions with high electricity prices, abundant sunlight, and supportive policy frameworks.

By considering the setup costs, maintenance expenses, and potential government incentives or subsidies, stakeholders can better evaluate the economic feasibility and attractiveness of integrating solar power with EV charging infrastructure. Government policies and incentives play a crucial role in incentivizing investment and accelerating the adoption of sustainable energy solutions, ultimately contributing to the transition toward a low-carbon transportation system.

4.8 Case Studies and Successful Implementations of RES-EV Charging Systems

There have been several successful implementations and case studies of renewable energy sources (RES) integrated with electric vehicle (EV) charging systems. Here are a few notable examples:

1. Amsterdam's Vehicle-to-Grid (V2G) Project: In Amsterdam, the V2G project was initiated to investigate the capabilities of bidirectional charging. The project entailed installing V2G chargers, allowing electric vehicles (EVs) to feed energy back into the grid during periods of peak demand [44]. The system effectively showcased its capacity to stabilize the grid, diminish peak load, and enhance the incorporation of renewable energy sources.
2. Smart Solar Charging Initiative in the Netherlands: The Smart Solar Charging initiative in the Netherlands integrated solar panels, battery storage, and EV charging infrastructure [45]. Through optimizing solar energy generation and EV charging schedules, the initiative sought to optimize the utilization of solar energy for EV charging. It demonstrated how RES-EV charging systems can efficiently manage energy supply and demand, alleviate grid strain, and enhance the self-consumption of solar energy.
3. Nissan's Vehicle-to-Home (V2H) System in Japan: Nissan implemented a V2H system in Japan that allows Nissan Leaf EVs to supply electricity to homes during power outages or as a backup power source [46]. The system enables EV owners to use their vehicles as mobile energy storage and provide power to the home, reducing reliance on the grid and supporting grid stability during emergencies.
4. E.ON Drive Solar Project in Germany: E.ON, a German energy company, launched the Drive Solar project, combining solar energy with EV charging infrastructure [47]. The project integrated solar panels on carports and utilized the generated solar energy for charging EVs. The system demonstrated the feasibility of using renewable energy for EV charging and highlighted the potential for reducing carbon emissions.
5. Smart Grid Gotland Project in Sweden: The Smart Grid Gotland project aimed to create a fully integrated smart grid ecosystem on the Swedish island of Gotland [48]. The project integrated RES, energy storage, and EV charging infrastructure to optimize energy utilization and enhance grid stability. It showcased how a comprehensive RES-EV charging system can effectively manage renewable energy and support a sustainable energy transition.

6. San Diego's Smart City Initiative, California, USA: San Diego implemented a comprehensive smart city initiative that included the integration of RES and EV charging infrastructure. The project involved the installation of solar panels, battery storage systems, and EV charging stations [49]. It demonstrated the successful integration of renewable energy with EV charging, reducing greenhouse gas emissions and promoting sustainable transportation.
7. IONITY High-Power Charging Network, Europe: IONITY, a joint venture by major automakers, established a high-power charging network across Europe, powered by renewable energy sources [50]. The network enables fast charging of EVs along major highways, facilitating long-distance travel and reducing range anxiety. The integration of RES ensures that the charging network operates with clean energy and contributes to decarbonizing the transportation sector.
8. Electric Nation Vehicle-to-Grid Project, United Kingdom: The Electric Nation Vehicle-to-Grid project in the UK aimed to assess the feasibility of V2G technology at scale [51]. The project involved the installation of V2G chargers in residential homes, allowing EVs to export excess energy back to the grid. It successfully demonstrated the potential for EVs to support grid stability, manage peak demand, and increase the utilization of renewable energy.
9. Enel X JuiceNet Project, United States: Enel X, an energy services company, implemented the JuiceNet project in the United States, integrating smart charging technology with renewable energy sources [52]. The project used intelligent charging algorithms to optimize EV charging based on renewable energy availability and grid conditions. It showcased the ability to maximize the use of renewable energy for EV charging and promote grid-friendly charging practices.
10. Smart Grid Integration Lab, Singapore: Singapore's Smart Grid Integration Lab (SGIL) focuses on research and development of advanced energy systems [53]. One of their projects involves the integration of solar energy, energy storage, and EV charging infrastructure to create a sustainable and efficient energy ecosystem. The project showcases how RES-EV charging integration can contribute to grid stability, demand response, and increased renewable energy utilization.

These case studies demonstrate the successful implementation of RES-EV charging systems in various regions, showcasing their positive impacts on carbon reduction, grid stability, and sustainable transportation. They provide valuable insights into the potential and benefits of integrating renewable energy sources with EV charging infrastructure.

4.9 Comparative Analysis of Global Best Practices in Integrating RES and EV Charging

Here's a brief discussion on this topic:

4.9.1 Policy and Regulatory Frameworks:

1. Norway: Norway emerges as a global frontrunner in electric vehicle (EV) adoption, driven by robust policy incentives such as tax exemptions, toll discounts, and complimentary parking for EVs. Furthermore, the nation advocates for renewable energy integration by implementing feed-in tariffs and net metering policies, thereby facilitating the widespread deployment of renewable energy source (RES)-integrated EV charging infrastructure.
2. California, USA: California's zero-emission vehicle (ZEV) mandate and Low Carbon Fuel Standard (LCFS) incentivize EV adoption and renewable energy integration. The state also has ambitious renewable energy targets and supportive grid integration policies, driving investment in RES-integrated EV charging solutions.
3. Germany: Germany's Energiewende (energy transition) initiative advocates for the integration of renewable energy and EV charging infrastructure via public–private partnerships. Collaborative endeavors involving utilities, automakers, and technology providers have spearheaded pioneering solutions like smart charging networks and vehicle-to-grid (V2G) systems.
4. Netherlands: The Netherlands has established public–private partnerships to deploy RES-integrated EV charging infrastructure at scale. Initiatives such as the Amsterdam Electric Project and the Dutch National Charging Infrastructure Plan focus on coordinated planning, funding, and implementation of EV charging infrastructure powered by renewable energy sources.
5. Denmark: Denmark has pioneered the use of wind power for EV charging through projects such as the Parker Project and the Danish Electric Mobility Program. Innovative solutions such as wind-powered charging stations and dynamic grid management systems demonstrate the potential for integrating RES and EV charging infrastructure in a sustainable manner.
6. Japan: Japan has invested in advanced technology solutions for RES-integrated EV charging, including bidirectional chargers, vehicle-to-home (V2H) systems, and smart grid integration. These innovations enable efficient energy management, grid balancing, and demand response, enhancing the reliability and resilience of renewable energy-powered EV charging networks.

4.9.2 Community Engagement

1. Scotland: Scotland's Community and Renewable Energy Scheme (CARES) supports community-led renewable energy projects, including RES-integrated

EV charging infrastructure. Community-owned solar and wind projects with EV charging facilities promote local energy resilience, economic development, and community engagement.
2. New Zealand: New Zealand's Electric Vehicle Showcase program encourages community participation in EV adoption and renewable energy integration. Community-based initiatives such as EV enthusiast groups, neighborhood EV charging cooperatives, and renewable energy cooperatives play a vital role in raising awareness and driving deployment.

4.9.3 Key Takeaways

1. Collaborative Governance: Successful integration of RES and EV charging infrastructure often requires collaboration between government agencies, utilities, private sector stakeholders, and community organizations.
2. Policy Alignment: Aligning policies and incentives to promote EV adoption, renewable energy deployment, and grid integration is essential for creating an enabling environment.
3. Technology Innovation: Investing in technology innovation and research to develop advanced solutions for RES-integrated EV charging can drive efficiency, reliability, and scalability.
4. Community Engagement: Engaging communities in the planning, implementation, and ownership of RES-integrated EV charging infrastructure projects fosters local support and enhances project sustainability.

By analyzing global best practices, policymakers and stakeholders can identify successful strategies, lessons learned, and emerging trends in integrating RES and EV charging infrastructure, ultimately informing decision-making and accelerating the transition to a sustainable and low-carbon transportation system.

5 Challenges and Opportunities

5.1 Technical Challenges and Solutions

While the integration of renewable energy sources (RES) into electric vehicle (EV) charging infrastructure offers numerous benefits, it also presents several technical challenges and solutions. Here are some of the key challenges and possible solutions associated with this integration:

1. Grid Integration and Stability: The intermittency and variability of renewable energy sources like solar and wind necessitate meticulous management when integrating them into EV charging infrastructure to maintain grid stability. Achieving a balance between electricity supply and demand, particularly

during peak charging times, demands sophisticated control systems and energy management methodologies [54].

2. Charging Infrastructure Planning and Sizing: Matching the capacity of the EV charging infrastructure with the intermittent nature of renewable energy sources can be a challenge. Proper planning and sizing of charging stations and related infrastructure are essential to avoid overloading the grid during periods of high demand or underutilization during periods of low generation [55].
3. Energy Storage and Demand-Side Management: Energy storage systems play a pivotal role in mitigating the variability of renewable energy generation and stabilizing fluctuations in electricity supply. By integrating energy storage solutions into EV charging infrastructure, surplus renewable energy generated during peak periods can be stored and subsequently discharged during times of heightened charging demand. Additionally, effective demand-side management strategies are essential for maximizing the utilization of renewable energy for EV charging [56].
4. Smart Charging and Vehicle-to-Grid (V2G) Integration: Smart charging technologies and V2G systems facilitate enhanced coordination between EV charging and renewable energy generation. Utilizing smart charging algorithms, charging schedules can be optimized based on factors such as renewable energy availability, grid limitations, and user preferences. V2G technology enables EVs to release stored energy back into the grid during periods of peak demand, thereby bolstering grid stability and maximizing the utilization of renewable energy [57].
5. Interoperability and Standardization: Ensuring compatibility and standardization across diverse EV charging infrastructure providers and renewable energy systems is vital for streamlined integration. Employing shared communication protocols, data exchange formats, and interoperable hardware and software solutions facilitates efficient coordination and harmonization between renewable energy generation and EV charging infrastructure [58].
6. Grid Infrastructure Upgrades: Incorporating extensive renewable energy generation and EV charging infrastructure may necessitate enhancements to the current grid infrastructure. This entails bolstering transmission and distribution networks to accommodate augmented capacity, integrating power quality and stability measures, and deploying advanced monitoring and control systems [59].
7. Cybersecurity and Data Management: The integration of renewable energy sources and EV charging infrastructure introduces new cyber-security risks and data management challenges. Protecting charging infrastructure and ensuring secure communication between renewable energy systems, charging stations, and the grid are crucial to maintain the integrity and reliability of the overall system [60].

5.2 Economic Considerations and Cost-Effectiveness

1. The integration of renewable energy and electric vehicles (EVs) involves various economic considerations and cost-effectiveness factors. Here are some key points to consider:
2. Initial Investment Costs: The initial investment outlay for renewable energy infrastructure, like solar panels or wind turbines, and EV charging infrastructure can be significant. Nonetheless, these expenses have been diminishing over time owing to technological progress, economies of scale, and supportive governmental policies. Although the upfront expenditure may surpass that of traditional fossil fuel-based systems, the long-term operational and maintenance costs are frequently lower for renewables and EVs [61].
3. Cost of Energy Generation: Renewable energy sources have lower or zero fuel costs compared to fossil fuels, which can lead to cost savings in the long run. Once renewable energy systems are installed, the cost of energy generation becomes more predictable and stable, as it is less affected by fluctuating fuel prices. This can provide economic benefits by reducing the vulnerability to fuel price volatility and improving energy cost predictability for consumers and businesses [62].
4. Operational and Maintenance Costs: Renewables and electric vehicles generally have lower operational and maintenance costs compared to their fossil fuel counterparts. For renewable energy systems, the main costs are associated with periodic maintenance and repairs, which are generally lower than the ongoing fuel costs of conventional power plants. Similarly, electric vehicles have fewer moving parts and require less frequent maintenance compared to internal combustion engine vehicles, resulting in potential cost savings over the vehicle's lifetime [63].
5. Grid Integration and Infrastructure Costs: The integration of renewable energy into the existing power grid and the establishment of EV charging infrastructure require additional investments. Upgrading and expanding the grid to accommodate renewable energy sources and managing the increased electricity demand from EVs may incur costs. However, these investments can enhance grid resilience, reduce transmission and distribution losses, and support the growth of a clean and sustainable energy system [64].
6. Government Incentives and Policies: Government incentives, subsidies, and policies can play a crucial role in making the integration of renewables and electric vehicles more cost-effective. Supportive policies, such as feed-in tariffs, tax incentives, grants, and rebates, can help offset the initial investment costs and incentivize adoption. These measures can reduce the payback period and improve the cost-effectiveness of renewable energy and EV technologies [65].
7. Life Cycle Cost Analysis: A comprehensive life cycle cost analysis takes into account the entire lifespan of renewable energy systems and electric vehicles, including installation, operation, maintenance, and decommissioning costs. Such analysis can provide a more accurate assessment of the economic viability and cost-effectiveness of these technologies. It is important to consider factors such

as the projected lifespan of the equipment, energy production or consumption patterns, and potential future cost reductions in making cost-effective decisions.

8. Externalities and Social Benefits: The amalgamation of renewables and electric vehicles presents social advantages that are often overlooked in conventional economic assessments. Diminished air pollution, enhanced public health, job generation, energy self-sufficiency, and climate change mitigation are significant societal benefits linked with these technologies. Although these benefits may not yield immediate cost reductions, they substantially contribute to overall welfare, environmental sustainability, and enduring economic robustness [66].

5.3 Policy and Regulatory Frameworks for RES-EV Integration

To seamlessly and effectively integrate renewable energy sources (RES) and electric vehicles (EVs) into the current energy system, it is imperative to establish suitable policy and regulatory frameworks [67]. Here are some key considerations for policy and regulatory frameworks for RES-EV integration:

1. Renewable Energy Targets: Establish ambitious objectives for renewable energy deployment to incentivize the integration of RES and offer incentives for their grid integration. These targets may manifest as a defined percentage of the overall energy portfolio or as sector-specific goals, such as in transportation.
2. Feed-in Tariffs and Power Purchase Agreements (PPAs): Establish feed-in tariffs or implement PPAs to provide a guaranteed and attractive price for renewable energy generation. This encourages RES project development and ensures a stable revenue stream, making integration with EV charging infrastructure more economically viable.
3. Grid Access and Connection Standards: Develop grid access and connection standards that facilitate the integration of RES and EV charging infrastructure. These standards should ensure non-discriminatory access to the grid, specify technical requirements for connection, and streamline the approval process to minimize barriers for RES-EV projects.
4. Demand Response and Smart Charging: Implement policies that promote demand response programs and smart charging solutions. These mechanisms facilitate the synchronization of EV charging with RES generation patterns, enhancing the integration of intermittent renewable energy sources and optimizing resource utilization.
5. Incentives and Rebates: Offer financial incentives, tax credits, or rebates for the purchase of electric vehicles and installation of renewable energy generation systems. These incentives can accelerate the adoption of EVs and RES technologies, driving their integration in the energy system.
6. Regulatory Framework for Vehicle-to-Grid (V2G): Establish regulations and standards governing V2G systems, which facilitate bidirectional energy flow

between EVs and the grid. V2G systems empower EVs to function as mobile energy storage units, offering grid flexibility and aiding RES integration by storing surplus energy and reintroducing it into the grid as required.

7. Interoperability and Data Standards: Establish interoperability and data standards for EV charging infrastructure and renewable energy systems. Common standards enable seamless communication and data exchange between different components of the energy system, promoting efficient integration and interoperability.
8. Collaborative Stakeholder Engagement: Foster collaboration among key stakeholders, including policymakers, regulators, utilities, EV manufacturers, RES developers, and consumer representatives. Engaging all relevant parties ensures that policy and regulatory frameworks are informed by diverse perspectives and address the needs and concerns of different stakeholders.
9. Research and Development Support: Allocate funding for research and development initiatives focused on RES-EV integration. This support can drive innovation, technological advancements, and cost reductions, further facilitating the integration of renewable energy and electric vehicles.
10. Monitoring, Evaluation, and Adaptive Policy: Establish mechanisms to monitor and evaluate the effectiveness of policy and regulatory frameworks for RES-EV integration. Regular assessments can identify areas for improvement and allow for adaptive policy-making to address emerging challenges and opportunities.

These policy and regulatory frameworks serve as the cornerstone for incorporating renewable energy sources and electric vehicles into the energy system. Nevertheless, it's crucial to recognize that the precise approaches may differ based on the local context, energy composition, and policy objectives of individual jurisdictions.

5.3.1 Central Technical Regulations and Guidelines in India

In India, the market for electricity is heavily controlled, with both federal and state laws in place. Power connections available for EV charging are subject to a series of laws and rules, some of which are general and some of which were made especially for charging stations.

The CEA [68] has announced changes to the law that will make it easier for charging infrastructure to connect to the grid. The regulatory provisions concerning EV charging are outlined as follows:

1. Amendments to the Technical Standards for Connectivity of Distributed Generation Resources Regulations, 2019.
2. Amendments to Regulations Regarding Safety Measures and Electric Supply, 2019.

5.4 Current Status of EV Integration in Rich State of India

India has been making significant efforts to promote EV adoption and integration into its transportation system. While EV adoption is a nationwide endeavor, some states have been particularly active in promoting and implementing EV-friendly policies and infrastructure [69]. Among the richer states in India, Maharashtra, Karnataka, and Delhi have been leading in terms of EV integration. Here's a brief overview:

1. Maharashtra: Maharashtra has been actively promoting EVs and has set up charging infrastructure across major cities like Mumbai, Pune, and Nagpur. The state offers incentives such as exemptions from road tax and registration fees for EV owners. Additionally, the Maharashtra State Electricity Distribution Company Limited (MSEDCL) has been working on setting up EV charging stations and promoting EV adoption.
2. Karnataka: Karnataka has been at the forefront of EV integration in India. The state government has implemented various initiatives, including tax exemptions, subsidized electricity rates for charging, and setting up EV charging infrastructure in Bengaluru and other cities. Additionally, the Bangalore Electricity Supply Company (BESCOM) has been actively involved in promoting EV charging infrastructure and encouraging EV adoption.
3. Delhi: The national capital, Delhi, has been taking steps to encourage EV adoption and integration. The Delhi government offers financial incentives and subsidies for the purchase of electric vehicles and has implemented the Delhi EV Policy. The policy aims to accelerate EV adoption by providing incentives for electric two-wheelers, three-wheelers, and four-wheelers. Delhi also plans to establish a network of EV charging stations across the city.

Since India's EV ecosystem is still in its infancy, different DISCOMs have different levels of preparedness for EV accommodations. While some states, including Delhi, West Bengal, Karnataka, Maharashtra, Kerala, and Telangana, have made significant advancements in the construction of the infrastructure for EV charging, the corresponding state electricity distribution companies have taken a variety of steps to manage the resulting increase in demand in their distribution networks. However, there is currently very little EV penetration in the majority of the states; as a result, there is little demand for EV charging in these areas from DISCOMs.

6 Future Trends and Research Directions

6.1 Emerging Technologies and Innovations

Future trends and research directions in emerging technologies and innovations of electric vehicle-renewable energy sources (EV-RES) integration are shaping the evolution of sustainable transportation [70–72]. Some key areas of focus for future research and development include:

1. Advanced Energy Management Systems: Developing advanced energy management systems that optimize the utilization of renewable energy sources for EV charging. This includes real-time monitoring, forecasting, and control algorithms to maximize the use of available renewable energy, minimize grid impacts, and balance energy demand and supply.
2. Vehicle-Grid Integration (VGI): Advancing VGI technologies and exploring their full potential for grid services. Research can focus on bidirectional power flow control, grid stability assessment, and the development of VGI platforms that enable dynamic interaction between EVs, charging infrastructure, and the grid.
3. High-Power Charging Infrastructure: Investigating technologies and infrastructure designs for high-power charging to enable faster charging times and increased convenience for EV owners. This includes research on ultra-fast charging, advanced charging connectors, and high-power charging networks along major transportation corridors.
4. Vehicle-to-Home (V2H) and Vehicle-to-Building (V2B) Integration: Investigating the advantages and hurdles associated with integrating V2H and V2B, allowing EVs to supply backup power to residences and structures during grid disruptions or peak demand periods. Research may center on system designs, energy management tactics, and the economic feasibility of this integration.
5. Smart Grid and Artificial Intelligence (AI) Applications: Utilizing smart grid technologies and AI algorithms to enhance the integration of EVs and RES. This includes advanced demand response mechanisms, grid forecasting models, and AI-based optimization algorithms for EV charging and grid management.
6. Vehicle Energy Storage and Second-Life Applications: Investigating the potential for EV batteries to serve as stationary energy storage systems after their useful life in vehicles. Research can focus on battery management strategies, repurposing EV batteries for residential or commercial energy storage, and exploring circular economy concepts for EV battery materials.
7. Renewable Energy Microgrids for EV Charging: Exploring the concept of localized renewable energy microgrids that are specifically designed to support EV charging infrastructure. Research can focus on decentralized energy generation, microgrid management systems, and exploring the synergies between renewable energy generation and EV charging at a local level.

8. Cybersecurity and Data Privacy: Addressing cybersecurity and data privacy concerns associated with EV-RES integration. Research can focus on developing secure communication protocols, encryption techniques, and privacy-enhancing mechanisms to safeguard EV charging transactions and protect sensitive user data.

By pursuing research in these directions, we can advance the integration of EVs and renewable energy sources, enhance the performance and efficiency of EV-RES systems, and contribute to the development of a sustainable and resilient transportation ecosystem.

6.2 Scalability and Replicability of RES-EV Charging Systems

Scalability and replicability are important considerations for the successful implementation of RES-EV charging systems [73]. Here are some key aspects to consider regarding scalability and replicability:

1. Standardization: Standardization of RES-EV charging systems is crucial for scalability and replicability. Common technical standards, protocols, and interoperability ensure compatibility and seamless integration of different components, such as EVs, charging infrastructure, renewable energy sources, and grid systems. Standardization enables easy replication of systems across different locations and facilitates the scalability of RES-EV charging infrastructure.
2. Modular Design: Adopting a modular design approach allows for easier scalability and replication of RES-EV charging systems. By designing systems in modular units, it becomes simpler to add or remove components based on the specific needs and requirements of different locations. Modular design also facilitates easy deployment and scaling up of charging infrastructure to meet increasing demand.
3. Flexibility in Deployment Models: RES-EV charging systems should be flexible enough to accommodate various deployment models. This includes considering different charging scenarios, such as public charging stations, workplace charging, residential charging, and destination charging. Each deployment model may have unique requirements, but a flexible system design can be adapted and replicated across diverse settings.
4. Grid Integration Considerations: Ensuring effective grid integration is vital for scalability and replicability. RES-EV charging systems should be designed with grid-friendly features that help manage the impact of high-power charging on the electrical grid. This includes incorporating demand response capabilities, load management algorithms, and grid-balancing mechanisms to mitigate potential grid congestion and stability issues as the number of EVs and charging stations increases.

5. Planning for Future Expansion: Scalable RES-EV charging systems should account for future growth and demand. Planning for additional capacity, considering future technology advancements, and anticipating changes in EV adoption rates are important factors. This includes ensuring adequate power supply, grid infrastructure upgrades, and the ability to expand the charging network without major disruptions.
6. Knowledge Transfer and Best Practices: To promote replicability, knowledge transfer and sharing best practices are crucial. Documenting successful case studies, lessons learned, and technical guidelines can facilitate the replication of RES-EV charging systems in different regions. Collaboration among stakeholders, including governments, utilities, automotive industry, and research institutions, can help disseminate knowledge and promote standardized approaches for scalability and replicability.

By addressing these considerations, RES-EV charging systems can be designed and implemented in a scalable and replicable manner. This allows for the efficient expansion of charging infrastructure, wider adoption of renewable energy sources, and the realization of a sustainable and low-carbon transportation ecosystem.

6.3 Research Gaps and Areas for Further Exploration

Although considerable advancements have been achieved in integrating renewable energy sources (RES) with electric vehicle (EV) charging infrastructure, there remain research gaps and areas deserving of further investigation. Some key areas for future research include:

1. Grid Integration and Management: More research is needed to develop advanced grid integration and management techniques for RES-EV charging systems. This includes studying the impact of high-power charging on the electrical grid, optimizing grid stability, managing grid congestion, and implementing effective demand response strategies.
2. Energy Storage Solutions: Investigating energy storage technologies and their integration with RES-EV charging systems is important. Research can focus on optimizing energy storage capacity, exploring innovative storage options, and evaluating the economic feasibility and performance of different storage solutions to support increased renewable energy utilization and grid stability.
3. Dynamic Charging and V2X Technologies: Further exploration is needed in dynamic charging technologies, which enable charging while the vehicle is in motion. Research can focus on developing efficient and safe dynamic charging systems, addressing technical challenges, and understanding the impacts on battery life, vehicle range, and infrastructure requirements. Additionally, there is a need to advance vehicle-to-X (V2X) technologies to enable bidirectional energy flow between EVs, buildings, and the grid, unlocking the full potential of EVs as flexible energy assets.

4. Scalability and Interoperability: Research is required to develop scalable and interoperable RES-EV charging systems. This includes standardizing communication protocols, hardware interfaces, and charging infrastructure deployment models. Understanding the scalability limits of different components and identifying strategies to overcome scalability challenges will be crucial.
5. Economic and Policy Considerations: Further research is needed to evaluate the economic viability of RES-EV charging systems, including cost analysis, cost-effectiveness studies, and business models. Additionally, exploring policy frameworks, regulations, and incentives that support the widespread adoption of RES-EV charging infrastructure will be essential.
6. Environmental Impacts and Life Cycle Analysis: Conducting life cycle assessments and environmental impact studies of RES-EV charging systems is necessary to comprehensively evaluate their sustainability. Research can focus on quantifying the environmental benefits, analyzing the life cycle impacts of different technologies, and identifying strategies to minimize the overall environmental footprint.
7. Consumer Behavior and Adoption: Understanding consumer behavior, preferences, and barriers to EV adoption and the use of RES-EV charging systems is crucial. Research can explore consumer perceptions, charging behavior patterns, range anxiety, and factors that influence EV purchase decisions. This knowledge can inform the development of effective policies, communication strategies, and user-friendly charging experiences.

By addressing these research gaps and exploring these areas further, we can enhance the understanding and implementation of RES-EV charging systems, promote sustainable transportation, and accelerate the transition to a low-carbon energy future.

7 Conclusion

7.1 Summary of Key Findings from the State-of-the-Art Review

The state-of-the-art review on EV-RES integration reveals several key findings:

1. Importance of Sustainable Transportation: The necessity for sustainable transportation solutions has gained prominence in response to environmental concerns. Electric vehicles (EVs) fueled by renewable energy sources present a promising avenue for curtailing greenhouse gas emissions and lessening dependence on fossil fuels.
2. Electric Vehicle Supply Equipment (EVSE): Serving as the fundamental component of EV charging infrastructure, EVSE facilitates secure and regulated charging of electric vehicles (EVs). It integrates control systems for user

authentication, authorization, data logging, and network administration, fostering efficient and secure charging operations.

3. Conductive Charging Technology: Conductive charging, also known as plug-in charging, stands as the predominant method utilized for electric vehicle (EV) charging. The specifications for electric vehicle supply equipment (EVSE) are contingent upon factors including vehicle type, battery capacity, charging methodologies, and power ratings.
4. Integration of RES with EV Charging Infrastructure: Integrating renewable energy sources (RES) with EV charging infrastructure offers numerous benefits. It reduces emissions by addressing both the transportation and electricity sectors' environmental impacts. RES-EV integration enhances energy security, promotes energy diversification, and supports the growth of a sustainable energy ecosystem.
5. Benefits of RES-EV Charging Systems: RES-EV charging systems offer various advantages, including reduced carbon footprint, improved air quality, energy independence, and potential cost savings for EV owners. They contribute to grid stability, support the integration of intermittent renewable energy, and foster the growth of a resilient and decentralized energy infrastructure.
6. Technological Advancements: Technological advancements in EV-RES integration include smart charging capabilities, vehicle-grid integration, dynamic charging, and bidirectional energy flow (V2G/V2X) capabilities. These innovations optimize energy management, grid interaction, and resource allocation, enabling efficient utilization of renewable energy and enhancing the flexibility of EVs in the energy system.
7. Case Studies and Successful Implementations: Several successful case studies demonstrate the feasibility and benefits of RES-EV charging systems. These include projects involving solar-powered charging stations, wind-powered charging infrastructure, and smart grid-integrated EV charging systems. These examples showcase the practical implementation and positive outcomes of combining renewable energy and EV charging.
8. Scalability and Replicability: Scalability and replicability are critical for the widespread adoption of RES-EV charging systems. Standardization, modular design, flexibility in deployment models, and grid integration considerations are key factors in ensuring scalable and replicable solutions.
9. Research Gaps and Future Directions: Despite significant progress, research gaps exist in areas such as grid management, energy storage, dynamic charging, scalability, economic viability, and consumer behavior. Future research should focus on addressing these gaps, exploring emerging technologies, advancing energy management systems, and understanding the socioeconomic and environmental impacts of EV-RES integration.

In summary, the state-of-the-art review highlights the potential and benefits of integrating renewable energy sources with EV charging infrastructure. It emphasizes the importance of technological advancements, scalability, and replicability while identifying future research directions to drive the further development and implementation of RES-EV charging systems.

7.2 Implications and Benefits of RES-EV Charging Integration

The fusion of renewable energy sources (RES) with electric vehicle (EV) charging infrastructure carries substantial implications and presents numerous advantages. Below are some notable implications and benefits of integrating RES with EV charging:

1. Environmental Impact Reduction: Integrating renewable energy sources (RES) with electric vehicle (EV) charging infrastructure plays a pivotal role in mitigating greenhouse gas emissions and addressing climate change. Leveraging renewable energy sources such as solar, wind, or hydroelectric power for EV charging substantially diminishes the carbon footprint of the transportation sector. This contributes to enhancing air quality, alleviating the environmental repercussions of transportation, and fostering a sustainable, low-carbon future.
2. Energy Independence and Security: Incorporating renewable energy sources (RES) into electric vehicle (EV) charging infrastructure diminishes dependency on fossil fuels and bolsters energy autonomy. Through generating electricity from renewable sources, nations can broaden their energy portfolio and mitigate susceptibility to fluctuations in fossil fuel costs and geopolitical instabilities. This fosters enhanced energy resilience and fosters indigenous energy generation.
3. Grid Flexibility and Stability: RES-EV charging integration can contribute to grid flexibility and stability. EVs can act as distributed energy resources, enabling the storage and utilization of renewable energy. Through vehicle-to-grid (V2G) or vehicle-to-building (V2B) technologies, EVs can provide valuable grid services, such as load balancing, peak demand management, and grid stabilization. This enhances the overall reliability and resilience of the electrical grid.
4. Cost Savings and Energy Efficiency: The integration of renewable energy sources (RES) with electric vehicle (EV) charging infrastructure can result in cost savings and enhanced energy efficiency. Through harnessing renewable energy sources, EV owners can access more economical electricity in contrast to conventional fossil fuel-based energy. Employing time-of-use charging strategies, wherein EVs are charged during times of decreased electricity demand or heightened renewable energy generation, can additionally optimize cost reductions and amplify energy efficiency.
5. Advancement of Renewable Energy Utilization: The integration of renewable energy sources (RES) with electric vehicle (EV) charging infrastructure fosters the adoption and utilization of renewable energy. Heightened demand for renewable energy to fuel EVs can stimulate investments in renewable energy initiatives and catalyze the expansion of clean energy production. This engenders a constructive feedback mechanism wherein the proliferation of EVs propels the advancement of renewable energy infrastructure.
6. Employment Generation and Economic Prospects: The integration of renewable energy sources (RES) with electric vehicle (EV) charging infrastructure

has the potential to spur job creation and offer economic prospects. The establishment, deployment, and upkeep of renewable energy generation systems and EV charging infrastructure generate novel job prospects within the renewable energy domain. Furthermore, it nurtures innovation, technological progress, and the expansion of associated sectors, thereby bolstering economic development and competitiveness.

7. Public Perception and Consumer Adoption: RES-EV charging integration enhances the public perception of EVs by reinforcing their clean and sustainable image. The availability of renewable energy-powered charging infrastructure addresses concerns about the environmental impact of EVs and increases consumer confidence in adopting electric mobility. This, in turn, can accelerate the transition toward electric transportation and drive higher EV adoption rates.

Overall, the integration of RES with EV charging infrastructure brings about multiple benefits, including environmental sustainability, energy independence, grid flexibility, cost savings, job creation, and enhanced consumer acceptance of electric vehicles. These implications underscore the importance of continued efforts to expand and optimize RES-EV charging integration worldwide.

7.3 Recommendations for Future Research and Implementation

Key recommendations for future research and implementation in the integration of renewable energy sources (RES) with electric vehicle (EV) charging infrastructure include:

1. Optimize grid integration and management of RES-EV charging systems.
2. Explore energy storage technologies and their integration with RES-EV charging.
3. Establish common standards and protocols for RES-EV charging systems.
4. Research smart charging algorithms and V2X technologies for grid participation.
5. Develop innovative business models and market mechanisms to incentivize RES-EV integration.
6. Utilize data analytics and artificial intelligence for optimization of RES-EV charging.
7. Conduct comprehensive assessments of socioeconomic and environmental impacts.
8. Foster collaborative research and pilot projects for practical demonstrations.
9. Promote public awareness and education about the benefits of RES-EV charging integration.

Implementing these recommendations can lead to enhanced grid stability, increased renewable energy utilization, optimized charging management, cost savings, and reduced environmental impact. It will also contribute to energy security, job creation, and the widespread adoption of clean transportation.

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Chapter 10
Solar and On-Grid Based Electric Vehicle Charging Station

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Abstract This chapter proposes an on-grid solar-based smart DC electric vehicle charging station (EVCS) to minimize overload on the utility grid and enhance efficiency. The EVCS uses solar power to charge EVs, avoiding grid consumption during peak hours and reducing the load on the utility by relying on renewable energy. This work proposes a system with a common DC bus connected to a solar PV array via a DC-DC boost converter, utilizing a fuzzy logic-based MPPT technique to maximize solar panel output power. A single-phase grid is also connected to the common DC bus through a single-phase full-bridge inverter with bidirectional power flow, and this inverter is controlled by the current control method using the d-q framework. The DC bus is connected to the grid via a bidirectional single-phase full-bridge inverter. This inverter, controlled by the current control method using the d-q framework, manages power flow effectively in both directions. An LCL filter is employed to minimize harmonics in the system. Additionally, an EV battery is integrated via a bidirectional DC-DC converter to stabilize the bus voltage, with control provided by a voltage controller. This multimode EV charging station, powered by renewable energy, can significantly promote the adoption of electric vehicles and lower the cost per unit of charging, supporting a more sustainable and cost-effective approach to EV infrastructure.

1 Introduction

Electric vehicles are now a very common form of transportation. Increasing gasoline prices may be the primary factor in the growing acceptance of electric vehicles in a relatively short period. Electrical vehicles have become popular for a variety of

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reasons. The adoption of more environmentally friendly modes of transportation was also influenced by efforts to promote green energy and minimize air pollution [1]. Although the usage of EVs has grown knowingly in recent years, poor countries are still having a difficult time adopting them on a large scale. The key concerns are the lack of charging infrastructure, expensive vehicle costs, limited driving ranges, lengthy charging times, and a dearth of repair and maintenance facilities. The most pressing constraint of the time is to build and improve rapid charging station for EVs to facilitating the broad use of electric vehicles. We cannot claim that electric vehicles are entirely environmentally beneficial. After all, the electricity used to charge them still originates from power plants powered by fossil fuels because the majority of present EV charging points is grid-based. With a high demand in the energy industry and to prevent environmental degradation from unnecessary use of non-renewable resources of energy, PV solar systems are becoming more and more common amongst all renewable energy resources. For PV solar systems that are connected to the utility grid, various system configurations are available. For grid-connected PV solar applications, four basic types of arrangement are used: centralized inverter systems, string inverter systems, module-integrated inverter systems, and multi-string inverter systems**.** The key benefits of employing grid-connected solar PV systems include their low impact on the environment, their ability to be put nearby to buyers, which reduces transmission-line losses, their decreased repair costs due to absence of moving parts, and their high efficiency and system's modularity which prevents carbon dioxide emissions from entering the environment. But once more, EV charging stations that are powered by solar are having certain drawbacks such as their reliance on weather and sunlight. Because at night, solar PV generates very less amount of power due to the absence of sunlight. Also, a lot of auxiliary equipment is needed with the solar PV system; hence, total installation cost of EV charging system based on solar will increase [2]. As, previously indicated, there are some technical issues with EV charging system that are powered by solar PV system. EV charging station operating on solar panels and utility both will be discussed in this suggested work to reduce load on main grid. Thus, MATLAB Simulink is used to perform an EV battery charging system which is operated by both solar PV and the utility grid.

2 Benefits of EVs

Electric vehicles are more advantageous than the conventional type which is powered by petrol or diesel engines, not in terms of reducing environmental pollution but also improving the global efficiency of transportation system. Also, the rising price of diesel and petrol is one of the main reasons, and it is imperative to select cheap modes of transportation. Electric vehicles may go up to 250 to 360 miles on just one charge and cost the consumer between 280 and 400 Indian Rupees, which is significantly less than the cost of travelling the exact same distance in a vehicle powered by gasoline [3].

The achievement of the nation's net carbon zero targets is another advantage of the deployment of electric vehicles. In several cities where environmental damage has risen to dreadfully high levels, such as Delhi, New York, and Rio, electric vehicles could prove to be a very viable alternative. This is because it is abundantly known that they are an environmentally beneficial form of transportation. It can also be used in situations where it is important to prevent additional air quality degradation. Nothing could be better than electric automobiles if they were charged with renewable energy sources.

3 Challenges for EVs

Lack of nearby charging outlets is the biggest barrier in adoption of EVs. Although overall range of battery-powered automobiles on a single charge is an issue, this problem can be solved by using high capacity contemporary li-ion batteries. The price of EVs is a major worry for potential purchasers, but these days, thanks to government subsidies for purchasing them; their price is practically on par with that of conventional vehicles. The purchaser is simply hesitant to accept novel ideas and technologies because of the dependability issue and a lack of knowledge about electric vehicle technology. First and foremost, charging stations must be installed at sufficient distances, just like petrol stations, and at a far faster rate for the public to accept EVs on a wide scale.

4 Literature Review

One of today's most fundamental demands for humanity is electricity. Solar energy conversion results in better power production while also lowering pollution from fossil fuels. Solar panels' output power depends on temperature, load impedance, and irradiance. The performance of integrated photovoltaic systems built using various algorithms shows that there are often 20 to 25% losses in the production of power [4]. These are mostly brought on by incongruous losses, partial shadows, variations in I-V characteristic curves, variation in solar surface inclination, and influence of weather. The use of appropriate electronics, such as a cheap, highly efficient DC-DC boost converter [5] with MPPT features, can reduce these losses.

MPPT extracts or measures highest solar power which is generated by PV solar panels at any point of temperature and solar irradiance. We know that productivity of solar power is not very great due to variations in irradiance and temperature, so it must be guaranteed that maximum efficiency is achieved. Hence, MPPT is used to attain maximum power from a variable energy source. On a VI graph, the intersection point represents the maximum point of power at a certain value generated by the PV solar. The maximum power point from solar can now be measured using a variety of MPPT techniques, including the perturb and observe (P&O) approach, the incremental conductance (INC) method, the modified P&O method, and the modified INC method. However, there are also some more sophisticated MPPT techniques, such as MPPT based on neural networks and fuzzy logic. Compared to traditional MPPT approaches, these modern MPPT techniques are more intelligent and effective.

Due to aids like high-power factor, low current harmonics, and the ability for bidirectional energy flow, grid-connected single-phase inverters are frequently used in distributed generation, PV-to-grid integration, grid control devices, etc. The current control is crucial in ensuring the effectiveness and permanence of inverters. In these systems, the single-phase grid-connected inverter typically only injects active power. This task can be successfully completed by the proportional-integral (PI) used in the d-q frame. However, due to the local loads or faults in grid scenarios, grid-connected single-phase inverters are now also necessary to provide reactive power or multi-functions.

5 EV Charging System Powered by Utility Grid

Depending on the situation and need, an EV can be powered through various types of methods. As a result, different kinds of EV charging infrastructure have been developed. Standard electric vehicle charging stations that are grid-connected receive their electricity from power plants based on fossil fuel. As a result, these charging stations have an indirect negative impact on the ecosystem and are not environmentally friendly. Electricity for charging electric vehicles is available around the clock at these grid-based charging stations [8].

5.1 Design of Grid-Connected EV Charging System

In this grid-connected charging station configuration, an AC-DC converter is connected to main grid.

In order to increase voltage, it also contains DC bus that links DC-DC converter to electric vehicle charging station. The utility grid provides three-phase power and is then fed to a step-down transformer, so that level of voltage can be decreased from the EV charging level to the distribution level. And generally, for AC to DC power conversion, AC-to-DC converter is used. And DC-DC converter [6] can connect number of EV batteries to DC bus for charging [7]. Figure 1 depicts the schematic layout of an EV charging station connected to the grid.

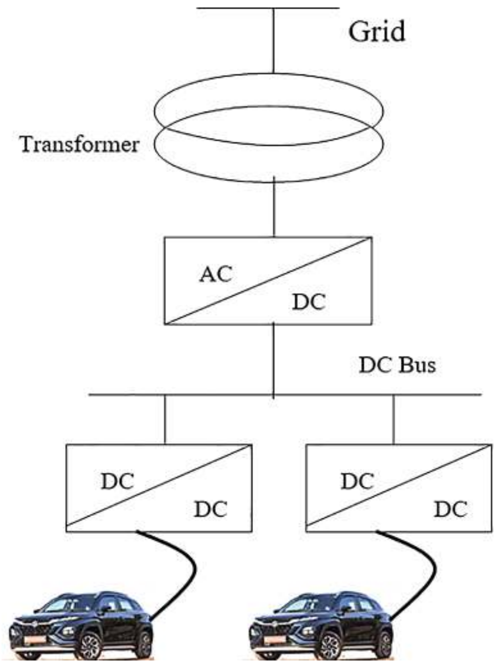


Fig. 1 Grid-connected EV charging station [8]

5.2 Grid-Connected EV Charging Station Limitations

Due to the increased demand for electricity, this architecture places additional stress on the utility system when used to charge electric vehicles. Peak hours cause this situation to worsen even further. It is clear from a thorough analysis of the effects of integrating electric vehicles with the grid that charging and discharging techniques for battery-powered vehicles, such as vehicle-to-grid (V2G) and grid-to-vehicle (G2V), have an impact on the quality of power, grid stability, and energy economics [8]. There could be one or more of the following power quality problems such as high-order harmonics, stray fluxes, phase imbalances, voltage surges and dips, and DC offset. The fundamental reason for the aforementioned problems is the nonlinear behaviour of high-speed DC chargers that are employed to charge electric automobiles. The efficiency and longevity of the electricity distribution system network are adversely affected by these concerns regarding power quality.

6 EV Charging Stations Powered by Solar

As we know that EV stations powered by solar are one of the finest examples of electric vehicle charging systems using a renewable energy source. It uses solar energy, or we can say that it extracts power from solar radiation. These solar-powered

EV charging stations are entirely environmentally friendly and do not emit any carbon emissions. Thus, we can say that solar-powered EV charging stations are clean and green. As we know MPPT is used to maximize power of solar PV systems. Now these charging stations use a constant voltage approach, which is known as CV method, to manage highest output power of solar panels [8]. Output voltage of solar is compared to a reference voltage to determine highest voltage point at which maximum power is obtained.

6.1 Solar-Powered EV Charging System Design

A fast EV charging system requires DC power of nearly 230V, which is obtained by using the DC-DC buck and boost converter. DC-DC buck converter is used when we need to decrease the level of voltage. DC-DC boost converter is used for increasing the voltage level. Using a bidirectional DC-DC converter, battery storage is utilized to store electricity generated by solar panels. To control the process of charging and discharging of EV batteries, some control mechanism is used, so it can prevent the battery from getting overcharged. Nowadays, EV vehicles are charged by regular DC fast chargers which can be achieved by using renewable sources. Figure 2 depicts the infrastructure of solar-powered EV charging system.

6.2 Solar-Powered EV Charging Station Limitations

Primary issue with EV charging station is that it totally depends on weather. Solar panels will produce more power on bright, sunny days, but their output will also be lowered on gloomy or wet days. This makes the charging station less reliable. We require uninterrupted power, so that charging stations can be installed on a wide scale. Implementation of solar-powered EV charging station is affected by a few factors, including the need for a large space for solar panel installation, the high expense, and maintenance of solar panel. In addition to all, this type of charging station also uses a lot of auxiliary parts which increases the total cost of the EV charging station.

7 Hybrid EV Charging System

This charging system is known as hybrid or multimode because it can be powered by both renewable energy sources and the grid. These stations can work in two modes, for example, when an EV is connected then it gets power from a solar PV system, but at night charging of EV is completed by main grid. By doing that, it also reduces the overload on grid. This scheme of dealing with EV charging station procedure allows for optimal solar energy consumption while drastically reducing the overload on the

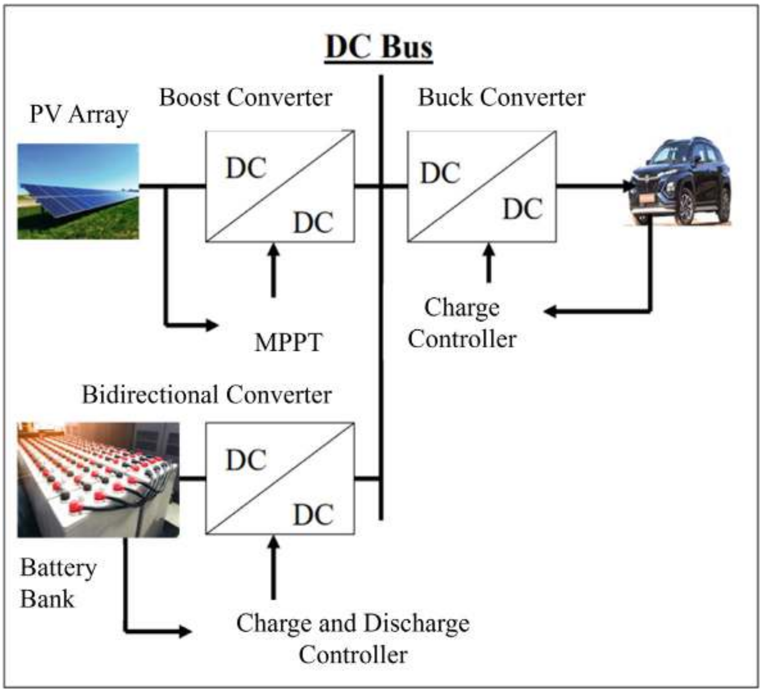


Fig. 2 Solar-based electric vehicle charging system [8]

main grid. These optimum results can only be obtained when both sources of power are used in a coordinated manner. And it is controlled by some effective techniques of controlling such as current control techniques [5, 8].

7.1 Design of Solar-Based EV Charging System

Figure 3 depicts the design of an EV charging station powered by solar and grid. System requires solar system, DC-DC boost converter, AC bus, utility grid, grid-tied inverter, battery, and control unit that controls the switching operation of charging from solar to the main grid. DC-DC converter is used to increase solar output voltage, and MPPT control unit makes sure that maximum output power is being extracted from solar panels. Voltage-based algorithm is used for a smooth shift between the solar-connected approaches of charging the EVs to the grid-connected approach of charging. Now this whole system is connected to an AC bus via an automatic switching control unit. For regulating the charge and discharge operation of electric vehicles, a switching controller [8] is also used. This prevents the battery to get overcharged. In this type of method, a lot of auxiliary equipment is also required for a smooth operation of the charging and discharging process of EVs [5].

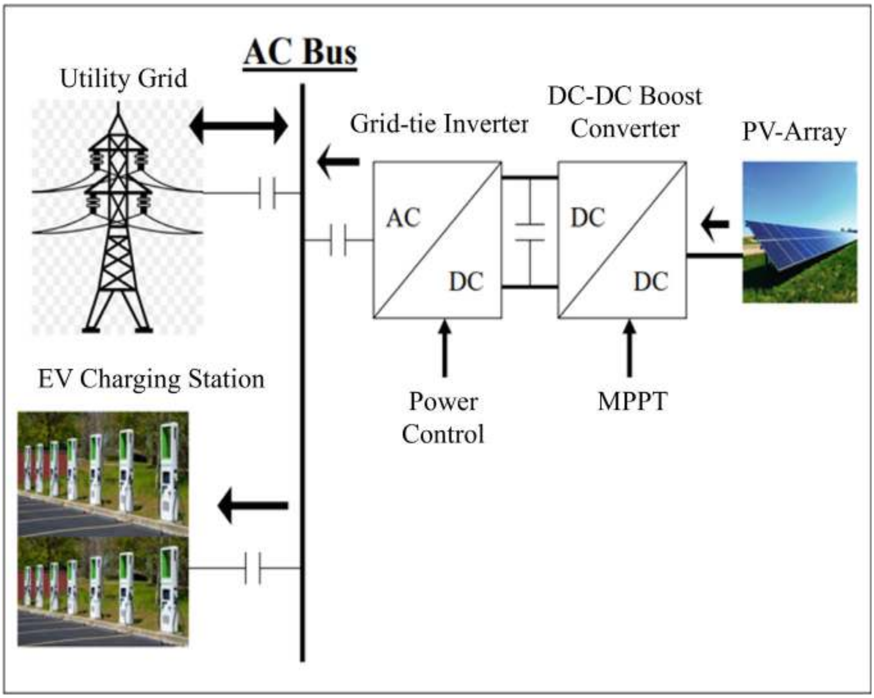


Fig. 3 EV charging system based on solar and grid both [8]

7.2 *Hybrid EV Charging System Operation*

EV charging station will operate in solar panel mode when there is enough sunlight and the sky is clear since solar panel's output is sufficient to charge the battery. For solar panels to produce highest output, an MPPT controller is utilized. When insufficient solar power and solar panel output is very low, an automatic switching device based on a voltage comparison algorithm switches the load to the utility grid automatically. Thus, in peak hours, EV charging stations are powered by solar, and during off-peak hours, stations are powered by the main utility grid [8].

8 Advantages of Grid Integration with Solar

(1) As local solar electricity is produced to power electric vehicle charging stations, demand for energy from main utility grid is decreased.
(2) DC sources are more effective at charging electric vehicles than the AC grid is at doing so.

(3) Solar energy-based EV charging system are more practical for remote and mountainous area where AC grid connection cannot be established.
(4) Infrastructure for charging stations can be easily and widely built using renewable energy sources.
(5) Coupling of renewable energy-based systems with grid can greatly lower the cost per unit of charging electric vehicles.
(6) As a result of the main grid's reduced overload, grid stability and electricity quality have both greatly increased.
(7) An environmentally responsible way to power electric vehicles is through integrated solar energy-based charging infrastructure.
(8) Grid-based charging infrastructure's efficiency and dependability can be considerably improved by integrating renewable energy sources.
(9) This kind of setup is ideal for public parking lots and government buildings where cars are kept for long stretches of time during the day [9].

9 Photovoltaic System

PV cell is an electrical device which works on the photovoltaic effect to convert solar energy into DC. It is a well-designed component of the sun-oriented energy system and a crucial source of alternative energy. These are made of silicon that has been cemented or doped with various substances to affect the conductivity of electrons or holes. A variety of different materials are developed such as including gallium arsenide (GaAs), cadmium telluride, and copper indium diselenide (CIS) for making PV cells [4]. These materials are also combined in photovoltaic cells. The PV cell is built in such a way that the junction can be exposed to visible sunlight, infrared light, or ultraviolet light. A variation in voltage is given between the materials of the P sort and the N sort at the location where such radiation contacts the P-N intersection. Current can be taken from the PV cells using terminals connected to the semiconducting material coatings.

For connecting the two different stacks to the cell, metallic connections are offered. For mechanical assurance, the PV cell is positioned beneath a glass spread that is attached to it. Thus, the efficiency of a solar PV cell varies between 15 and 19%, generating a voltage for open circuit of 0.65 V and maximum current density of 35 to 40 mA/cm^2 at its peak [4].

9.1 Working Principle of Photovoltaic Cell

Energy transformation in solar-powered cells involves two crucial processes. The primary result of light absorption is an electron–hole pair. The gadget's design isolates the electron and gap, connecting the electron to the negative end and the opening to the terminal that is used to produce electrical force.

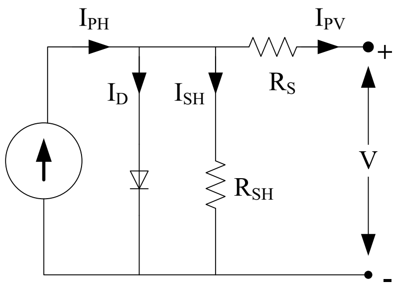


Fig. 4 Solar PV cell equivalent circuit

Figure 4 shows a solar PV cell's equivalent circuit, which includes a DC supply, resistors in parallel and series, and a diode. The current source defines the photon current, and the diode and resistors define the leakage current and the current which is going to the load flows through the series resistance.

Current–voltage characteristics of solar cell:

$$Is = Iph - Id - Ish \tag{1}$$

$$Id = Io\left[\exp\left(\frac{q(V + IRs)}{kT}\right) - 1\right] \tag{2}$$

$$Is = Iph - Io\left[\exp\{q(V + IRs/KT)\} - 1)\right] - (V + IRs/Rsh) \tag{3}$$

where Is is cell current (A), Iph is light-generated current (A), Io is diode saturation current (A), Q is charge on electron ($1.6 \times 10^{-19} C$), K is Boltzmann constant (J/K), V is output voltage (V), Rs is series resistance (Ω), and Rsh is cell shunt resistance (Ω) [10].

9.2 Solar PV System: Block Diagram

The block illustration of the PV solar arrangement and MPPT is shown in Fig. 5. A solar array is connected in series with a resistive load, via DC-to-DC boost converter.

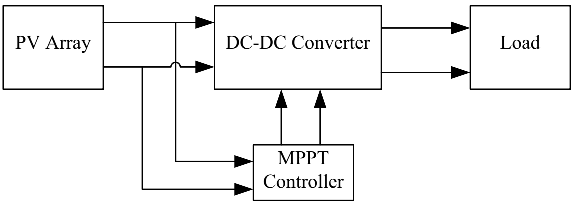
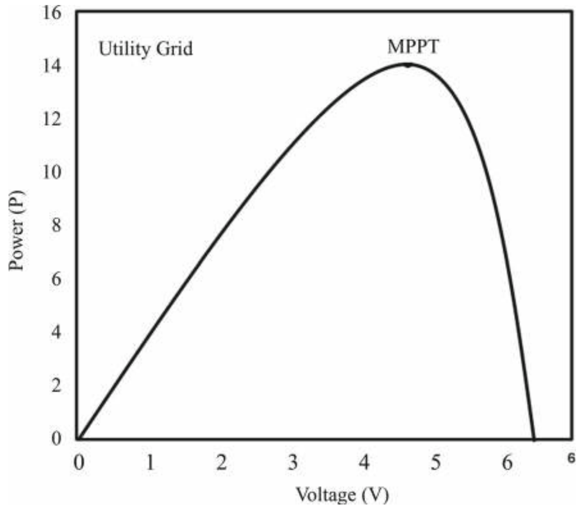


Fig. 5 Block diagram of solar system

MPPT controller uses the current as well as the voltage from the output as inputs to track the spot at which the maximum power can be produced. MPPT controller output depicts duty cycle. Duty cycle generates a PWM signal with help of a comparator to gate DC-DC boost converter [11]. The output of solar PV cell, i.e., P–V and I–V characteristics, is shown in Figs. 6 and 7 [4].

Fig. 6 P–V characteristics



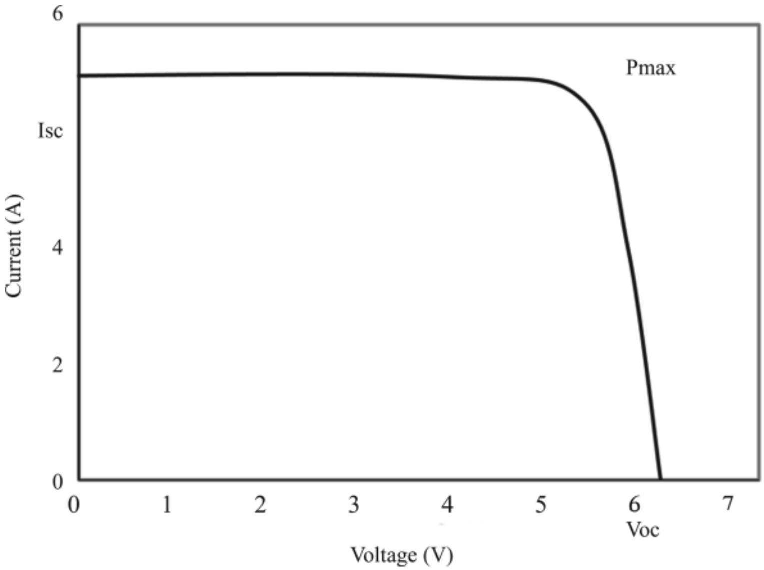


Fig. 7 I-V characteristics

In Fig. 6, MPP is a point on PV graph where maximum output is obtained for a specific value of irradiance. If this point is shifting towards left, then it means voltage should be increased, and if it shifts towards right side of the curve, then we should reduce voltage. So, it is significant to stabilize maximum point to obtain highest output power.

9.3 Maximum PowerPoint Tracking

MPPT is a unique methodology which can be used in a variety of situations to improve power production from solar PV modules and turbines. MPPT controller can track maximum current and voltage values (I-V) and detect the generated voltage of solar panels in real-time in such a manner that the battery can be charged by the system with the highest possible output power. To synchronize with batteries, solar panels, and workloads, MPPT can be used in photovoltaic inverters [4].

9.4 Principle of MPPT

During EV charging, output of solar system requires to be greater than voltage and current of EV battery; otherwise, output current will be minimum or zero. Hence, peak voltage (Vpp) of solar PV panel, which is determined with 25 ° C ambient temperature, would be set at roughly 17 V for safety. In exceptionally hot conditions, the peak voltage of a solar system would fall up to 15 Volts, but in extremely cold conditions it may reach up to 18 V.

As we know, the MPPT settings are factory defaulted to maximize output power of solar PV panel and MPPT would monitor maximum power point in real time. If the tracking method is efficient, then more power will be obtained. And this will improve the charging quality. Apparently, a solar PV system is 50% extra efficient than a standard power system if we use an MPPT controller. But practically, due to losses of energy in the environment, the efficiency of MPPTs can only be enhanced by only 20 to 30%.

Thus, MPPT solar charging controllers will eventually replace the typical solar converters for better efficiency.

9.5 Working of a Maximum Power Point Tracker

MPPT is controlling unit which helps in increasing power output of PV system. As we know, output of the solar panels is used after converting into high-frequency AC. Thus, for charging the EV batteries, voltage and current are maintained in the AC bus. MPPT works between 20 and 80 kHz, which is a distinctive range for

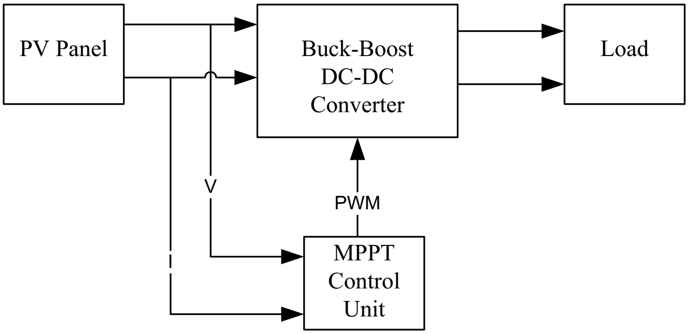


Fig. 8 Block diagram of solar system with MPPT and DC-DC boost converter

high frequencies. The benefit of designing high-frequency circuits is having the option to employ tiny components and transformers with extremely high efficiency. Comparable to how a radio transmitter can affect radio and television transmissions, problems with certain "broadcasting" circuit components can make designing high-frequency circuits very difficult. Isolation and noise termination becomes essential. MPPT controller first tracks output of solar panels before setting the output power to its maximum level, and it generates desired output for converter.

Some MPPT control is linear, or non-digital. Hence, it is significantly simpler and less expensive to create and design digital alternatives. They slightly increase efficiency, but total effectiveness might vary greatly. Some have been observed to miss their "tracking point" and become worse. Figure 8 shows how MPPT control unit take current and voltage from PV as input and generates duty cycle for DC-DC boost converter via PWM generator.

MPP controller is no different from other DC-to-DC converters in that they all function by converting the input current from DC to AC, then distributing it by using a transformer, and then again reversing it through the regulator to convert it from AC to DC. This is a firmly electronic method in the majority of DC-to-DC converters. Excluding the minor output voltage adjustment, no actual intelligence is at play. But due to constantly varying sunlight, temperature, and battery voltage throughout the whole day, the solar PV controllers requires more intelligence.

9.6 Importance of MPPT in Solar PV System

At a point of solar irradiation and temperature, MPPT measures highest power generated by solar panel. Productivity of solar panel is normally not very great, so it must be guaranteed that it works at the highest efficiency possible for any given irradiance and temperature. This is why MPPT is used. The MPPT technique may help you attain the most power out of a variable source. On a graph, the intersection of the exaggeration of equation $V \times I$ corresponding constant and the features of the solar generator for a certain value of irradiation represents the point of maximum power [12]. As observed, the tangent point changes immediately which does depend on the solar energy stages and temperature variations. It is the responsibility of MPPT to locate such a maximum power point moment by instant. Due to solar PV panel's nonlinear I-V curve, it is difficult to power the load. In order to solve this problem, the system is modified by adding boost converter in parallel to MPPT. MPPT seeks to maintain a specific duty cycle in order to provide the associated load with as much DC power as possible. The duty cycle can be adjusted.

9.7 Various MPPT Algorithms

(1) **Perturbation and Observation (P&O)**

To provide maximum power, the algorithm modifies operating voltage. Since there are sophisticated and optimized variations of the algorithm, the fundamental P&O MPPT methodology used here is a key concept [13, 14].

(2) **The Incremental Conductance (INC) Technique**
This technique has excellent tracking efficiency and requires moderate implementation. It does not rely on a solar PV array for MPPT. Voltage and current are the sensing parameters, and the convergence speed is medium and analogue in nature [13–15].
(3) **Fuzzy Logic Control-based MPPT:** depending on PV array, good tracking efficiency, extremely sophisticated implementation, quick convergence, and digital type [13–15].
(4) **Neural-Network-based MPPT:** also has good tracking efficiency, very difficult execution, and quick and digital type convergence [15].
(5) **Linear Current Control-based MPPT:** depending on the PV array, with poor tracking efficiency, medium implementation complexity, quick convergence, and irradiance as the digital type of the sensing parameter [14–16].
(6) **Temperature-based MPPT:** It depends on solar PV array, great efficiency of tracking maximum power, simple implementation, and relatively accurate MPP; voltage and temperature are the sensing parameters [16].

Perturb and observe is commonly used MPPT algorithm. It is for its easy employment. It is also due to its high dependability. But using of fuzzy MPPT makes system more efficient.

10 Fuzzy Logic Control-Based MPPT

According to system application demand, voltage manipulation is required. Voltage level conversion is done using boost converter which is associated with solar PV panel. This study uses boost converter and converts voltage level of photovoltaic system to required voltage level. While maintaining maximum power level, boost converter increases output voltage in relation to input voltage. Additionally, it controls the voltage of solar PV panels, which is continuously fluctuating because of the impacts of variation in temperature and irradiance. For abstracting maximum output from solar panel, duty cycle is generated using fuzzy logic-based technique.

MPPT system works on “maximum power transfer theorem”. According to this theorem if load impedance matches with source impedance, then the load will receive maximum power in output. Thus, here, MPPT is doing the work of impedance matching under the varying temperature and solar irradiance called the maximum power point. As we know, here we are using fuzzy logic-based MPPT to generate duty cycle which is then fed to boost converter connected to solar panel as shown in Fig. 9.

10.1 Fuzzy Logic Control

A member of the soft computing family is fuzzy logic. Nonlinear properties of solar panel are resolved by this method. Step size can be automatically adjusted, and it deals with unfavourable conditions like any abrupt change in temperature or irradiance. Fuzzy logic-based algorithms do not require special changes to deal with temporary scenarios in contrast to conventional approaches.

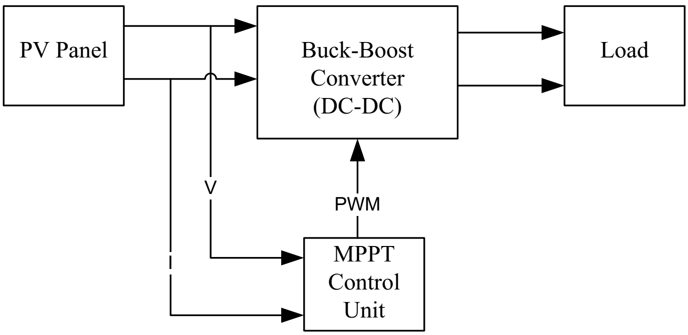


Fig. 9 Block diagram of fuzzy MPPT-based solar

10.2 Fuzzy Logic

Fuzzy is a word which means "inaccurate" [6, 7]. Fuzzy logic mimic humans thought processes. Due to flexible and nonlinear approach, it is an alternative for control system applications.

FLC [5] essentially has four steps-

(a) Fuzzification
(b) Inference systems
(c) Rule bases
(d) Defuzzification

(A) **Fuzzification**

In process of "fuzzification", input variables are transformed into verbal variables in manner of various functions. Accuracy will grow as membership function goes up, but complexity of rule-making process will also rise.

(B) **Inference System**

The tool for making decisions is the inference system. A rule-based system is used to guide decision-making. In the rule base algorithm, an output variable is produced by a conditional statement that combines input parameters and conditional operators.

(C) **Rule-Based**

The input variables and logical operators in the IF–THEN rules combine to create an output variable. Several distinct kinds of fuzzy rule systems can be created depending on what is needed. There are three types of them which are single input, single output, multiple inputs and outputs.

(D) **Defuzzification**

The process of defuzzification involves turning linguistic variables into distinct variables. Centre of gravity, area centre, area bisector, and other defuzzification techniques are also available. But most widely used technique is known as the centroid method or the centre of gravity method.

Figure 10 illustrates block diagram of fuzzy-based MPPT. It measures voltage and current of PV array and calculate output power. By comparing current power and voltage to previous values, error is computed. Hence, variation in error calculated and given to fuzzy logic algorithm, and consequently, the output is obtained which is a duty ratio. Then change in duty ratio is obtained which is given to a boost converter according to our system requirement.

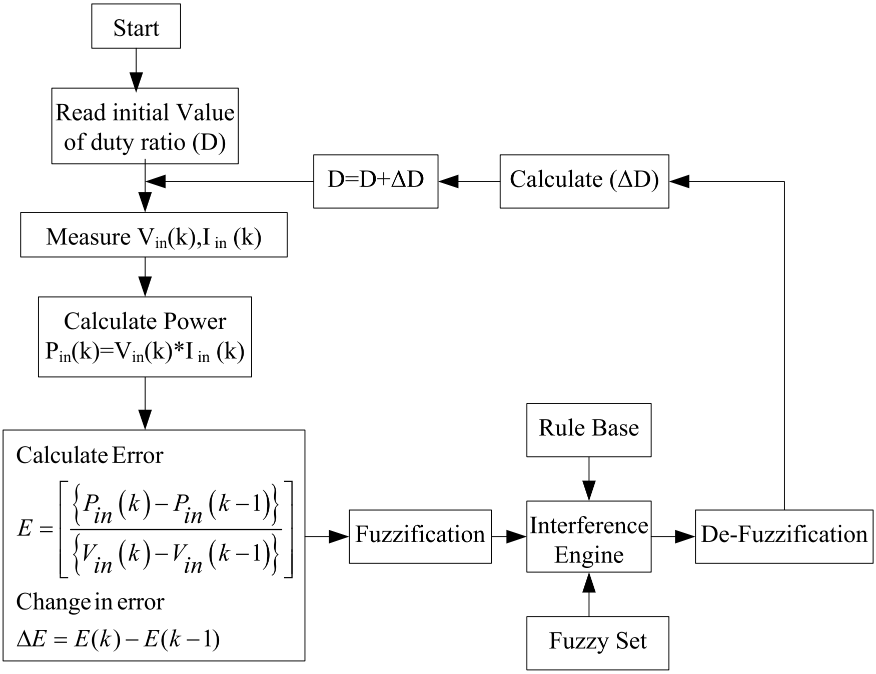


Fig. 10 Flowchart of fuzzy MPPT

11 Boost Converter

Boost converter is simplest DC-DC converter. Converter enhance voltage using an input, as its name implies. With regard to increasing the amount of DC voltage, it is comparable to a step-up transformer. The PV panel's voltage needs to be raised because of the PV panel's extremely low output, so it can be connected to the grid. A very small DC voltage is produced by the solar panel. So, to increase the voltage without using a transformer, a boost converter is needed. A support converter's main components are inductor, diode, and high-repetition switch. To maintain consistency of heap voltage, one capacitor is connected over the end of heap.

It is made up of supply voltage, resistive load, switching device, capacitor, inductor, diode, and resistor. Figure 11 shows boost converter's circuit diagram.

11.1 Modes of Operation

In assistance converter, there are two ways to operate it. These are in consideration of switch's closing and opening. Switch is closed in first mode, also referred to as the charging technique of operation. The second mode, sometimes referred to

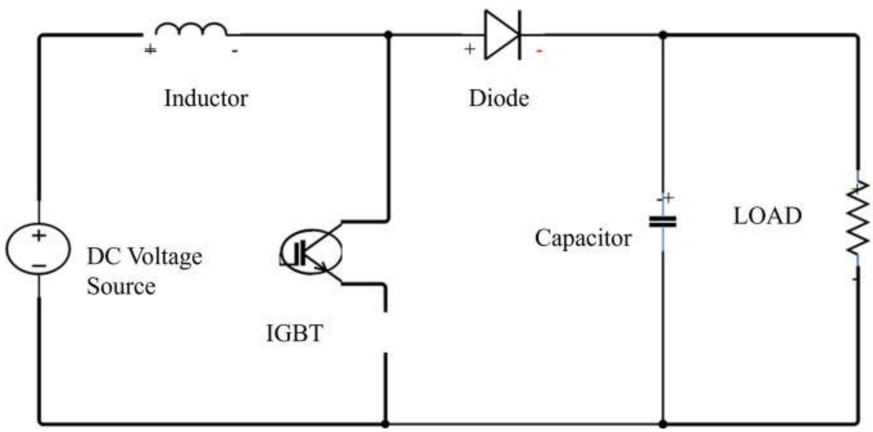


Fig. 11 Circuit diagram of boost converter

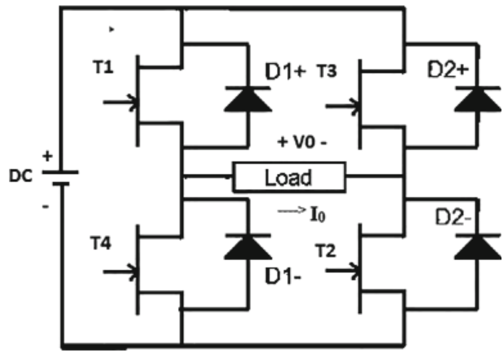
as the releasing technique of operation, is the state in which the switch is open. Figure 12 shows the circuit diagram for a support converter.

(1) When switch is ON
(2) When switch is OFF

Inductor current starts to increase when switch is ON and is closed. Because it is unable to discharge during this time and the diode will be reverse-biased, the capacitor remains charged. Of course, because the current ramps up to some extent gradually.

Moreover, input current to inductor abruptly increases when switch is in OFF state and is open. Also, the inductor opposes this abrupt change in current because it is intended to ensure a steady current flow. As a result, it produces a strong voltage with a polarity opposite to that of the voltage that was initially applied to it. In conjunction with the supply voltage, the inductor works as a voltage source. As a result, diode will be forward-biased.

Fig. 12 Full-bridge single-phase inverter



The output capacitor thus reaches a larger voltage charge and increases the voltage.

12 Full-Bridge Single-Phase Inverter

Square-wave inverters and PWM inverters are both acceptable types of single-stage inverters. The simplest way to convert DC to AC is the square wave kind; but, because of its low recurrence, it has difficulty cutting through background noise to keep the music from returning to the transformer's primary side. Because the sounds are powered by a PWM inverter, they are louder than the basic (line) recurrence, which reduces the need for an inverter's separate output.

12.1 Circuit Diagram

Figure 12 illustrates the circuit diagram of a full-bridge single inverter which has four switches connected as two bridges S1, S2, S3, and S4. To get square-wave AC yield signal, switches (denoted S1 through S4) are controlled using square-wave switching technique. By using control pulse with a fifty per cent duty cycle connected to S1 and S4, the AC output is achieved. Additionally connected to S2 and S3 is a modified version of the same sign. This trading strategy ensures that S1 and S4 consistently operate even when other two switches S2 and S3 turned off and produces square wave shown in Fig. 13. Benefits of H-bridge inverter is that it requires one straightforward control signal to manage four transistors. Square wave's low-quality AC output, which pumps lots of music into the heaps it is powering, is, however, a downside.

The same H-span architecture can be used with PWM control indications. In comparison with the square-wave exchanging plan, the PWM exchanging plan is less clear, which is a disadvantage.

The PWM inverter's transistors are anticipated to be controlled by several, relatively complex control signals. However, the PWM exchanging strategy's interesting feature is that it can provide a higher sinusoidal yield than square-wave types.

13 Single-Phase D-Q Transformation Theory:

$\alpha\beta$-components are determined from instantaneous phase voltages (Va and Vb). Current can be calculated in the same way as voltage. Without any matrix transformation, single-phase system can convert straight into $\alpha\beta$-frame. Original current and voltage are converted into imaginary variable by rotating it by 90 degrees and as a result, original signal and imaginary signal both reflect load current in $\alpha\beta$ co-ordinates

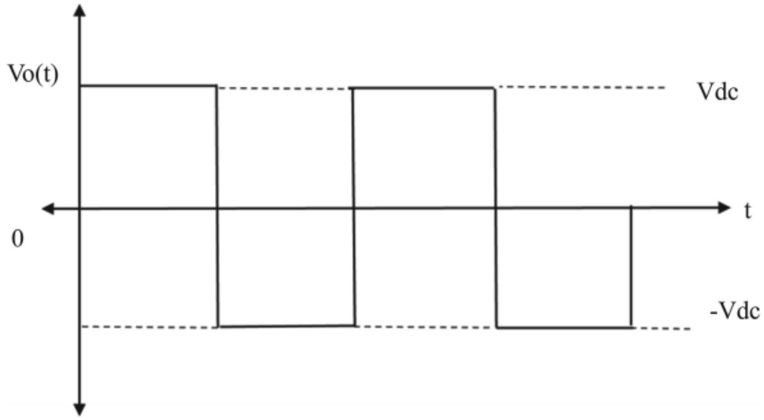


Fig. 13 Square-wave output of an inverter

[23].

$$\begin{bmatrix} i_{L\alpha} \\ i_{L\beta} \end{bmatrix} = \begin{bmatrix} i_{L(\omega t+\emptyset)} \\ i_{L(\omega t+\emptyset+\pi/2)} \end{bmatrix} \tag{4}$$

From the above equation, we can write as

$$\begin{bmatrix} i_{Ld} \\ i_{Lq} \end{bmatrix} = \begin{bmatrix} \sin(\omega t) & -\cos(\omega t) \\ \sin(\omega t) & \sin(\omega t) \end{bmatrix} \begin{bmatrix} i_{L\alpha} \\ i_{L\beta} \end{bmatrix} \tag{5}$$

Fundamental and harmonic components can be derived from i_{Ld} and i_{Lq} by employing the proper filters. LPF and AC components are used to produce the DC components i_{Ld} and i_{Lq}, and HPF is used to obtain i_{Ld} and i_{Lq}.

Since we are employing a DC component to generate the reference current in this case, the indirect technique is referred to as such. The fundamental parts of source current is all it required.

$$\begin{bmatrix} i_{Ld}^{*} \\ i_{Lq}^{*} \end{bmatrix} = \begin{bmatrix} i_{Ld}^{-}+0 \\ 0+0 \end{bmatrix} \tag{6}$$

$$\begin{bmatrix} i_{s\alpha}^{*} \\ i_{s\beta}^{*} \end{bmatrix} = \begin{bmatrix} \sin(\omega t) & -\cos(\omega t) \\ \cos(\omega t) & \sin(\omega t) \end{bmatrix}^{-1} \begin{bmatrix} i_{Ld}^{*} \\ i_{Lq}^{*} \end{bmatrix} \tag{7}$$

The preceding equation includes component i_{DC} in order to achieve constant voltage of DC across active filter.

$$\begin{bmatrix} i_{s\alpha}^{*} \\ i_{s\beta}^{*} \end{bmatrix} = \begin{bmatrix} \sin(\omega t) & \cos(\omega t) \\ -\cos(\omega t) & \sin(\omega t) \end{bmatrix} \begin{bmatrix} i_{Ld}^{-}+i_{DC} \\ 0 \end{bmatrix} \tag{8}$$

Therefore, the reference signal is

$$i_{s\alpha}^{*}(\omega t) = \sin(\omega t)\left(i_{Ld}^{-} + i_{DC}\right) \tag{9}$$

To make gating pulses for inverter switches, which then inject compensatory current into line, created reference current is employed [23].

13.1 LCL Filter Topologies

High-frequency harmonics arises in gird system due to nonlinear loads. These are removed by using L filters. As L filters are voluminous and inefficient for removing harmonics standard regulations, there are three types of filters are advised in the literature:

1. First order (L)
2. Second order (LC),
3. Third order (LCL) [23].

Reduced power losses and high attenuation performance filters are given preference when selecting the best filter topology.

LCL and L filters exhibit similar attenuation behaviour at low frequencies. While the L filter offers superior attenuation, LC and LCL filters both have a significant resonance peak in the second zone that can make the system unstable. LCL filters provide stronger attenuation for high frequencies than L and LC filters, and it is in this range that they are most useful. LCL filters appear to be more suited for our application when cost, weight, and harmonic attenuation are taken into account; however, they have resonance peaks that can be removed using a passive damping technique.

14 Modelling of Hybrid EV Charging System Using MATLAB

A hybrid EV charging system is created in MATLAB Simulink. It consists of solar array, DC-DC boost converter, fuzzy logic controller block, battery considered as EV battery, bidirectional converter, and full-bridge single-phase inverter.

For modelling the system, grid-connected solar system with an EV battery system requires a PV array and each panel is connected in series. This array can generate a total power of 2000 watts at standard test conditions (Table 1).

So, from P–V and I–V characteristics of solar array, for 1000 $\frac{\text{watts}}{\text{m}^2}$ we get maximum power of around 2000 watts and changes according to variation in irradiance. So, solar system is associated with common DC bus through DC-DC boost converter.

Table 1 Ratings of PV array

Maximum power	W	250
Open circuit voltage	V_{OC}	37.3
Short-circuit current	I_{SC}	8.66
Voltage at maximum power point	V_{mp}	30.7
Current at maximum power point	I_{mp}	8.15
Temperature	T	25

For maximum power traction, fuzzy logic controller is used, and it provides gate pulse to the boost converter. Here, this fuzzy system is created using the Mamdani algorithm which is a product implication method. Two inputs of fuzzy logic system are change in voltage and change in power which occurs due to variations in irradiance, and output of system is given to PWM generator that generate gate pulses.

Input variables of fuzzy system:

- Change in power
- Change in voltage

Output of fuzzy system:

- Duty cycle

The range for input variables for both inputs of MPPT is (−3 3), and for output membership functions range taken is (−0.2 0.9).

The fuzzy logic approach is used to construct rules for precisely tracking the MPPT based on P–V curve of PV panels. Both input variables and output variables in this case use five membership functions. Three membership functions are of the triangular type, while two are of the trapezoidal kind. These five are known by the abbreviations Negative Big, Negative Small, Zero, Positive Small, and Positive Big. Along with IF–THEN logic, AND logical operator is used to join the two input variables. For the operation, a list of 25 rules is developed. The created fuzzy rule is displayed in Table 2.

Table 2 Fuzzy rule table [19] for $\Delta Vpv * \left[\frac{o}{p}\right]$

$\Delta Ppv\left[\frac{i}{p}\right]$ or DP	$\Delta Vpv\left[\frac{i}{p}\right]$ or DV				
	NB	NS	ZE	PS	PB
NB	PB	PS	PS	NS	NB
NS	PS	PS	PS	NS	NS
ZE	ZE	ZE	ZE	ZE	ZE
PS	NS	NS	NS	PS	PS
PB	NB	NS	NS	PS	PB

Table 3 Rating of EV battery

Nominal voltage	V	240
Rated capacity	Ah	48
State of charge (SOC) %	%	50

The fuzzy rule algorithm operates as follows: -

- When both change in voltage and change in power are increasing, output duty cycle must be decreased.
- When change in voltage is up and change in power is down, output duty cycle must be increased.
- When change in voltage is down and change in power is up, output duty cycle must be increased.
- When both change in voltage and change in power (DP) are decreasing, output duty cycle must be decreased.

After measuring voltage and current, it is given to fuzzy algorithm as input variables and then it generates a duty cycle. Then, this duty cycle is processed via a PWM generator to generate the gate pulse which controls IGBT of boost converter.

Next, a battery that is considered as an EV battery is associated with same DC bus through bidirectional converter. Ratings of EV battery is given in Table 3.

State of charge (SOC): Distinction between EV battery fully charged and one that is currently in operation is known as the state of charge. It is related to how much power is still there in the cell. It is determined by dividing battery's maximum charge transfer capability to battery's remaining charge. As shown below, it is represented as a percentage.

$$\%\, SOC = \frac{100(Qo + Q)}{Q\,\text{max}} = SOCo\,\% + \frac{100Q}{Q\,\text{max}} \tag{10}$$

where $\frac{Qo}{mAh}$ is the initial charge of battery and $\frac{Q}{mAh}$ is the amount of electricity supplies or delivers. It operates in accordance with the current convention, which states that it is negative during discharge and positive when charging,

$$\text{The maximum charge that can be stored} = \frac{Q\,\text{max}}{\text{mAh}}$$

SOC% = primary state of charge (SoC/%).

DC bus voltage must be maintained by regulating the voltage of bidirectional DC-DC converter linked to EV battery. As a result, single-phase grid connection ensures that 400 V nominal voltage is maintained. Actual bus voltage is compared to reference voltage for bidirectional DC-DC converter voltage management. Based on the error signal, a PI controller creates duty cycle. Additionally, a PWM generator processes this duty cycle to produce the pulse.

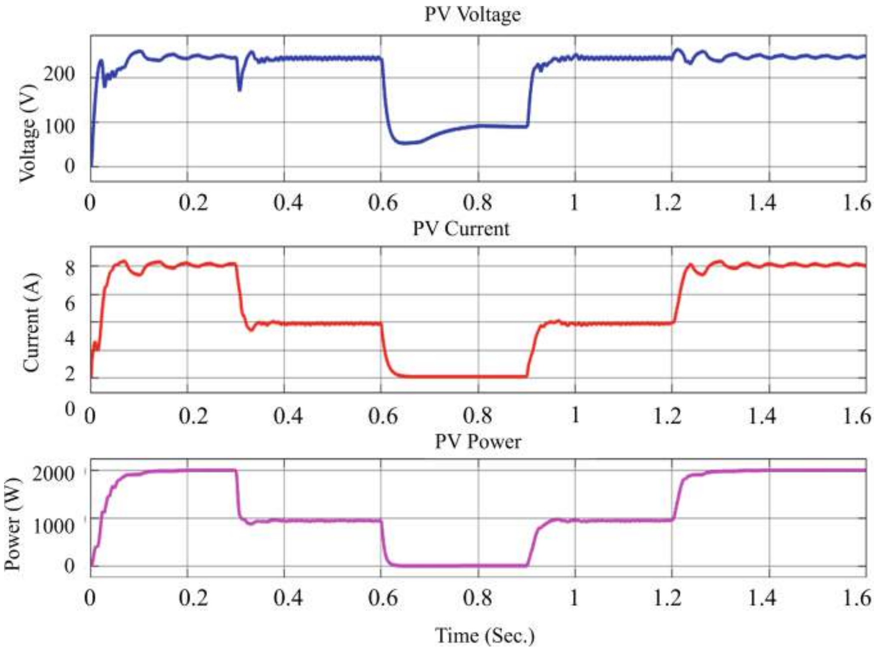


Fig. 14 Voltage, current, and power curves of PV array

For grid synchronization, single-phase grid with ratings of 230 V and 50 Hz is connected to DC bus via an LCL filter and single-phase full-bridge inverter. Now for generation of current reference, PV power and reference power at MPP is used to generate current reference in unbalanced d-q fame. So, using the inverter current, d-reference and q-reference currents are generated by means of ab to d-q conversion. After that, d-q reference currents are compared to grid current by using current PI controller and controlled output is generated. Now this controlled output current is again converted into ab quantity by means of d-q to ab conversion, and then, only 'a' quantity is being used to generate control signal for single-phase converter. This control signal is processed via PWM generator to generate the pulse for single-phase inverter.

Hybrid system for charging EV battery is modelled using MATLAB Simulink shown in Fig. 14.

15 Simulation Results

An EV battery charging powered by both solar PV and grid is performed in MATLAB Simulink. Figure 14 shows graphs of voltage, current, and power of solar system. When irradiance is 1000 watts/metre sq., then output power of PV is around 2000

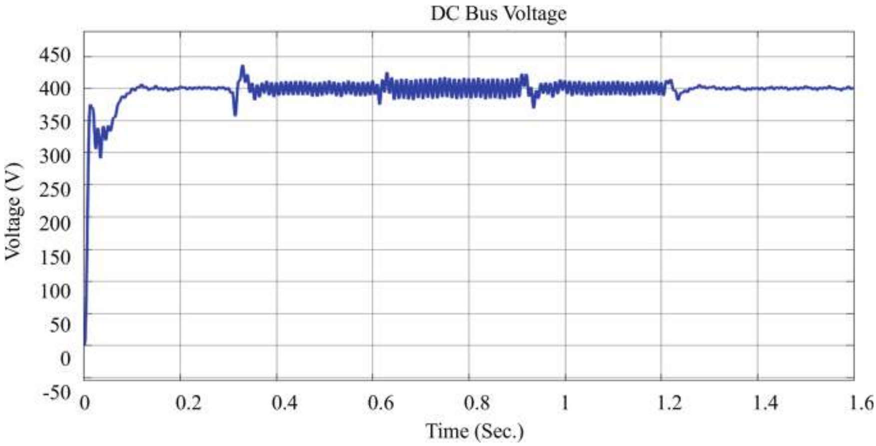


Fig. 15 DC bus voltage graph

watts and voltage, and current outputs are 230 V, and 8 A. Now, when irradiance is decreased to 500 watts/metre sq., then power is also decreased from 2000 to 1000 watts. Hence, output current also drops.

Now Fig. 15 shows DC bus voltage graph which is maintained at 400V after boosting the PV voltage by using DC-DC boost converter.

Figure 16 shows the graphs of voltage, current, and power of EV battery associated with DC bus through bidirectional converter. According to results when output current and power is around 8 Amps and 2000 watts, then EV battery gets charged. And -8 Amps shows that EV battery is charging.

But when the PV power drops, then battery is continuously supplied by grid connected to same common DC bus which is maintained at 400 Volts. And EV charging system is based on solar system and grid. Figure 17 illustrates state of charge of battery in percentage.

Figure 18 illustrates the output graphs of grid connected to DC bus through single-phase inverter. Now when output power of PV drops, battery gets power from grid as shown in Fig. 19. This illustrates that when output power of PV drops due to change in irradiance from 2000 watts to 1000 watts, then remaining 1000 watts is supplied by the grid to charge the EV battery, so that 2000 watts of power at EV battery is maintained.

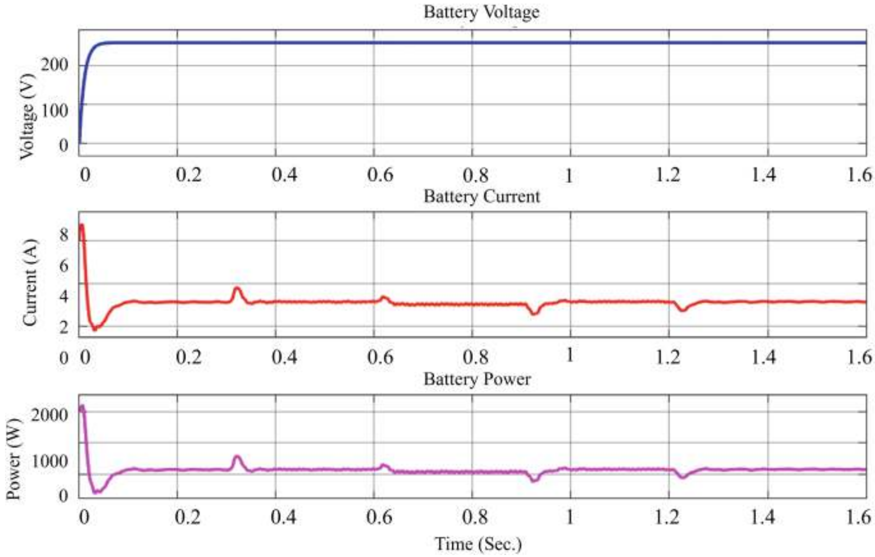


Fig. 16 Voltage, current, and power curves of EV battery

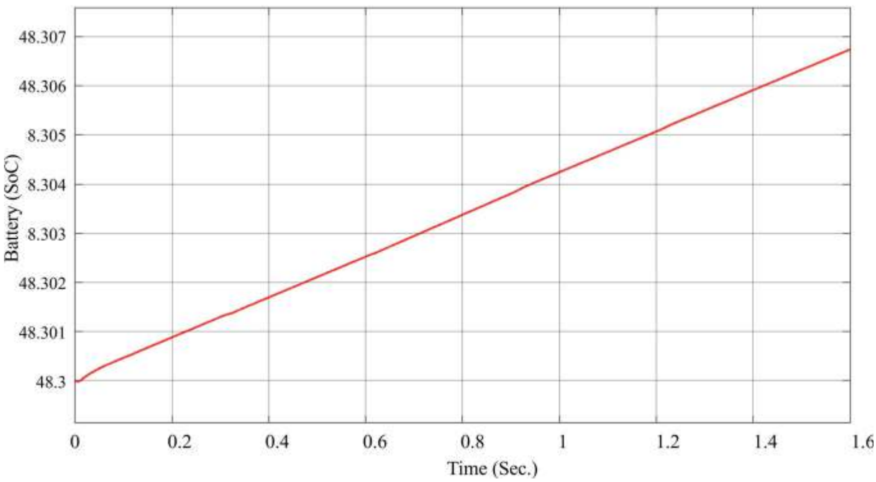


Fig. 17 SOC of battery

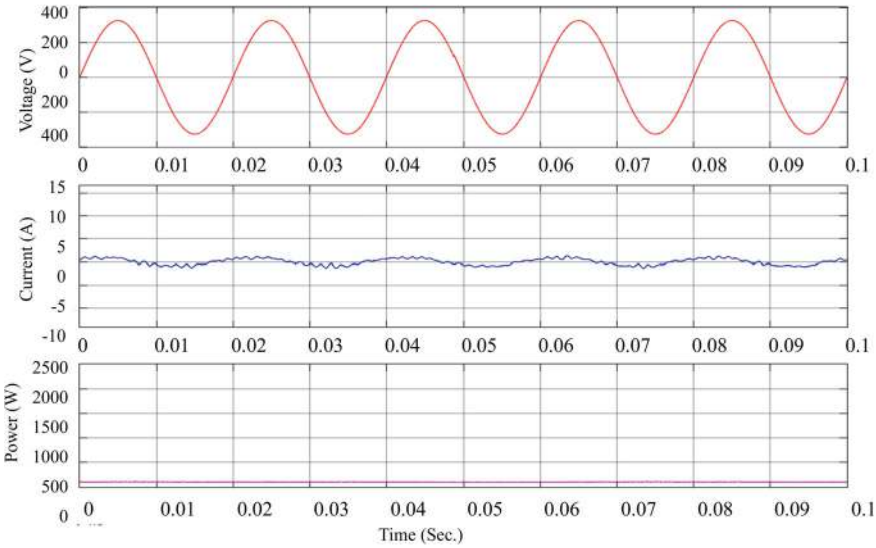


Fig. 18 Voltage, current, and power curves of grid

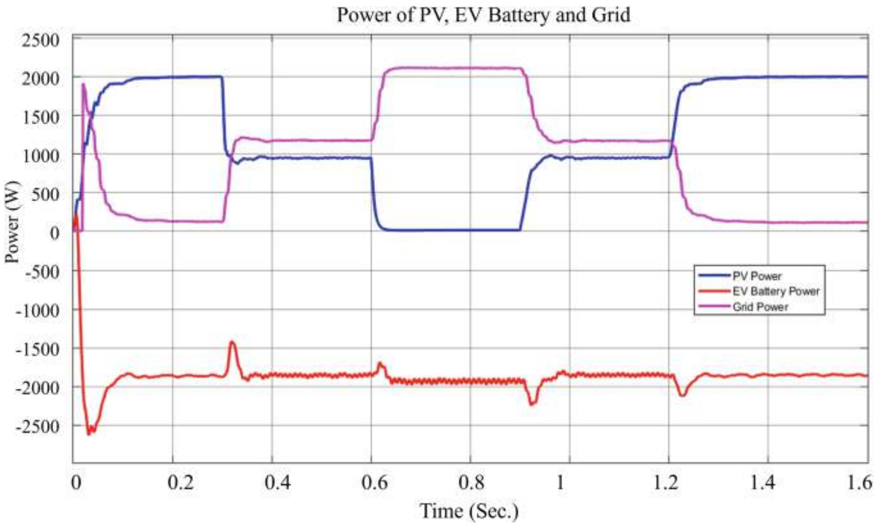


Fig. 19 Output powers of PV, EV battery, and grid

16 Conclusion

EV charging system based on photovoltaic (PV) solar power system is a practical and accessible option among available renewable energy sources. When solar irradiance and temperature is sufficient, CS harnesses power from PV array to feed EV battery connected, and when there is less sunlight then, EV battery is fed by a grid connected to a common DC bus which is maintained at 400V. Then, the battery starts charging at 240V DC without any interruption irrespective of change in irradiance. Fuzzy logic-based MPPT is efficient than the other conventional techniques. By giving clean and sustainable energy to electric vehicles, which already run in an environmentally favourable manner, this multimode EV charging station helps move us closer to our aim of reaching net carbon zero. Although there are many advantages to integrating green energy with the main grid, there are also some important integration challenges that must be considered. To overcome these obstacles and implement hybrid charging infrastructure on a broad scale, appropriate techniques must be used.

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Chapter 11
Effective Multiport Battery Charging Facility, Operation and Control in Hybrid Isolated Microgrid System

Sombir Kundu, Ashutosh K. Giri, Madhusudan Singh, and Sukhbir Singh

Abstract The transportation sector emits a substantial quantity of carbon dioxide and substances into the atmosphere across the world. The use of Electric Vehicles (EVs) has the potential to significantly cut co_2 emissions while also providing essential storage of energy to contribute to the acceptance of distributed renewable energy sources (RESs). This chapter presents the development of a hybrid isolated microgrid (MG) system based on the Intelligent Generalized Maximum Versoria Criterion Filtering (IGMVCF) control algorithm (Badoni et al. in CSEE J. Power Energy Syst. 9:722–732, 2023 [1]). This system is used for charging several batteries and supplying electricity to single-phase loads in remote places. This study presents a concept and approach for promoting EV adoption through automated battery swapping at charging stations. In addition, the proposed IGMVCF control with VSC preserves power quality (PQ), load balance, and power support under dynamic conditions. The proposed approach offers unique approaches to some of the most essential issues facing adoption of EV today, including range anxiety, battery swapping with zero waiting periods, and cost.

Keywords Isolated hybrid MG · Battery swapping · Multiple ports · Power quality

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Nomenclatures

IGMVCF, MG	Intelligent Generalized Maximum Versoria Criterion Filtering, Microgrid
VSC, PQ	Voltage source converter, Power quality
BES	Battery energy storage
RES, SEIG	Renewable energy sources, Self excited induction generator
MPPT, PV	Maximum power point tracking, Photovoltaic
INC	Incremental conductance
OEMs	Original equipment manufacturer
v_{sa}, v_{sb}, v_{sc},	Source voltages
i_{La}, i_{Lb}, i_{Lc}	Load currents
i_{ca}, i_{cb}	Compensator currents
u_{pabc}, u_{qabc}	In-phase & quadrature unit templates
i_{b1} and i_{b2}	Battery currents
i_{sabc} and i^*_{sabc}	Sensed and reference source currents

1 Introduction

EVs are widely regarded as the potential of transportation by both auto sector professionals and leading original equipment producers throughout the world. Governments throughout the world are rapidly establishing zero-emission regulations to promote the transition to an all-electric future, complementing OEMs' promises. These criteria frequently include rules requiring manufacturers to cut vehicle emissions, as well as particular sales objectives for zero-emission vehicles (ZEVs), such as EVs. The California Air Resource Board's (CARB) ZEV policy aims to cut emissions by 40% in 2030 compared to 1990 levels, and 80% by 2050, utilizing rules and ZEV credits for manufacturers who build a substantial number of electric cars. China's New EV requirements are identical to the CARB criteria. Both seek to promote the use of ZEVs through a mix of legislative mandates and incentives. Under China's NEV program, manufacturers were expected to ensure that 2.5% of all automobiles sold were NEVs by 2018, with the goal rising to 8% in 2025. These aims are part of China's overall effort to decrease pollution and promote sustainable transportation [2]. According to [3], The expected increase in EV market share from roughly 1% now to over 30% in Europe and 15% in the United States by 2025, with an estimated 130 million EVs worldwide by 2030 presents major technological problems, notably in terms of grid dependability. The existing power generating and distribution infrastructure in many locations was not built to manage the increased demand that such fast EV adoption will entail [4, 5]. While transitioning to an all-electric future poses enormous difficulties, it also provides a chance to build a more sustainable, robust, and efficient energy system. The barriers to rapid EV adoption may be efficiently overcome by encouraging collaboration across industries and investing in essential infrastructure and technology. Successfully navigating these hurdles is critical to achieving the environmental and economic benefits of a fully electrified transportation system [6]. While DC fast charging allows for speedy recharging of an EV, it also accelerates battery degeneration when compared to slower AC charging. As the EV industry grows, solving these concerns through advances in battery technology and customer education will be critical to maintaining EVs' long-term dependability and performance [7]. While transitioning to an all-electric future poses enormous difficulties, it also provides a chance to build a more sustainable, robust, and efficient energy system. The barriers to rapid EV adoption may be efficiently overcome by encouraging collaboration across industries and investing in essential infrastructure and technology. Successfully navigating these hurdles is critical to achieving the environmental and economic benefits of a fully electrified transportation system [8]; Battery sharing stations and networks (BSSN) provide a possible alternative to traditional battery swapping models by addressing issues such as EV size and grid stability. While public acceptability and battery leasing problems must be carefully addressed, the potential benefits of higher grid reliability, improved battery management, and expanded accessibility make these options worthwhile. To ensure successful implementation, user concerns must be addressed, infrastructure investments made, and stakeholder participation fostered [9]. The proposed BSSN architecture provides a comprehensive solution to critical difficulties in EV uptake, battery management, and grid stability. By integrating diverse subsystems and using new technologies such as IOT and grid coupling, the BSSN intends to improve the overall efficiency and sustainability of the energy system. This novel concept might offer a more adaptable, dependable, and scalable solution to meet the rising demand for electric cars and their impact on the power grid [10]. A RES integrated with the BSS is expressed in [11]. An appropriate BSS arrangement should balance the battery packs and number of chargers, taking into account aspects such as demand, charging time, and operating efficiency [12]. For a Battery Swapping Station (BSS) and Battery Sharing Network (BSN) to efficiently handle both grid-to-vehicle (G2V) and vehicle-to-grid (V2G) power transfers, appropriate converter and charger topologies are required. These topologies enable more efficient power transfer between the grid, cars, and energy storage devices [13]. Effective energy management in MGs requires a multifaceted approach that includes economic scheduling at multiple time scales, integrating renewable energy sources, controlling deferrable demands, and encouraging communication within MG clusters. MGs can improve dependability, save costs, and contribute to a more sustainable energy system by implementing advanced forecasting, control systems, and optimization approaches, which was examined in [14, 15] for exchanging energy and allocating reserves. MATPOWER is a strong tool for scheduling electricity across several generation sources, including wind, nuclear, gas-based DG, and hydro, as well as managing reserve capacity. By leveraging its skills for efficient power flow and economic dispatch, we may effectively manage and optimize the functioning of different energy sources while maintaining system dependability and cost-effectiveness [16]. The energy management of numerous MGs with heat and electrical energy systems was described in [17] Using a distributed optimization technique for an AC-DC hybrid MG and including demand response programs requires a complicated interaction of various parameters. Dividing the optimization problem into digestible subproblems, coordinating between AC and DC systems, and incorporating demand response strategies was presented in [18], Using Hong's two-point estimation method to describe uncertainties, as well as a mix of Particle Swarm Optimization (PSO) and fuzzy logic systems for economic dispatch, gives a robust solution to community MG management. This technique enables appropriate resource scheduling while handling the unpredictable nature of load demand and RESs [19, 20]. A grid-connected MG may be optimized to save overall costs while meeting load demand, controlling the fluctuation of RESs, and incorporating distributed generation, solar systems, and battery storage. MG energy management is made efficient and economical by utilizing sophisticated optimization techniques such fuzzy logic systems and PSO in conjunction with real-time and predictive control [21]. Dynamic programming-based economic dispatch in grid-connected MGs was presented in [22, 23] for minimizing total operational costs. Several steps are required to economically schedule a grid-connected MG with hybrid energy sources utilizing Distributed Model Predictive Control (DMPC) and Mixed Integer Linear Programming (MILP). This technique optimizes MG operation by taking into account both the economic and technical limits of diverse energy sources. The economic schedule of a grid-connected MG with hybrid energy sources was created using the distributed model predictive control approach and solved with mixed integer linear programming [24, 25]. In [26], Using quadratic programming to reduce grid costs in a grid-connected MG equipped with PV, BES, and a diesel engine enables effective power dispatch optimization. By precisely modeling costs and restrictions and solving the QP issue, you may create a cost-effective and dependable power dispatch plan that balances renewable energy, storage, and backup production [27–30]. A well-structured optimization issue may be handled using PSO to lower operating costs in an island hybrid system that consists of PV systems, wind turbines (WT), diesel generators (DG), fuel cells (FC), and BSS. To reduce the system's net present cost (NPC), it is necessary to evaluate these components' optimum capacity [31–34]. Two stage methodology introduced in [35] for dynamic power dispatch in isolated MGs using micro turbines and energy storage devices with demand side control. This two-step technique enables a full analysis of various options and selection of the best choice for energy scheduling in isolated MGs. The application of dominance-based evolutionary algorithms aids in the generation of a varied range of near-optimal solutions, while decision analysis assures that the final option successfully satisfies all operational and economic objectives [36–40]. The use of robust optimization approaches for energy management in MGs has been addressed [41]. Critical difficulties in this form of MG include power balancing and reserve power allocation. Furthermore, numerous academics have addressed the energy management problem using adaptive control systems. According to a comprehensive analysis of the most current research, several studies have mostly focused on battery switching, numerous battery charging ports, and improving the overall power quality of a hybrid isolated MG system.

The main contribution of this chapter is given as.

(1) The proposed IGMVCF control with VSC provides harmonics elimination, load balancing, and enhancement in overall PQ in wind-solar-BES based hybrid isolated MG system.
(2) A battery swapping technology is employed to provide fully charged battery facility with zero waiting periods for commercial vehicles.
(3) An MPPT control-based PV system and multiple batteries for charging are connected at DC link of the VSC and load side with nonlinear load diode rectifier of the proposed isolated MG system.
(4) The Total Harmonic Distortion (THD) of source current is found less than 5% which meets the IEEE-519 standard.

2 System Topology

A detailed block diagram of the multiple ports charging-based isolated hybrid system is displayed in Fig. 1. The proposed system consists of an MPPT boost converter for the PV system, wind-driven SEIG, single-phase loads, VSC, and multiple batteries charging facility. The output of the PV system defines the DC bus voltage, and it varies with changes in solar intensity level. The batteries are connected at DC link side and load side with diode rectifier. Further, an IGMVCF-based control approach with VSC is also implemented to maintain the parameters of isolated system and battery charging facility.

3 Control Strategies for Isolated System

A detailed discussion of the IGMVCF control approach and the selection criteria for its gains is presented in this section. The load current processing procedure is discussed to deal with abnormal conditions of wind, solar, and unbalanced load and achieve synchronized operation of the standalone system. The development of an IGMVCF technique to control the multiple batteries charging based isolated hybrid MG system is discussed in this section. The IGMVCF control approach aims to draw the fundamental component from the non-sinusoidal & imbalanced load currents, generate reference currents, and then take part in the gating pulse-generating process for the VSC used in the configuration.

(a) **Modeling of IGMVCF control approach**

The modeling of the IGMVCF control approach is given as,

$$d(m) = x(m)^T \Delta_o + V_m \tag{1}$$

where the input and output vectors are $x(m) = [x(m), x(m-1), \ldots\ldots, x(m-L+1)]^T$ and $d(m)$, the variables time index (m), ,

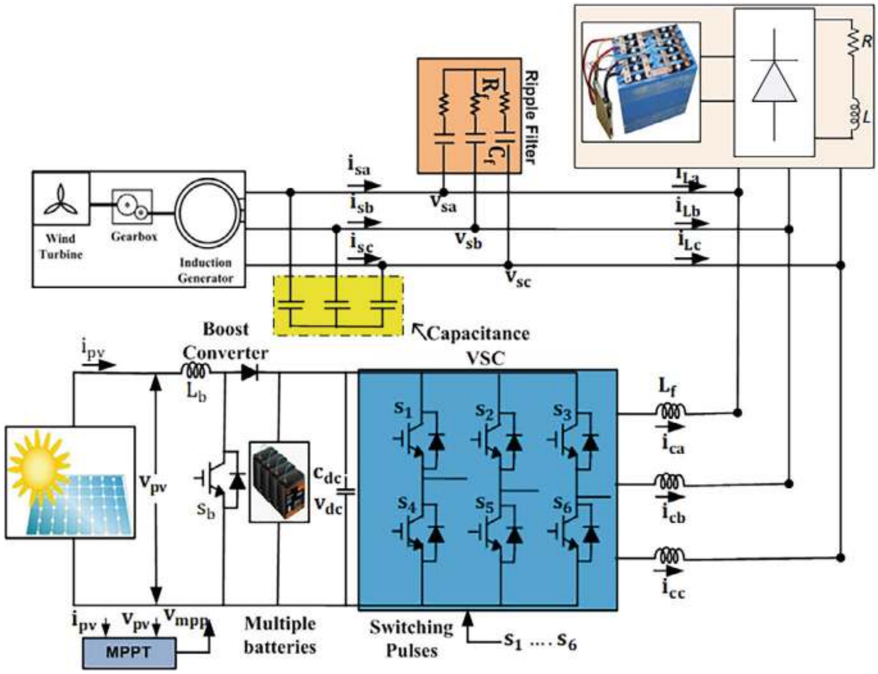

Fig. 1 System topology for multiple batteries charging based isolated hybrid MG system

filter length (L) and transpose of the unit vector (T), Signal distortion (V_m) and ρ_o is the undefined weight vector that is required to be determined. The equation for the computation of output $e(m)$ error is formed as

$$e(m) = d(m) - x(m)^T \Delta_o - 1 \tag{2}$$

where $\rho_o - 1$ defined the iteration $(m - 1)$th of ρ_o.

The Versoria function is employed in the proposed approach and is denoted as,

$$f\{e(m)\} = \frac{8c^3}{4c^2 + e(m)^2} = 2c\frac{1}{1 + \{e(m)/2c\}^2} \tag{3}$$

where, 'c' is the radius of the Versoria generating circle ($c > 0$).

A generalized Versoria function based on the generalized Gaussian probability density function is shown as,

$$f\{e(m)\} = 2c\frac{1}{1 + \{e(m)/2c\}^s} = 2c\frac{1}{1 + \tau|e(m)|^s} \tag{4}$$

where (s) is the shape parameter ($s > 0$) and parameter $\tau = (2c)^{-p}$ is the Versoria shape parameter. The generalized versoria criteria is now expressed as,

$$J\{w(m-1)\} = E\left[\frac{1}{1+\tau|e(m)|^{s}}\right] \tag{5}$$

where, $E[.]$ shows the expectation operator. Finding the gradient of the Versoria cost function yields the suggested robust adaptive control method (after separating $E[.]$) given in (5), concerning $\rho(m-1)$ as,

$$\nabla J\{\rho(m-1)\} = \tau\rho\frac{1}{(1+\tau|e(m)|^{s})^{2}}|e(m-1)|^{s-1}\ \text{sign}\ \{e(m)\} \times (m) \tag{6}$$

The weight vector renew equation of the maximum Versoria criteria strategy may be found using the stochastic gradient technique, as given in [42, 43]

$$\rho(m) = \rho(m-1) + \nabla J\{\rho(m-1)\} \tag{7}$$

$$\rho(m) = \rho(m-1) + \mu\frac{1}{(1+\tau|e(m)|^{s})^{2}}|e(m-1)|^{s-1}\ \text{sign}\ \{e(m)\} \times (m) \tag{8}$$

where (μ) is the step size parameter. Weight vector updating Eq. (8) of the maximum Versoria criterion is employed to harness fundamental active/reactive values from the nonlinear load currents. These equations for deriving fundamental active/reactive values of $i_{\text{La}},\ i_{\text{Lb}},$ and i_{Lc} are provided as Eqs. (9–14)

$$\rho_{\text{pa}}(m) = \rho_{\text{pa}}(m-1) + \mu\frac{1}{(1+\tau|e_a(m)|^{s})^{2}}|e_a(m-1)|^{s-1}\ \text{sign}\ \{e_a(m)\}u_{\text{pa}} \tag{9}$$

$$\rho_{\text{pb}}(m) = \rho_{\text{pb}}(m-1) + \mu\frac{1}{(1+\tau|e_b(m)|^{s})^{2}}|e_b(m-1)|^{s-1}\ \text{sign}\ \{e_b(m)\}u_{\text{pb}} \tag{10}$$

$$\rho_{\text{pc}}(m) = \rho_{\text{pc}}(m-1) + \mu\frac{1}{(1+\tau|e_c(m)|^{s})^{2}}|e_c(m-1)|^{s-1}\ \text{sign}\ \{e_c(m)\}u_{\text{pc}} \tag{11}$$

$$\rho_{\text{qa}}(m) = \rho_{\text{qa}}(m-1) + \mu\frac{1}{(1+\tau|e_a(m)|^{s})^{2}}|e_a(m-1)|^{s-1}\ \text{sign}\ \{e_a(m)\}u_{\text{qa}} \tag{12}$$

$$\rho_{\text{qb}}(m) = \rho_{\text{qb}}(m-1) + \mu\frac{1}{(1+\tau|e_b(m)|^{s})^{2}}|e_b(m-1)|^{s-1}\ \text{sign}\ \{e_b(m)\}u_{\text{qb}} \tag{13}$$

$$\rho_{\text{qc}}(m) = \rho_{\text{qc}}(m-1) + \mu\frac{1}{(1+\tau|e_c(m)|^{s})^{2}}|e_c(m-1)|^{s-1}\ \text{sign}\ \{e_c(m)\}u_{\text{qc}} \tag{14}$$

After the evaluation of active/reactive fundamental components as shown in Fig. 2, the control strategy for the generation of reference currents is described below.

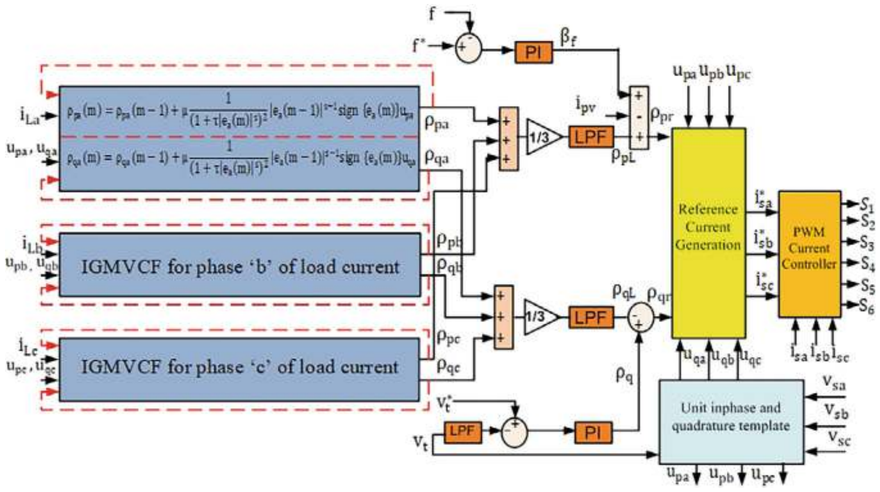

Fig. 2 Control architecture of the proposed multiport battery charged based isolated hybrid system

(b) **Generation of reference current**

The equation shown below can be employed to evaluate voltage amplitude at the PCC,

$$v_t = \sqrt{2\left(v_{sa}^2 + v_{sb}^2 + v_{sc}^2\right)/3} \tag{15}$$

The in-phase unit vectors u_{pa}, u_{pb} and u_{pc} are evaluated using Eq. (15) as [28, 44, 45]

$$u_{pa} = \frac{v_{sa}}{v_t}; \quad u_{pb} = \frac{v_{sb}}{v_t}; \quad \text{and} \quad u_{pc} = \frac{v_{sc}}{v_t} \tag{16}$$

The observed generated voltage is given to the 3-phase PLL and the actual frequency (f) value is determined. The comparison in reference frequency ($f*$) and observed frequency (f) is supplied to the PI controller. The sum of PV current (i_{SPV}) and the PI controller output (β_f) is subtracted from the active component of the fundamental load current $\left(\rho_{pl}\right)$, yielding the consequent active component of reference source current. The following is the method used to obtain the difference after sampling the frequency at the s_{th} sampling instant:

$$f_e(s) = f^*(s) - f(s) \tag{17}$$

The obtained value from Eq. (17) is forwarded to the PI controller (18), which produces the loss component (β_f) output as,

$$\beta_f(m+1) = K_{\text{pd}} \times f_e(m) + K_{\text{id}} \times \int_0^t f_e(m)dm \tag{18}$$

The solarPV current (i_{SPV}) is employed to illustrate the contribution of SPV power in the reference currents. This is the ratio of SPV power ($p_{\text{SPV}} = v^*_{\text{SPV}} i_{\text{SPV}}$) to the voltage amplitude at the PCC (V_A). The active load weight component resulting from the computation of the fundamental active components of load currents in (9), (10), and (11) is estimated as,

$$\rho_{\text{pl}}(m) = \frac{\rho_{\text{pa}}(m) + \rho_{\text{pb}}(m) + \rho_{\text{pc}}(m)}{3} \tag{19}$$

To compute the reference active weight component (ρ_{pr}), use the formula

$$\rho_{\text{pr}} = \rho_{\text{pl}} + \beta_f - i_{\text{SPV}} \tag{20}$$

In addition to u_{pa}, u_{pb} and u_{pc}, (Eq. 16) the component (ρ_{pr}) is utilized to get the fundamental reference active current signals as

$$i^*_{\text{pa}} = u_{\text{pa}} \times \rho_{\text{pr}}, \quad i^*_{\text{pb}} = u_{\text{pb}} \times \rho_{\text{pr}} \quad \text{and} \quad i^*_{\text{pc}} = u_{\text{pc}} \times \rho_{\text{pr}} \tag{21}$$

The quadrature vectors u_{qa}, u_{qb} and u_{qc} are evaluated from the unit in phase vectors as

$$u_{\text{qa}} = -\frac{u_{\text{pb}}}{\sqrt{3}} + \frac{u_{\text{pc}}}{\sqrt{3}},\ u_{\text{qb}} = \sqrt{3}\frac{u_{\text{pa}}}{2} + \frac{(u_{\text{pb}} - u_{\text{pc}})}{2\sqrt{3}},\ \text{and}\ u_{\text{qc}} = -\sqrt{3}\frac{u_{\text{pa}}}{2} + \frac{(u_{\text{pb}} - u_{\text{pc}})}{2\sqrt{3}} \tag{22}$$

Fundamental reactive components acquired in (12), (13) and (14) are utilized to determine the resultant reactive weight component as follows,

$$\rho_{\text{ql}}(m) = \frac{\rho_{\text{qa}}(m) + \rho_{\text{qb}}(m) + \rho_{\text{qc}}(m)}{3} \tag{23}$$

To adjust the voltage at the PCC, a different PI controller is given the error (V_{Aerr}), which is observed by utilizing the reference voltage (v^*_t) and the measured voltage amplitude (v_t). The result of PI is expressed as

$$\rho_q(m+1) = K_{\text{pq}} \times V_{\text{merr}}(m) + K_{\text{iq}} \times \int_0^t V_{\text{merr}}(m)dm \tag{24}$$

Estimates for the reference reactive weight component (ρ_{qr}) are made as

$$\rho_{qr} = \rho_q - \rho_{ql} \tag{25}$$

The multiplication of Eqs. (22) and (25) is employed to generate the quadrature reference current for the standalone MG system as,

$$i_{qa}^* = u_{qa} \times \rho_{qr},\ i_{qb}^* = u_{qb} \times \rho_{qr} \quad \text{and} \quad i_{qc}^* = u_{qc} \times \rho_{qr} \tag{26}$$

The currents obtained in Eqs. (21) and (27) are used to determine the entire reference source currents as,

$$i_{sa}^* = i_{pa}^* + i_{qa}^*,\ i_{sb}^* = i_{pb}^* + i_{qb}^*, \quad \text{and} \quad i_{sc}^* = i_{pc}^* + i_{qc}^* \tag{27}$$

Current errors are formed by comparing the generated currents (i_{sa}^*, i_{sb}^* and i_{sc}^*) with the measured generated currents (i_{sa}, i_{sb} and i_{sc}). To generate switching pulses for the converter, the collected error signals are forwarded to the PWM current controller.

(c) **INC-MPPT control technique**

In the proposed standalone MG system, the PV is connected at DC side of the VSC. To extract maximum power from the VSC, an INC control technique is implemented. The proposed INC technique uses the SPV current (i_{SPV}) and voltage (v_{SPV}) to alter the duty cycle as

$$\text{if } \frac{\mathrm{d}i_{SPV}}{\mathrm{d}v_{SPV}} > -\frac{i_{SPV}}{v_{SPV}} \Rightarrow D = D_{pi} - \Delta D \tag{34}$$

$$\text{if } \frac{\mathrm{d}i_{SPV}}{\mathrm{d}v_{SPV}} = -\frac{i_{SPV}}{v_{SPV}} \Rightarrow D = D_{pi} \tag{35}$$

$$\text{if } \frac{\mathrm{d}i_{SPV}}{\mathrm{d}v_{SPV}} < -\frac{i_{SPV}}{v_{SPV}} \Rightarrow D = D_{pi} + \Delta D \tag{36}$$

where, D_{pi} denotes the previous iteration value and D denotes the update size. The gating pulses are generated by comparing D to a sawtooth signal [33]. The aforesaid control techniques are implemented on the proposed multiport batteries charging based isolated MG system and the outputs waveforms are shown in Sect. 4.

4 Results and Discussion

Here, an IGMVCF control approach is proposed for EVs multiple charging ports based isolated hybrid MG system. The main purpose of this work is to provide fast charging for EVs, battery swapping with zero waiting periods, and supply to single-phase loads for isolated locations. The system comprises various components, including PV panels, batteries, DC to DC converters, single-phase loads, and VSC.

The results of batteries and parameters of isolated hybrid systems are plotted under dynamic conditions of wind speed, solar power, and load perturbation.

(a) **Performance with changing wind speeds and unbalanced loads**

Figure 3 shows the waveform of multiple port battery based isolated hybrid MG system under change in wind speed and unbalanced loading conditions. The wind speed is varied from 17 m/s to 13 m/s and 13 m/s to 15 m/s at $t = 2$ s and $t = 2.1$ s. A small single-phase load is supplied to the proposed hybrid system and the one-phase load is detached at $t = 2.1$ and inserted again $t = 2.2$ s.

During the dynamic conditions of load, the IGMVCF control approach with VSC maintains the (v_{sabc}), (i_{sabc}) and freq. (f) constant. The battery (b_1) is connected at Dc link of the VSC and the battery (b_2) is attached at single-phase nonlinear load. The battery charging current (i_{b1}) is reduced (1.9A) during the dynamics in wind speed and raised (2.1A) during reduction in load. The battery (b_2) charging current is constant during dynamics.

(b) **Performance of batteries and isolated MG system under change in solar intensity**

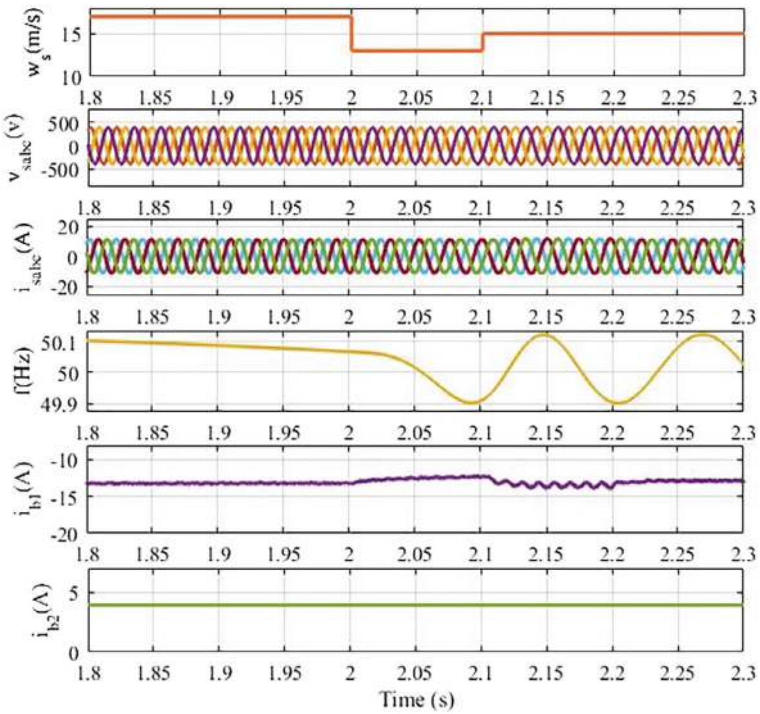

Fig. 3 Performance under change in wind speed and unbalanced load

Figure 4 displays the waveform of batteries current and various parameters of isolated hybrid MG system. The results display the solar intensity level is changed from 1000 w/m^2 to 700 w/m^2 and 700 w/m^2 to 900 w/m^2 at $t = 1.9$ s and 2.1 s. The solar power (S_{pv}) from 3.1 kW to 2.35 kW and 2.35 kW to 2.72 kW and PV current (i_{pv}) from 12.9A to 8.8A and 8.8A to 10.92A are decreased, respectively.

In the proposed work, the single-phase loads for the local consumers is taken minimum, the maximum is supplied by the EV batteries which are connected at DC link side and diode rectifier at load side. The load side battery (b_2) is charged with a constant supplied current. On the other side, the battery (b_1) shows the dynamics during charging. The battery charging current (i_{b1}) is increased or decreased during the change in solar power. The proposed IGMVCF control approach maintains stable source voltage. In this work, battery swapping technology is employed to provide fast charged batteries for commercial vehicles.

(c) **Performance of EV charging batteries and isolated MG system under unbalanced load**

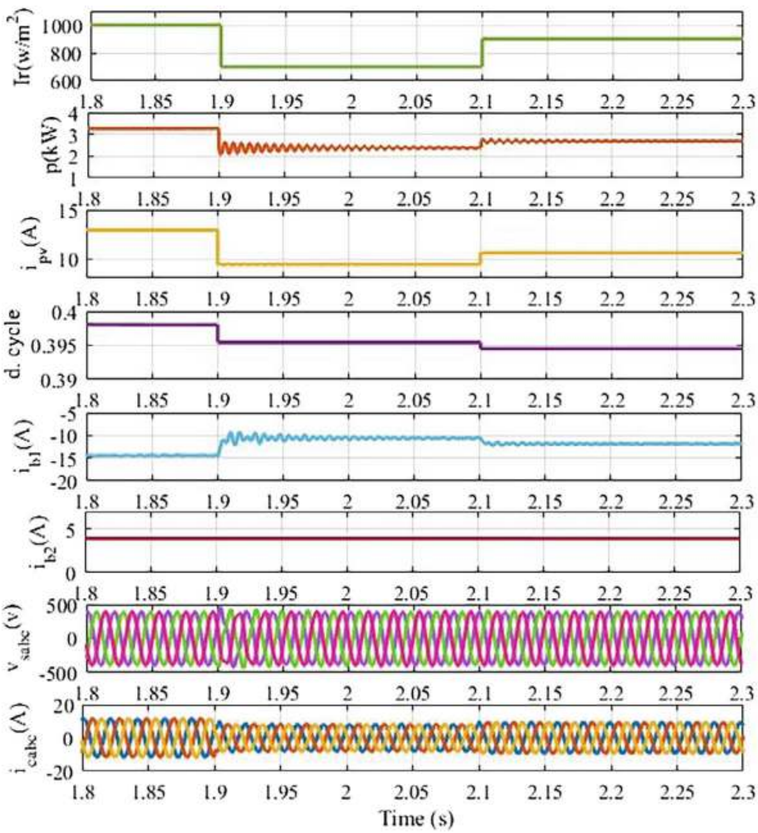

Fig. 4 Performance of batteries and isolated MG system under change in solar intensity

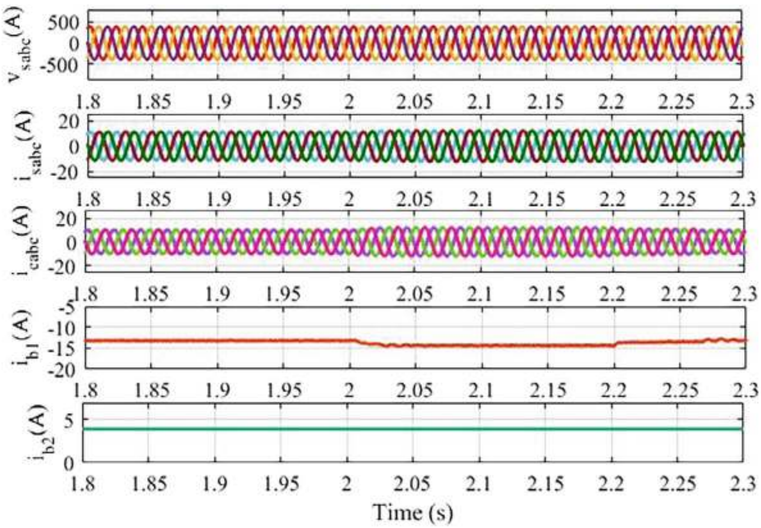

Fig. 5 Performance of EV charging batteries and isolated MG system under unbalanced load

Figure 5 shows the performance of EV charging batteries and isolated MG system under unbalanced load. The load of phase '*a*' is detached at $t = 2$ s and inserted at $t = 2.2$ s. The charging current of battery (b_2) is increased during the declination in load and battery is charged fast. The battery (b_1) gets constant charging current. The compensator current maintains the source voltage and source current sinusoidal.

(d) **Harmonic waveform of EV charging based isolated MG system**

Figure 6 shows the harmonic waveform of EV charging based isolated MG system. The result shows the source current and load current THD is 4.08% and 23.51%, respectively. Figure 6 presents the THD of source current is less than 5% which satisfies the limit of IEEE-519 standard.

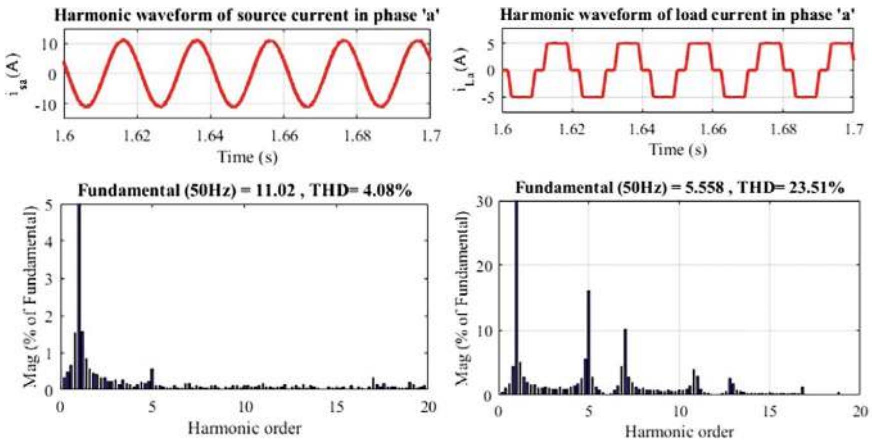

Fig. 6 Harmonic waveform of EV charging based isolated MG system

5 Conclusion

The rising popularity of EVs offers new opportunities for research into renewable integration. The purpose of this work was to design and develop an adaptive IGMVCF control strategy for an isolated hybrid system with multiple batteries charging support powered by wind and solar energy. This research also looks into the significant potential that renewable resources have for generating power in off-grid places. The proposed technique is useful for properly using available renewable resources to curtail GHG emissions and distribution grid stress as a result of EV multiple port charging. This research focuses on combining solar and wind resources for EV charging and establishing an effective energy management system for the proposed system.

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Chapter 12
Application of Power Converters in EV Charging Infrastructure

B. K. Karunakar Rao

Abstract Efficient and reliable EV charging systems are crucial for the widespread adoption of electric vehicles. High-efficiency power converters are essential to minimize energy losses and maximize charging speed. Effective thermal management is critical to dissipate heat generated during the charging process, ensuring the long-term reliability and safety of charging infrastructure. Understanding these fundamental aspects is vital for designing and deploying efficient, robust, and sustainable EV charging solutions.

1 Prolog

The rapid expansion of electric vehicle (EV) adoption has spurred significant developments in charging infrastructure. As EVs become increasingly integrated into our transportation systems, the demand for efficient, reliable, and scalable charging solutions has intensified [1]. Power converters play a pivotal role in enabling diverse charging options, enhancing grid integration, and optimizing energy transfer in EV charging infrastructure. This chapter explores the application of power converters the backbone of EV charging infrastructure, highlighting their importance in facilitating the growing prevalence of electric vehicles [2].

The escalating global pursuit of sustainable transportation, propelled by apprehension over climate change, air pollution, and energy security, has ignited a surge in the popularity of electric vehicles (EVs). As a cleaner and more energy-efficient substitute for conventional fossil fuel-powered vehicles, EVs present a compelling solution to these pressing challenges. Nevertheless, the widespread acceptance of EVs hinges upon the establishment of a robust and efficient charging infrastructure capable of accommodating the escalating number of electric vehicles traversing our roads.

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This chapter explores the pivotal role of power converters in developing electric vehicle charging networks. Power converters are indispensable to converting and regulating electrical energy, facilitating the efficient transfer of power between the electric grid and EV batteries. As such, they are integral components of EV charging stations, influencing charging speed, efficiency, and reliability.

The chapter initiates with a review of the present state of electric vehicle adoption and the associated challenges facing the expansion of EV charging networks [3]. It highlights the increasing demand for EV charging stations in urban centers, residential areas, and along major transportation corridors [4]. The chapter also examines the various charging standards and technologies employed in EV charging infrastructure, ranging from Level 1 and Level 2 to DC fast charging [5].

Next, the chapter delves into the fundamental principles of power conversion and the key characteristics of power converters used in EV charging stations [6]. It explores different topologies and various power converter topologies, including AC-DC and DC-DC converters, and bidirectional converters, highlighting their respective advantages and limitations [7]. Special attention is given to the efficiency, power density, and cost considerations associated with power converter design for EV charging applications [8].

The chapter then discusses recent advancements in power converter technology that are driving innovation in EV charging infrastructure. These include the development of high-efficiency wide-bandgap semiconductor devices, silicon carbide (SiC) and gallium nitride (GaN), innovative materials that surpass traditional silicon devices in terms of performance and reliability [9]. Additionally, advances in digital control techniques, thermal management, and grid integration are explored, demonstrating how these innovations are enhancing the performance and scalability of EV charging systems [10].

Furthermore, the chapter examines emerging trends and future directions in power converter design for EV charging infrastructure. This includes the integration of renewable energy sources, energy storage systems, and the vehicle-to-grid concept (V2G) capabilities into EV charging stations, enabling bidirectional power flow and grid services [11]. The chapter also discusses the potential impact of autonomous and connected vehicles on EV charging infrastructure and the role of smart grid technologies in optimizing charging operations and managing energy demand [12].

In conclusion, this book chapter offers a thorough examination of role of power converters in advancing electric vehicle charging infrastructure. By exploring the latest technologies, innovations, and future trends, the chapter aims to inform researchers, engineers, policymakers, and industry stakeholders about the vital role of power converters in molding the future of electric transportation.

2 Fundamentals of Power Converters in EV Charging

Power converters are essential components in EV charging systems, responsible for transforming power converters which facilitate the efficient transfer of electrical energy between various voltage and current levels, enabling the conversion of AC to DC and vice versa, ensuring compatibility between the grid supply and EV batteries. In EV charging infrastructure, power converters serve various functions, including voltage transformation, power factor correction, isolation, and modulation of charging rates.

2.1 AC-DC Conversion (Rectification)

- In most EV charging scenarios, the power from the grid is supplied as alternating current (AC), while the vehicle's battery requires direct current (DC) for charging.
- Power converters in EV charging systems perform AC-DC conversion, a process known as rectification.
- During rectification, the power converter transforms the incoming AC voltage into a pulsating DC voltage.
- This conversion is typically achieved using diode-based rectifiers or more sophisticated semiconductor devices such as thyristors or power transistors like metal–oxide–semiconductor field-effect transistors (MOSFETs) or insulated gate bipolar transistors (IGBTs).

2.2 DC Conversion

- Some EV charging systems, particularly DC fast chargers, require a DC power source. In such cases, if the grid supply is AC, another conversion step is necessary.
- Power converters in these systems perform DC-DC conversion, stepping down or stepping up the voltage level as required to match the voltage of the vehicle's battery.
- DC-DC converters leverage switching techniques for precise output voltage regulation.
- The most prevalent DC-DC converter configurations are buck, boost, and buck-boost converters.

2.3 Isolation and Safety

- Many EV charging systems incorporate isolation transformers for safety and to ensure electrical isolation between the grid and the vehicle.

- Isolation transformers prevent the flow of electrical currents between the grid and the vehicle, reducing the risk of electric shock and providing galvanic isolation.
- Galvanic isolation also helps in mitigating noise, voltage transients, and ground potential differences, enhancing the overall reliability of the charging system.
- Power factor correction is essential for optimizing EV charging system efficiency and mitigating grid harmonic distortion.
- Power converters with power factor correction (PFC) capabilities adjust the input current waveform to match the grid voltage waveform, thereby improving the power factor and reducing reactive power consumption.
- PFC techniques can be passive or active, with active PFC typically offering higher efficiency and better power factor correction.

2.4 Control and Regulation

- Power converters in EV charging systems require sophisticated control and regulation to ensure safe and efficient operation.
- Control algorithms regulate the output voltage and current, adjust charging rates based on battery characteristics, and manage power flow between the grid and the vehicle.
- State-of-the-art control methods like pulse-width modulation (PWM), hysteresis control, and predictive control are commonly used to achieve precise regulation and optimal performance.

2.5 Efficiency and Thermal Management

- Efficiency is a critical consideration in EV charging systems to minimize energy losses and maximize charging speed.
- Power converters must be designed with high-efficiency components and optimized circuit topologies to minimize conduction and switching losses.
- Effective thermal management is essential to dissipate heat generated by the power converters and ensure reliable operation over extended periods of charging.

Understanding these fundamental aspects of power converters in EV charging systems is essential for designing efficient, reliable, and secure charging infrastructure to underpin the growth of the electric vehicle market.

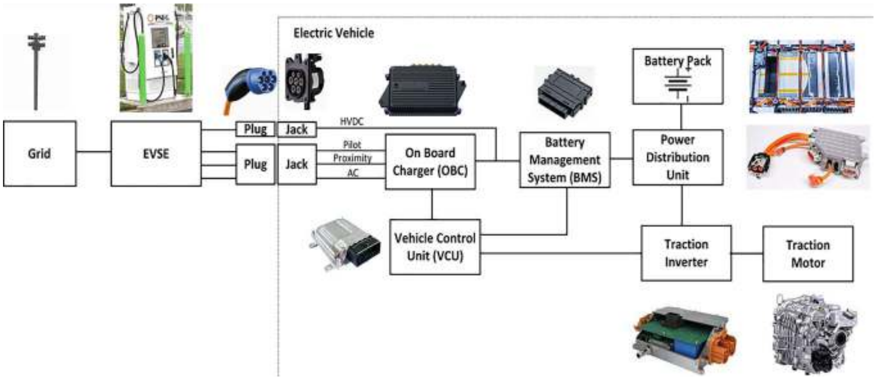


Fig. 1 **Electric vehicle** (EV) on board and onboard chargers charging system, *Courtesy of* M. Safayatullah et al.

3 Types of Power Converters in EV Charging Infrastructure

3.1 Onboard Chargers

Onboard chargers, seamlessly integrated within the vehicle, are responsible for converting AC power from the grid into DC power, which is then used to charge the vehicle's battery. These chargers typically utilize AC-DC power converters to rectify and regulate the incoming AC power [13].

Here is a more detailed elaboration on onboard charges.

Integration and Design:

- Onboard chargers are designed to be compact and lightweight to fit within the constraints of the vehicle's available space and weight limits.
- They are often integrated into the vehicle's power electronics system, alongside other components such as the traction inverter and battery management system (Fig. 1).

3.2 AC-DC Rectification

- Onboard chargers are primarily responsible for rectifying AC power from external sources into DC power for battery charging.
- This conversion process employs rectifying the incoming AC voltage into a pulsating DC voltage using diodes or semiconductor switches.
- The rectified DC voltage is then smoothed and regulated to provide a stable charging voltage compatible with the battery chemistry and voltage requirements.

3.3 Art of States of EV Charging

EV charging stations act as mini power hubs, enabling the simultaneous charging of multiple electric vehicles. Found in homes, businesses, and industrial areas, they provide the crucial infrastructure for a thriving EV ecosystem. Two main charging methods exist: AC charging, suitable for slower overnight charging, and DC charging, offering faster top-ups for on-the-go convenience. Additionally, three charging levels cater to different EV categories, ensuring compatibility and optimal charging speeds.

Demystifying EV Charging: **AC versus DC and Levels 1, 2, and 3**:

Plug your way to a full charge! Understanding EV charging can seem complex, but it boils down to two key factors: **AC versus DC power** and **charging levels**.

AC versus DC: Just like our homes, some EVs can directly use AC power from the grid. This is Level 1 and Level 2 charging, typically slower but suitable for overnight or longer sessions. These levels rely on the **onboard charger** built into the EV, often maxing out at 20 kW.

Level up with DC: For faster charging, think Level 3! This powerhouse uses DC power directly, bypassing the onboard charger and delivering a quick boost to the battery. Imagine it as a dedicated charging station, like a high-powered gas pump for your EV. However, due to the higher power involved, Level 3 charging generally necessitates standalone off-board chargers [17].

Level Breakdown:

- **Level 1**: Slow and steady, perfect for overnight charging using a standard 120/230 V AC outlet.
- **Level 2**: Faster than Level 1, often found at public charging stations and home wall boxes, also using AC power.
- **Level 3**: The speedster of the bunch, using DC power delivered directly to the battery, ideal for quick top-ups on the go.

3.4 Connecting to Power: Onboard Versus Off-Board Chargers

- Figure 2 shows the crucial difference between onboard and off-board chargers in how they connect to the EV battery. For AC charging (Levels 1 and 2), the onboard charger within the vehicle handles the conversion from AC grid power to DC for battery charging. However, for Level 3 DC fast charging, a station called electric vehicle supply equipment (EVSE) takes over. This powerful unit converts AC grid power to high-voltage DC directly, bypassing the onboard charger and delivering a much faster boost to the battery.
- Onboard chargers are like miniaturized power plants built into your EV, while off-board fast chargers are like high-powered gas pumps specifically designed

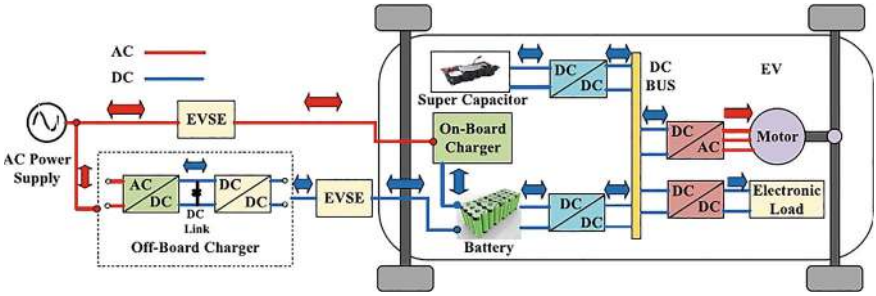


Fig. 2 **Electric vehicle** (EV) off-board and onboard chargers. *Courtesy of* M. Safayatullah et al.

for electric vehicles. These charging stations deliver regulated DC output voltage ranging from 100 to 800 V, enabling impressive charging speeds. In fact, they can charge a typical 20 to 40 kWh battery to 80% capacity in under 30 min, making them ideal for quick top-ups on the go [18].

3.5 Structural Options for AC-DC Conversion Stages

In an off board for EV fast charging, the AC-DC conversion process converter acts as the first step, transforming incoming AC grid power into DC electricity optimized for efficient battery charging. Think of it as the gatekeeper, controlling the flow and type of energy entering the system. Various converter designs (topologies) exist, each with its own strengths and weaknesses. These specialized circuits must handle the high power demands of fast charging, ensuring efficient and reliable energy transfer directly to the battery.

3.6 Three-Phase Buck Converter

The three-phase buck rectifier (TPBR) stands as a widely used option for off board EV fast charging, lauded for its remarkable efficiency, excellent power factor correction (PFC), and compact design. Its six-switch topology, depicted in Fig. 3, boasts a freewheeling diode for smooth operation and inherent protection against inrush currents and short-circuits.

However, the TPBR is not without its limitations. Under light load conditions, the input current can exhibit distortion caused by parasitic capacitance between ground and the DC-link output. This becomes particularly relevant when charging multiple EVs simultaneously, as a single TPBR's modulation index can dip below 0.5, compromising power quality.

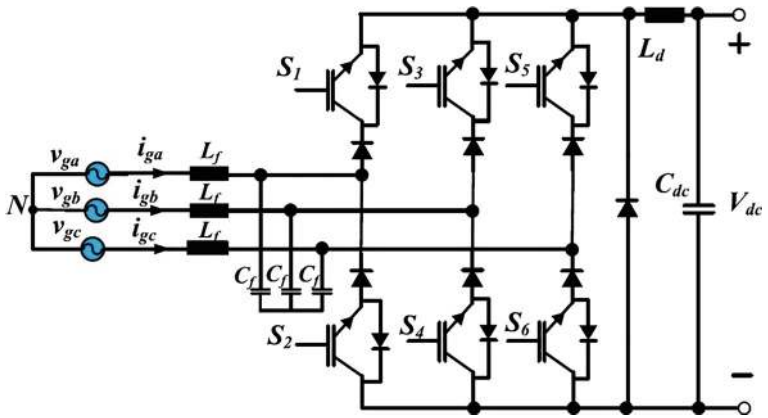


Fig. 3 Three-phase six-switch step-down converter. *Courtesy of* M. Safayatullah et al.

Fortunately, a clever solution exists: the matrix-type TPBR. This configuration leverages multiple TPBRs working in tandem, effectively distributing the load and ensuring stable power delivery even during peak charging periods. This approach maintains excellent power quality and safeguards grid integrity, making it ideal for scenarios involving numerous EVs.

In conclusion, the TPBR remains a valuable tool for off-board EV fast charging, offering high efficiency, compact design, and inherent safety features. However, understanding its limitations and exploring alternative solutions like the matrix-type TPBR is crucial for optimizing performance and ensuring grid stability, especially in high-demand environments [19].

3.7 Swiss Rectifier

The three-phase buck rectifier (TPBR) has a worthy successor in the form of the Swiss rectifier (Fig. 4). Building upon the TPBR's strengths, the Swiss rectifier boasts even higher efficiency and reduced common-mode noise, thanks to its two additional switches, leading to lower conduction and switching losses.

Furthermore, the Swiss rectifier shines in multi-unit configurations. Interleaved setups allow for smaller current and voltage ripples, contributing to increased reliability through redundancy: if one switch fails, others can pick up the slack, minimizing downtime. This interleaved architecture also enables high bandwidth, high power handling, and reduced filter requirements, making it a compelling choice for demanding applications.

However, the Swiss rectifier is not without limitations. While it excels at unidirectional power flow, achieving bidirectional functionality requires additional

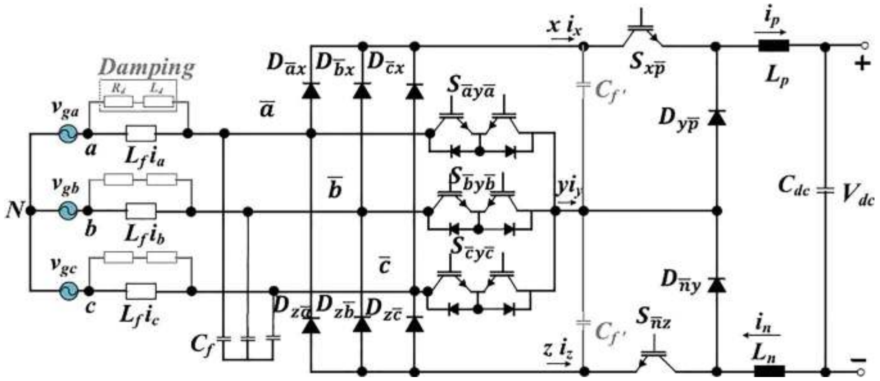


Fig. 4 Swiss rectifier. *Courtesy of* M. Safayatullah et al.

components and complex control mechanisms, potentially increasing cost and complexity.

In essence, the Swiss rectifier represents a significant advancement over the TPBR, offering improved performance and reliability in a multi-unit setup. Its limitations around bidirectional power flow require careful consideration when choosing the optimal solution for specific applications [20].

3.8 The Vienna Rectifier: A Versatile Choice for High-Power EV Charging

The three-phase Vienna rectifier (Fig. 5) enters the arena with its distinct approach to AC-DC conversion for EV fast charging. Unlike the TPBR and Swiss rectifier, it boasts three inductors at the input for voltage boosting, followed by six diodes, six switches, and two split capacitors for rectification and filtering. While it shares similarities with a conventional three-phase boost PFC rectifier, it lacks bidirectional power flow capability.

However, the Vienna rectifier shines in its simplicity. Its control mechanism is straightforward, achieving unity power factor and minimal total harmonic distortion while maintaining high efficiency even in compact designs. This makes it a strong contender for well-suited for high-power applications like EV fast charging, the Vienna rectifier has a hidden talent! By swapping its diodes with switches, it transforms into a bidirectional beast, enabling power flow in both directions—a crucial feature for vehicle-to-grid (V2G) applications [21].

To ensure smooth operation in various scenarios, the Vienna rectifier relies on specific pulse-width modulation (PWM) techniques. While carrier-based PWM and discontinuous PWM have limitations in interleaved configurations, a hybrid space vector PWM method emerges as the champion, overcoming distortion issues and

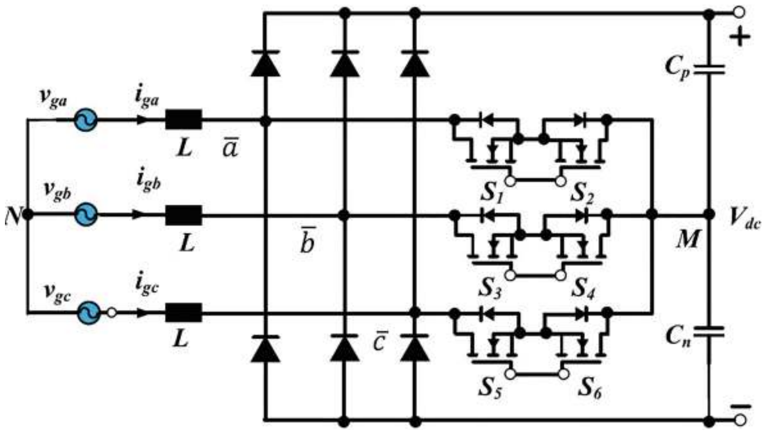


Fig. 5 Vienna three-phase rectifier. *Courtesy of* M. Safayatullah et al.

delivering optimal performance. In essence, the Vienna rectifier stands out with its simplicity, high efficiency, and potential for bidirectional power flow, making it a valuable option for high-power EV charging, especially when V2G integration is a consideration. Its adaptability to different PWM techniques further enhances its versatility and paves the way for efficient and flexible charging solutions [22].

3.9 Three-Phase Boost Type Rectifier

The three-phase six-switch boost rectifier (TPSSBR) (Fig. 6) throws its hat in the ring, offering a basic structure and the coveted bidirectional power flow capability. This makes it particularly interesting for vehicle-to-grid (V2G) applications.

A distinctive feature of the Vienna rectifier is its ability to maintain a continuous input current, resulting in a high DC voltage at the output. Each individual AC source is connected to an inductor for boosting purposes, effectively minimizing harmonic distortion in the input current. Moreover, the six switches, organized in pairs per leg and operating in a complementary manner, ensure smooth and uninterrupted operation. However, the TPSSBR is not without its drawbacks. The antiparallel diodes within each switch are prone to reverse recovery losses, which, in conjunction with the inherent switching losses of the MOSFETs, can compromise overall efficiency [23].

One potential solution lies by incorporating an ultra-fast DC rail diode at the DC-link side. This clever addition helps mitigate the reverse recovery losses, paving the way for improved efficiency. In conclusion, the TPSSBR presents a simple and potentially bidirectional option for AC-DC conversion. While its reverse recovery losses pose a hurdle, the potential solution using an ultra-fast DC rail diode suggests

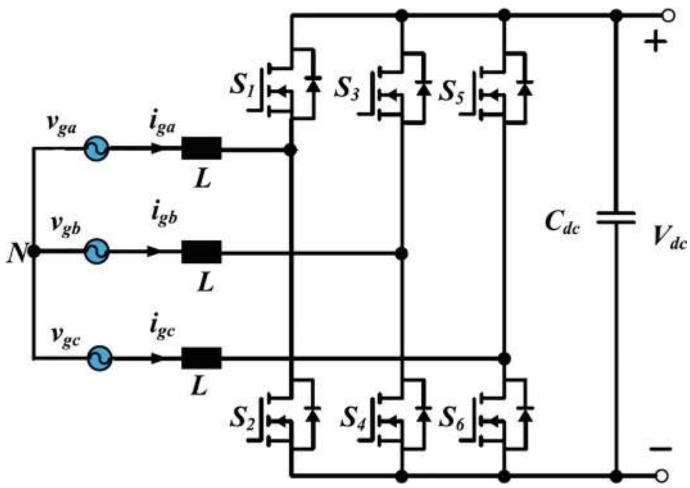


Fig. 6 Six-switch three-phase boost rectifier. *Courtesy of* M. Safayatullah et al.

its promise. Careful consideration of its limitations and potential workarounds is crucial when evaluating its suitability for specific EV charging applications [24].

3.10 Key Considerations for AC-DC Converter Choices in EV Fast Charging

This chapter delved into the diverse AC-DC converter topologies powering EV fast charging stations. Here, key insights include:

1. **Off-Board Chargers Reign Supreme**: Fast charging stations typically utilize off-board chargers (external to the EV) to minimize vehicle size and weight. This places the responsibility of AC-DC conversion on these external units.
2. **Efficiency and THD Champions**: Both TPBR and Swiss rectifiers boast superior efficiency and reduced total harmonic distortion, ensuring optimal power utilization and grid compatibility.
3. **TPBR**: **Efficiency with Caveats**: The conventional TPBR faces limitations like elevated voltage stress and diminished soft-switching capability, potentially impacting performance and reliability.
4. **Swiss Rectifier**: **Refined, But Unidirectional**: While offering improved efficiency and noise rejection compared to TPBR, Swiss rectifiers operate only in one direction and require complex control mechanisms.
5. **Vienna Rectifier**: **Simplicity and Trade-offs**: This topology leverages fewer switches, integrates seamlessly with bipolar buses, and eliminates neutral structures. However, it necessitates DC-link capacitors, adding cost and complexity.

6. **Three-Phase Boost Rectifier**: **Simple and Bidirectional, But Lossy**: This rectifier boasts a straightforward design and lower input current stress, offering bidirectional capability with continuous input current. However, its antiparallel diodes contribute to higher switching losses.

In Conclusion:

Choosing the optimal AC-DC converter topology hinges on specific application requirements. Consider factors like efficiency, THD, bidirectional capability, complexity, cost, and potential losses to make an informed decision. Remember, there is no one-size-fits-all solution, and the ideal choice depends on your unique EV charging needs and priorities.

4 Power Factor Correction (PFC)

- Many modern onboard chargers incorporate power factor correction (PFC) circuitry to optimize power performance quality of the charging system**.**
- PFC helps align the current waveform with the voltage waveform, reducing harmonic distortion and to enhance the overall efficiency of charger (Fig. 7).

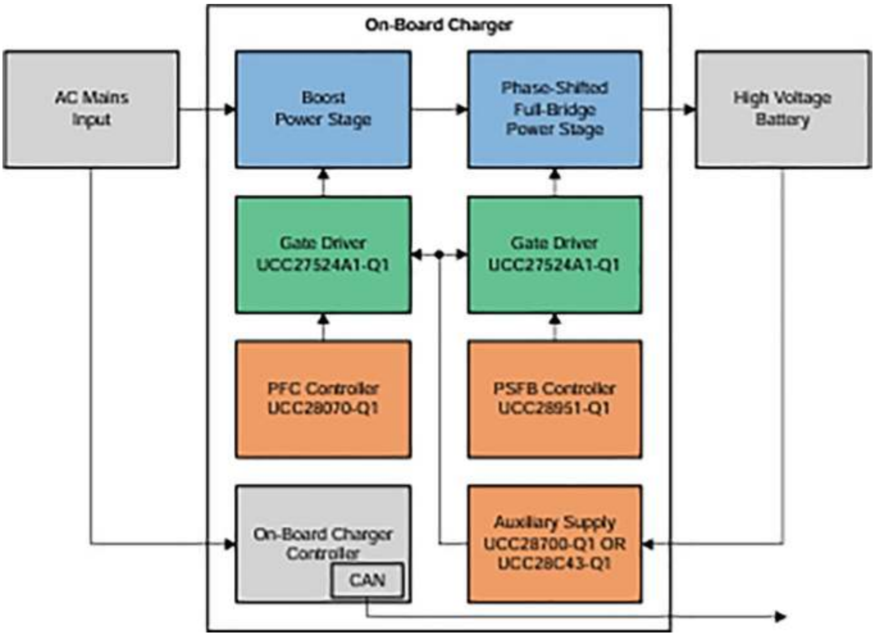


Fig. 7 Power factor correction structure

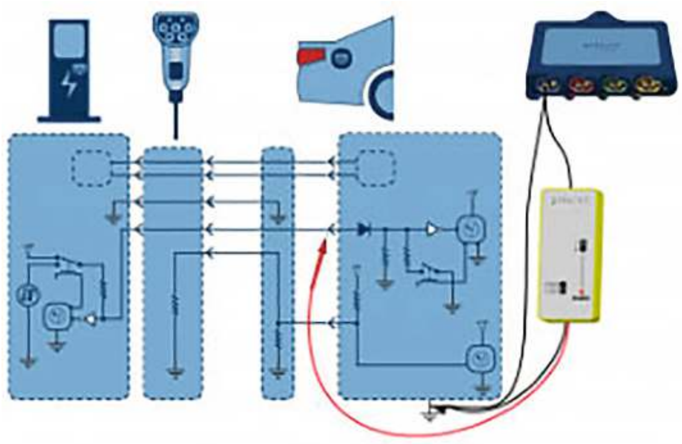


Fig. 8 Charger–vehicle circuits with a Type 2 connector

4.1 Charging Control and Communication

- Onboard chargers are equipped with control and communication systems to manage the charging process effectively.
- These systems monitor variables including battery state-of-charge, temperature, and charging voltage and current to ensure safe and efficient charging.
- Communication standards such as controller area network (CAN) or Ethernet allow the onboard charger to communicate with the vehicle's onboard systems and external charging infrastructure (Fig. 8).

4.2 Efficiency and Thermal Management

- Efficiency is a critical consideration in onboard charger design to minimize energy inefficiency during charging.
- High-efficiency components, such as wide-band gap semiconductors (e.g., silicon carbide or gallium nitride), are often used to reduce conduction and switching losses.
- Effective thermal management is essential to dissipate heat generated by the charger and maintain safe operating temperatures, ensuring reliable performance and longevity (Fig. 9).

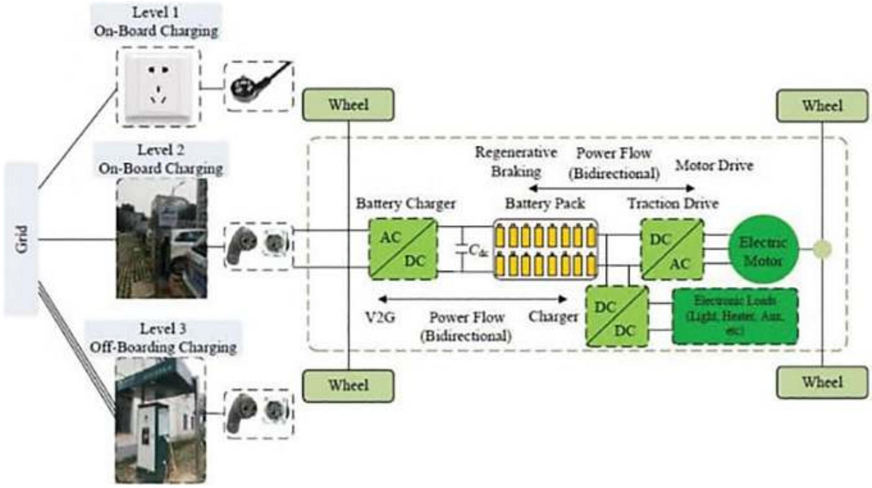


Fig. 9 Thermal management system

4.3 Charging Speed and Compatibility

- The charging speed of an onboard charger depends on its power rating and the charging infrastructure's capabilities.
- Onboard chargers are available in various power ratings, ranging from a few kilowatts for slow or overnight charging to tens of kilowatts for fast charging.
- Compatibility with different AC charging standards and voltages (e.g., Level 1 and Level 2) ensures that EVs equipped with onboard chargers can be charged at a wide range of public and private charging stations (Fig. 10).

Onboard chargers are indispensable components of electric vehicles, enabling efficient and convenient charging experiences. These vital systems rectify external AC power into DC power for battery charging as onboard charger technology advances, and we witness significant improvements in charging speed, efficiency, and compatibility. This progress is instrumental in driving the widespread adoption of electric vehicles, making them a more attractive and practical choice for consumers.

4.4 DC Fast Chargers

DC fast chargers provide a direct and powerful DC current to the vehicle's battery, substantially accelerating the charging process compared to conventional AC charging methods. These chargers employ DC-DC power converters to step down the voltage from the grid to match the battery voltage, enabling rapid charging without the need for onboard AC-DC conversion [14].

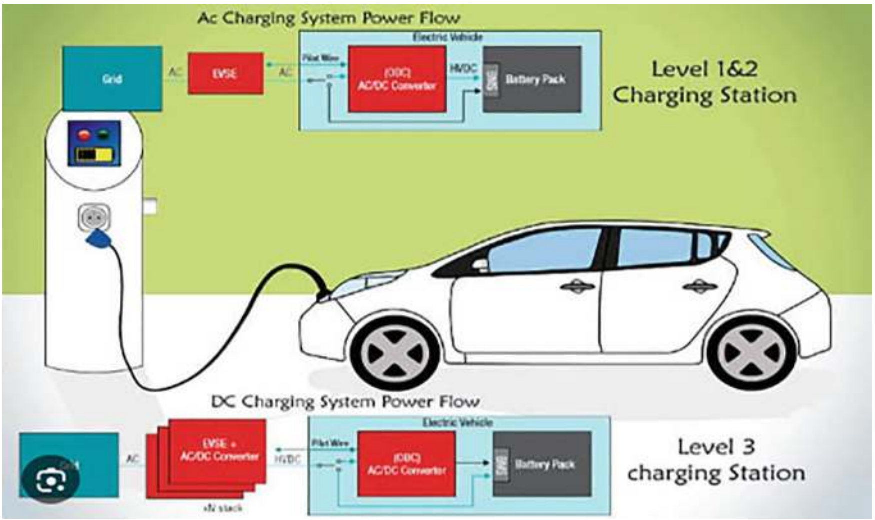


Fig. 10 DC charging system power flow

DC fast chargers often categorized as Level 3 chargers or high-speed chargers are essential elements of the electric vehicle (EV) charging infrastructure. These chargers deliver a substantial boost to charging speed compared to traditional Level 1 and Level 2 chargers. Deliver DC power directly to the vehicle's battery, and they bypass the onboard AC-DC converter, resulting in significantly reduced charging times. This efficiency enhancement is instrumental in the widespread adoption of EVs, addressing one of the key obstacles for potential buyers: the time required to replenish the vehicle's battery [25].

4.5 High Charging Power

- DC fast chargers are designed to deliver high-power DC directly to the vehicle's battery, enabling accelerated charging.
- Charging power output can vary from 50 to 350 kW or higher, depending on the charger's capabilities and the capabilities of the EV being charged.
- The high charging power allows EV drivers to replenish a significant portion of their battery capacity in a relatively short amount of time, making long-distance travel more practical and convenient (Fig. 11).

Fig. 11 High charging power stations

4.6 DC-DC Conversion

- In contrast to Level 1 and Level 2 chargers, which utilize onboard chargers for AC-DC conversion, DC fast chargers supply DC power directly to the vehicle's battery.
- This eliminates the need for an onboard AC-DC converter, streamlining the charging process and reducing charging time.
- DC-DC conversion is performed within the charger itself, utilizing high-power DC-DC converters designed for high-current applications and voltage (Fig. 12).

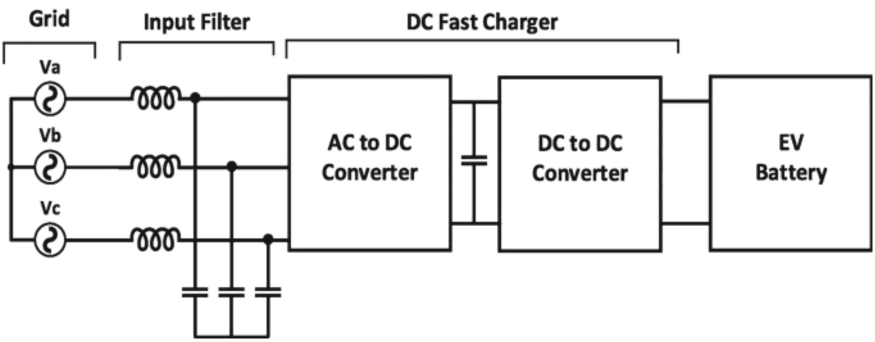


Fig. 12 AC power to the Vehicle's onboard charger for conversion to DC

5 Charging Protocols and Standards

- DC fast chargers support multiple charging protocols and standards, such as CHAdeMO, combined charging system (CCS), and Tesla Supercharger.
- CHAdeMO was one of the first DC fast charging standards and is commonly used by Japanese and some European EV manufacturers.
- CCS, a unified standard that integrates AC and DC charging a single connector, has gained widespread adoption in Europe and North America, supported by major automakers.
- Tesla Supercharger is a proprietary DC fast charging network operated by Tesla, offering high-speed charging exclusively for Tesla vehicles.

Standardized protocols and industry standards are crucial for the growth and success of the electric vehicle charging market. These standards provide the necessary flexibility to accommodate the diverse range of electric vehicles and the broader charging infrastructure ecosystem. By establishing a common framework, standardization will play a pivotal role in driving the development of future EV charging infrastructure, ensuring interoperability and seamless user experiences (Fig. 13).

5.1 EV Charging Protocols and Standards

Type 1 and Type 2 Connectors

Type 1 connectors were primarily used in North America and Japan. Also known as SAE J1772 (because the standard is maintained by SAE International—formerly the Society of Automotive Engineers), or J plug for short, these connectors have five pins

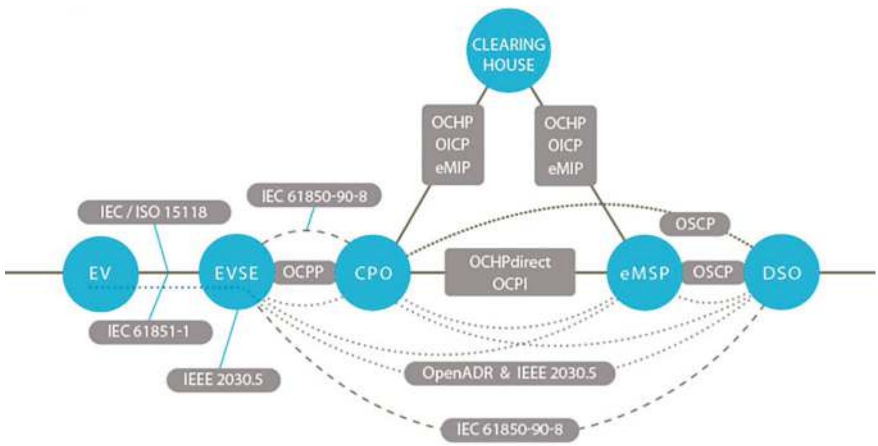
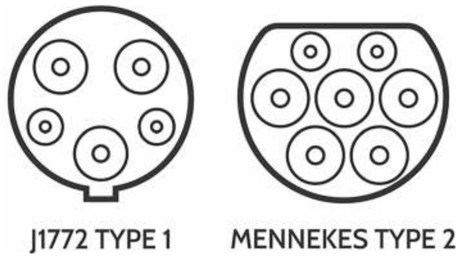


Fig. 13 DC fast chargers support multiple charging protocols and standards

Fig. 14 Cable types



and can deliver up to 19.2 kW of power (80 A at 240 V) over single-phase AC line. The connector is locked to and released from the vehicle through a manual mechanism. Finalized in 2009, the connector was added to the IEC 62196 international standard for plugs, socket, outlets, vehicle connectors, and vehicle inlets.

Type 2 connectors were the European equivalent of the North American Type 1 and are often referred to as "Mennekes" after the German company that designed them.

Introduced in 2013, these connectors have seven pins and can deliver up to 43 kW of power through a 70 A single-phase line or 63 A on a three-phase line at a maximum voltage of 500 V. The higher power rating made it sufficient for rapid charging. These connectors use an automatic locking and release mechanism initiated by the driver like Type 1, Type 2 connectors were also added to the IEC 62,196 standard.

Each of these connectors includes a control pilot (CP) line (specified in IEC 61851-1), which is used for communication between the vehicle and the charger using a pulse-width modulation (PWM) signal. A charging session is broken up into six states indicated by the voltage of the CP: standby, vehicle connected, charging allowed, ventilation, EVSE shut down, and error. For example, upon establishing a good connection between the EVSE and the vehicle, the CP voltage changes from 12 to 9 V. The "duty cycle" (the length of the pulse) determines the highest current the EVSE can deliver the vehicle. For example, a 10% duty cycle indicates 6A are available while a 96% duty cycle indicates 65A are available for charging.

Since the introduction of the CCS standard, Type 1 and Type 2 connectors are being phased out and you would have a hard time finding one today (Fig. 14).

5.2 CCS—Combined Charging System Standard

The combined charging system standard (CCS) is a comprehensive standardized protocol that encompasses various aspects of electric vehicle charging, including AC and DC charging, communication protocols between the charging station and vehicle, load balancing, authentication and authorization, and the vehicle coupler. The term "combined" signifies that CCS extends the existing Type 1 and Type 2 AC connectors to incorporate rapid DC charging capabilities. This integration results in Combo 1 (CCS1) and Combo 2 (CCS2) connectors, respectively, capable of delivering up to

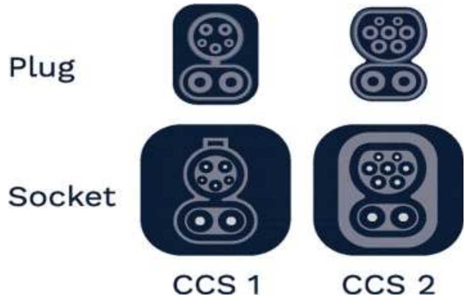


Fig. 15 Charging connectors

350 kW of power. CCS 1 connectors are prevalent in North America, while CCS 2 is the standard in Europe (Fig. 15).

CCS Connectors

The CCS standard, initially proposed by a consortium of seven automotive manufacturers, gained significant momentum with its first prototype demonstration in 2012. Recognizing its potential, the European Union mandated CCS2 for EV charging networks in 2014. In USA, the early adoption of CCS led to the development of extensive networks along major coastal corridors by 2016. The federal government's commitment to promoting EV adoption, evidenced by the allocation of $7.5 billion for national EV charging infrastructure, further solidified CCS as the preferred standard for companies seeking to access these funds.

NACS—North American Charging Standard

Tesla has dominated the North American EV market since 2012. The company did not adopt the CCS standard that became common in USA and Europe, but rather, used its own proprietary charging system. In November 2022, Tesla made its specification publicly available and announced it as the North American Charging Standard—NACS. Tesla charging stations outnumber CCS charging stations compared to all other service providers combined, making it the most common standard in USA. Like the CCS combo plugs, NACS offers a unique advantage by combining both AC and DC charging capabilities within a single plug. Notably, NACS surpasses CCS in terms of power capacity, delivering up to 1 MW of power on DC. Ford and General Motors have made a significant commitment to NACS, announcing their adoption of the standard. The first NACS-compatible vehicles from these manufacturers are expected to hit the market in 2025. To bridge the gap until then, GM and Ford drivers will require adapters to connect to existing NACS chargers (Fig. 16).

Fig. 16 Charging connectors, NACS (formerly Tesla) connector

5.3 OCPP—Open Charge Point Protocol

OCPP is a cornerstone protocol for enabling communication between electric vehicle charging stations and central management systems. As an international, open-source standard, OCPP is freely available to all industry participants. Created by the Open Charge Alliance (OCA), OCPP has become the industry standard for interoperability within the EV charging infrastructure. OCPP offers a proven method to optimize costs and mitigate risks associated with networked infrastructure investments.

ISO 15118 **Standard—Bidirectional Charging/Discharging**

ISO 15118 is a comprehensive international standard that governs bidirectional digital communication between electric vehicles and charging stations. This standard establishes a V2G (vehicle-to-grid) communication interface, facilitating both charging and discharging of electric vehicles. As a cornerstone of the plug and charge feature, ISO 15118 empowers EV drivers to effortlessly attach the charge plug to their vehicle, initiate charging, and depart once the battery is fully charged. This seamless process is made possible through a digital certificate embedded within the vehicle, enabling to facilitate communication between effectively with the charging point management system (CPMS). This streamlined interaction streamlines the end-to-end charging experience, encompassing automatic authentication, billing, and simplifying the charging process by eliminating the need for RFID cards, apps, or PIN memorization.

5.4 EV Charging Roaming Protocols

OCPI—Open Charge Point Interface

OCPI, a standardized protocol, enables efficient communication between charge point operators and e-mobility service providers, facilitating scalable and automated EV roaming. OCPI encompasses a wide range of use cases, including charge point information, charging session authorization, tariffs, reservations, roaming, registration management, and smart charging.

OCHP—Open Clearing House Protocol

OCHP, a standardized protocol, facilitates efficient communication between charging management systems and clearing house systems, enabling interoperable electric vehicle charging and fostering e-roaming.

OICP—Open Intercharge Protocol

Open intercharge protocol (OICP) was developed by Hubject as a standardized communication protocol designed to facilitate information exchange between e-mobility service providers (EMSPs) and charge point operators (CPOs) within the Hubject platform. OICP enables EMSPs and CPOs to establish contractual relationships and exchange relevant information through the Hubject platform, ultimately providing electric vehicle drivers with reliable roaming capabilities.

eMIP—e-Mobility Interoperation Protocol

eMIP, a platform developed by GIREVE, facilitates universal charging access services by offering a platform for charging authorization and data clearance API, coupled with access to a vast database of charging locations. This integrated approach empowers e-mobility service providers to seamlessly connect to various charging networks, expanding the reach and convenience of charging options for electric vehicle drivers.

5.5 Energy Management Protocols

OpenADR—Open Automated Demand Response

OpenADR, a fundamental protocol, enables efficient and standardized communication for automated demand response initiatives. It serves as a standardized framework for communication among distribution system operators, utilities, and energy management and control systems, enabling the balancing to address peak energy demand. OpenADR 2.0 drives standardization efforts for demand response (DR) and distributed energy resource (DER) communication, streamlining automated DR/DER processes. This protocol, furthermore, OpenADR 2.0 enhances customer energy management and prevents stranded assets, promoting a more efficient and sustainable energy landscape.

OSCP—Open Smart Charging Protocol 1.0

Open Smart Charging Protocol (OSCP) is a standardized protocol designed to facilitate communication between charging infrastructure management systems and energy management systems of site owners or distribution system operators (DSOs).

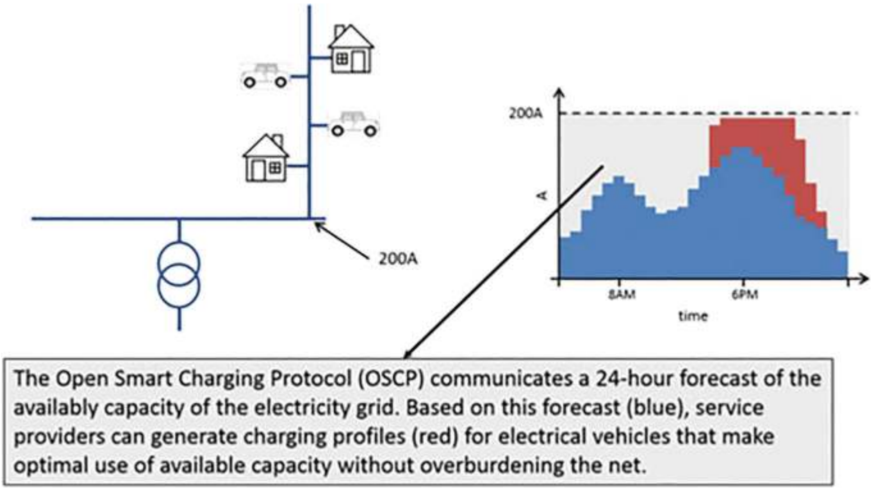


Fig. 17 Core principle of OSCP (*Image source* OCA)

OSCP enables the transmission of real-time predictions pertaining to the local electricity grid's capacity for charging infrastructure operators, fostering capacity-based smart charging of electric vehicles. This protocol is a key component of in optimizing grid utilization and ensuring a sustainable charging infrastructure (Fig. 17).

6 Cooling and Thermal Management

- Due to the high charging power levels involved, DC fast chargers require robust cooling and thermal control systems to expel generated heat during the charging process.
- Liquid or air-cooled systems are commonly employed to maintain the charger's components within safe operating temperatures and ensure reliable performance over extended periods of use.

The combined charging system (CCS) connector, also known as the SAE J1772 combo connector, has become the prevailing standard in the EV industry, which offers versatility by supporting both AC and high-power DC charging equipment. CCS connectors without liquid cooling typically handle charging power up to approximately 200 kW. However, incorporating CCS connectors with liquid cooling can significantly increase to 500 kW (500 A at 1 kV), enabling faster and more efficient charging experiences for electric vehicle owners (Fig. 18).

Fig. 18 Interior of connector reveals its intricate design, featuring AC cables (green) and a liquid cooling system for the DC cables (red). (*Image* Phoenix Contact)

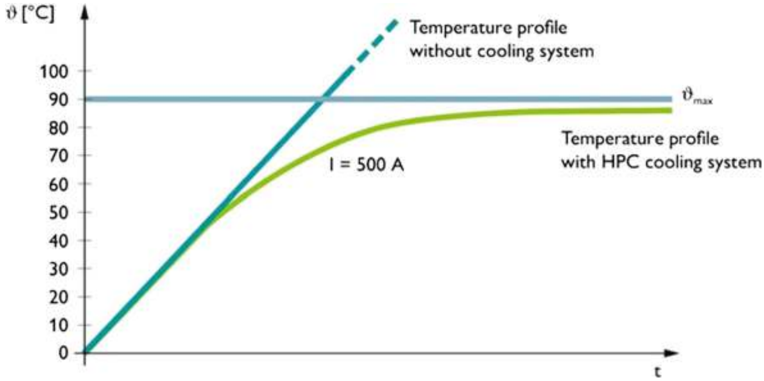


Fig. 19 CCS connectors have a temperature limit of 50 °C for their contacts (*Image* Phoenix Contact)

In addition to enabling smaller, lighter-weight cabling for high-power applications, liquid cooling also improves overall system efficiency. In the absence of active cooling, cables may become excessively heavy and cumbersome for users. While liquid cooling is a prerequisite for supporting 500 kW EV charging, it is not sufficient on its own. Active thermal management, including real-time temperature monitoring, is equally essential. By continuously monitoring temperatures, the system can ensure that the connector contact temperature remains below the + 50 °C specification limit (Fig. 19).

6.1 *Keeping EV Batteries and Inverters Cool*

Electric vehicle batteries and inverters require effective cooling to maintain optimal performance and efficiency. Several options are available, such as air and liquid cooling. Air cooling can be categorized as passive or active:

- **Passive air cooling** utilizes natural air circulation drawing air from the cabin or vehicle's exterior to regulate temperatures. This method can dissipate up to a few hundred watts of heat.
- **Active air cooling** involves the use of air from an air conditioner or heater, providing a more powerful cooling capacity of approximately 1 kW.

While air cooling offers a more cost-effective solution, liquid cooling systems are capable of handling significantly higher thermal loads, making them the preferred choice for EV inverters and battery packs. Both active and passive liquid cooling designs are available. The choice of coolant varies depending on the system, with options including ethylene glycol, oils, dielectric fluids, or water. High-performance systems may even employ refrigerants to optimize cooling efficiency.

EV inverters operate at higher temperatures compared to batteries, which can be more sensitive to temperature fluctuations beyond their optimal range. During discharge, most current EV batteries must be maintained within a temperature range of −30 to 50 °C. Charging requires a slightly narrower temperature window, between 0 and 50 °C. High-rate charging or discharging can significantly elevate battery temperatures. Batteries can become excessively cold, hindering their ability to deliver high discharge levels. This is particularly critical for high-performance EVs that guarantee consistent acceleration under varying environmental conditions. To maintain optimal performance in cold weather, batteries may require heating to support high discharge rates.

6.2 Unified Liquid Cooling System

The trend in EV thermal management is shifting away from separate systems for battery packs and inverters, favoring integrated liquid cooling solutions. By designing a unified cooling loop, manufacturers can significantly reduce the size, weight, performance requirements, and cost (SWAP-C) of the thermal management function. Key components of integrated liquid cooling systems include:

- Designing integrated liquid cooling systems that meet the distinct thermal management needs of inverters and battery packs requires careful consideration. Cold plate optimization and the selection of appropriate quick-connect liquid couplings are essential factors (Fig. 20).

6.3 Comprehensive EV Thermal Management

Liquid cooling is not limited to internal components of EVs, but is also essential for EV charging infrastructure. The connectors between EVs and XFC charging stations necessitate liquid cooling and quick-connect couplings for efficient and reliable charging, even under high-power conditions.

Fig. 20 Optimizing cold plates is crucial for the successful design of integrated liquid cooling systems for EV inverters and battery packs. (*Image* Laserax)

Fig. 21 High-power EV battery chargers necessitate liquid cooling (*Image* CEJN Industrial)

In contrast, a 150 kW fast DC charging station can achieve this in a mere 16 min. However, the power converter within a 150 kW fast DC charger must be compactly packaged and effectively cooled to prevent excessive temperature rise during a 10-min charge, which can exceed 200 °C. XFC charging stations place significantly higher liquid cooling is not optional but rather a necessity due to the demanding thermal management requirements (Fig. 21).

6.4 Hybrid Liquid–Vapor Cooling Solution

Until now, discussions have focused on single-phase cooling systems. However, two-phase systems are currently being developed to harness both the sensible heat (temperature increase) and latent heat (phase change from liquid to vapor) of

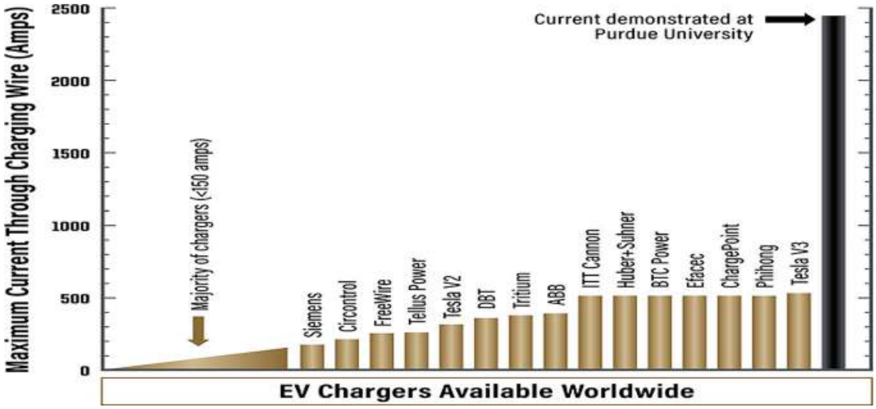


Fig. 22 Sub-cooled flow boiling thermal management is capable of supporting extremely substantial current levels in EV charger connectors (*Image* Purdue University)

the coolant, enabling them to handle significantly higher thermal loads. Many of these methods are not practical for implementation in XFC EV charging cables. A promising alternative for these cables is sub-cooled flow boiling.

Achieving 5-min charging for large commercial vehicles necessitates the delivery of substantial power, estimated at 1400 A. The majority of current EV charger designs are limited to a maximum current of 150 A, and XFC chargers are also capped at 500 A. Enabling 5-min charging will necessitate cables and connectors capable of handling significantly higher currents, potentially reaching up to 2500 A.

A groundbreaking innovative EV charging cable system has been developed, capable of delivering an impressive 2500 A. This innovative system incorporates a pump, a tube of comparable size to current XFC charging cables, along with essential controls and instrumentation. By leveraging two-phase sub-cooled flow boiling, the system effectively dissipates heat in both liquid and vapor forms. This innovative approach has demonstrated a remarkable tenfold increase in heat dissipation capacity compared to traditional single-phase liquid cooling implementations (Fig. 22).

6.5 Interoperability and Accessibility

- Interoperability is essential for the widespread adoption of DC fast chargers, allowing EV drivers to access charging infrastructure regardless of their vehicle's make or model.
- Many charging networks and service providers offer interoperable DC fast charging stations that support multiple charging standards, ensuring compatibility with a wide range of EVs.

Fig. 23 Types of EV chargers in India

- Increasing the accessibility of DC fast chargers along major highways, urban areas, and key destinations is crucial for promoting EV adoption and addressing range anxiety among drivers (Fig. 23).

The importance of interoperability in EV charging cannot be overstated. It is a major factor in promoting the growth of the electric vehicle market and creating a robust charging network. Here are some key aspects of interoperability in the EV charging domain:

- **Compatibility**: Interoperability ensures that EVs from different manufacturers can charge at any charging station, irrespective of the charging station's brand or infrastructure provider. This compatibility eliminates the need for EV owners to rely on specific charging networks, subscriptions, or adaptors, offering them greater convenience and flexibility.

Standardization: Standardization and interoperability of EV robust charging infrastructure is crucial for the widespread acceptance of electric vehicles. EV's. Implementing standardized charging protocols and connector types will ensure that EVs from different manufacturers can be charged at any charging station across the country. This will enhance convenience for EV owners, promote interoperability, and encourage the growth of a robust charging network in India.

Table 1 Ola Electric; Ather Energy; Hero Electric; Zypp; Okinawa Autotech

Electric two-wheeler company	Prominent models	Charging compatibility	Charging connectors
Ola electric	Ola S1, S1 Pro	Ola hypercharger network	Proprietary connectors specific to Ola electric
Ather energy	Ather 450X, 450 Plus, etc.	Ather grid	Ather's proprietary charging connectors
Other companies (Hero electric Zypp, Okinawa Autotech, etc.)	Hero- Optima, Photon, Nyx series, etc. Zypp- Zypp electric scooters Okinawa autotech-Praise, Ridge+, IPraise, etc.	Standard charging connectors	Common Indian three-pin plug (domestic AC charging) and Type 2 connectors (AC level 2 charging)

6.6 Electric Two-Wheeler Companies in India: Charging Compatibility and Connectors

Table 1 presents the electric two-wheeler companies, their prominent models, charging compatibility information, and the type of charging connectors used. Please note that the specific charging connectors and compatibility may vary within different models offered by each company.

6.7 Reasons for Diverse Chargers

See Fig. 24.

6.8 Global Statistics

See Fig. 25.

7 Grid Integration and Power Management

- DC fast chargers require careful grid integration and power management to minimize their impact regarding the electrical grid, guaranteeing stable operation.
- Smart charging algorithms and demand response capabilities enable DC fast chargers to tailor charging schedules based on grid conditions, renewable energy availability, and user preferences.

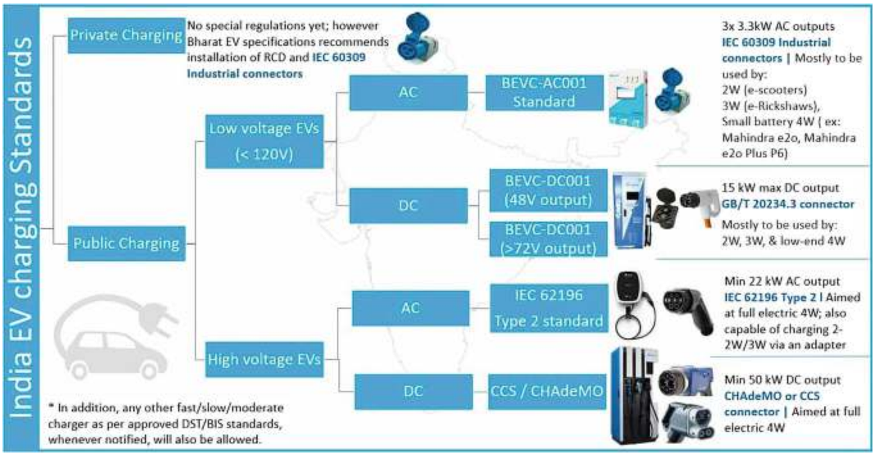


Fig. 24 E-mobility

Fig. 25 Standards and connector types for EV charging around the world (IESA)

- Bidirectional power flow capabilities, supported by some DC fast chargers, enable vehicle-to-grid (V2G) functionality, empowering EVs to serve as grid-integrated energy storage systems and enhance grid stability (Fig. 26).

In summary, DC fast chargers play a pivotal role in accelerating the adoption of electric vehicles by providing high-speed charging capabilities, enabling long-distance travel, and enhancing overall convenience for EV drivers. Continued advancements in DC fast charging technology, interoperability, and grid integration will further drive the growth of EV charging. Robust infrastructure and effective support are crucial for facilitating the transition to sustainable transportation.

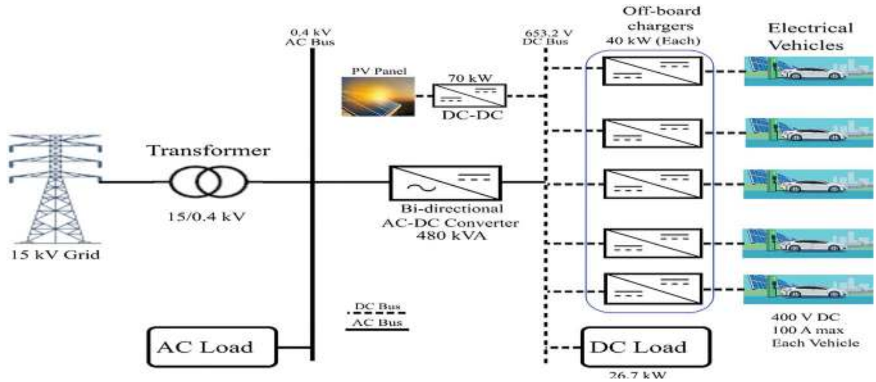


Fig. 26 Charging stations

7.1 Bidirectional Chargers (V2G)

Bidirectional chargers, also referred to as vehicle-to-grid (V2G) chargers, facilitate the bidirectional flow of power between EV batteries and the electrical grid. These chargers employ bidirectional DC-DC converters, enabling EVs to act as energy storage resources and deliver excess energy to the grid during peak demand periods [15] (Fig. 27).

Bidirectional EV charging is a groundbreaking technology that enables energy to flow in both directions: from the power grid to the EV and vice versa. Unlike conventional one-way EV charging, which solely powers electric vehicles, bidirectional chargers empower EVs to serve as energy storage units, capable of discharging energy back to the grid (V2G) or powering homes (V2H). This innovative technology unlocks new possibilities for grid management and energy efficiency.

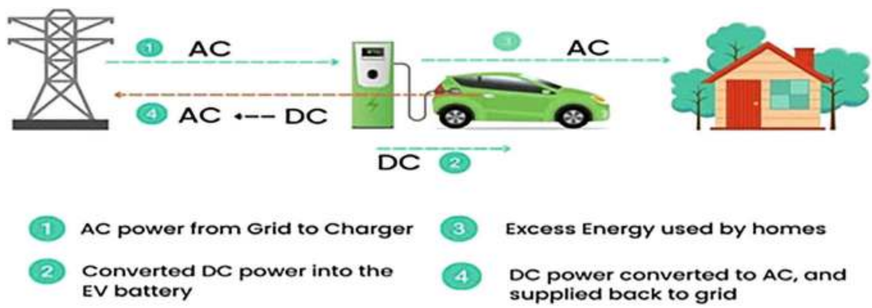


Fig. 27 Bidirectional EV charging (Energy flow cycle) in India

7.2 *Bidirectional EV Chargers Offer Several Advantages*

Supports Power Grid

As the number of electric vehicles in the nation grows, the power grid faces increasing strain. Bidirectional EV charging offers a solution by enabling empowers users to charge their EVs during off-peak hours and provide excess energy to the grid during peak demand, mitigating the need for costly grid upgrades and promoting a more sustainable and efficient energy infrastructure.

Make Money

Electric vehicles equipped with bidirectional chargers offer an opportunity to generate revenue by selling excess battery energy back to the power grid during peak demand periods. This energy, stored during off-peak hours through charging from solar panels, public EV chargers, or home power sources, can be profitably discharged into the grid.

Power Backup

Bidirectional EV chargers enable vehicle-to-home (V2H) functionality, providing a valuable backup power source for homes during emergencies or blackouts. The energy stored in EVs can be utilized to power essential appliances and systems within the home during peak energy demand periods. This innovative solution offers a reliable and sustainable approach to addressing power shortages, optimizing energy management, and enhancing grid resilience.

Save Money

In countries with dynamic energy tariffs or government incentives for off-peak charging, bidirectional chargers can significantly reduce electricity costs. By storing energy in EV batteries during low-demand hours (e.g., overnight), users can utilize this stored energy to power their homes during peak periods when electricity rates are higher. This strategic approach can lead to substantial savings on electricity bills over time.

Ecogears Take

As the electric vehicle market grows, energy storage and efficient utilization are becoming increasingly important. In the future, portable bidirectional EV chargers could offer significant cost savings and contribute to the effective utilization of renewable energy. For EV owners exploring opportunities to generate revenue by selling excess energy to the grid, investing in a bidirectional EV charger can be a strategic and financially rewarding choice.

8 Wireless Chargers

Wireless EV chargers use inductive power transfer to deliver energy wirelessly to the vehicle's battery. Power converters in wireless chargers facilitate the conversion of AC power from the grid to a high-frequency AC signal, which is then transmitted wirelessly to the vehicle's receiver coil and converted back to DC power for charging [16].

8.1 Integration Challenges and Solutions

Despite the numerous benefits of power converters in EV charging infrastructure, their integration poses several challenges, including grid stability, power quality, and interoperability. To address these challenges, advanced control algorithms, grid-friendly charging protocols, and standardization efforts are being implemented.

1. Grid-Friendly Charging: Smart charging algorithms are being developed to create optimal charging plans that consider grid conditions, renewable energy availability, and user preferences. These algorithms dynamically adjust charging rates to alleviate grid congestion, minimize peak demand, and enhance grid stability.
2. Quality Enhancement: Power converters with power factor correction (PFC) capabilities are essential for improving power quality and reducing harmonic distortion in EV charging systems. Active and passive PFC techniques help maintain high power factor and efficiency, ensuring compliance with grid regulations and standards.
3. Interoperability and seamless integration of EV charging infrastructure require standardized communication protocols, connector types, and charging interfaces. International standards such as CHAdeMO, combined charging system (CCS), and GB/T are fostering global interoperability and compatibility among EVs and charging stations (Fig. 28).

Fig. 28 Wireless EV charging

Wireless EV charging is comparable in efficiency and speed to traditional plug-in charging. While most EV plugs boast efficiency ratings of 80–95 percent, WiTricity, a pioneer in the field, has achieved 90–93 percent efficiency with its wireless EV chargers. These chargers can deliver up to 20 kW of charging power, equivalent to Level 2 charging speeds. While there are no technological barriers to achieving even higher speeds, supercharger-level charging is not anticipated in the near future.

8.2 Wireless EV Charging Options

Wireless EV charging is available in two primary configurations: static EV charging, which closely resembles the familiar plug-in charging method, and dynamic EV charging, designed for charging vehicles while in motion on open roads.

Static EV Charging (Home or Office Charging Station)

Static EV charging refers to the process of charging an electric vehicle while it remains stationary. Instead of plugging in, the wireless-equipped EV is positioned over the installed wireless charging coil within a designated parking space. This method eliminates the need for physical connections, providing a convenient and hands-free charging experience.

Dynamic EV Charging (Roads and Highways)

In the future, induction charging is anticipated to be embedded in roadways, enabling EV owners to charge their vehicles on the go. By eliminating the need for charging stops, this innovative approach will allow EV owners to travel long distances without the anxiety of running out of power.

8.3 Wireless EV Charging Benefits

While charging cables offer convenience, they also have inherent limitations. Wireless EV charging presents several advantages, especially for commercial vehicles. These advantages include eliminating the need for physical connections, reducing wear and tear on charging ports, and enhancing overall user convenience (Fig. 29).

No Wires

The primary advantage of wireless EV charging is the elimination of wires. EV owners are no longer burdened with carrying heavy charging cables or physically plugging their cars into charging stations. This convenience significantly alleviates range anxiety, allowing drivers to enjoy a more carefree and enjoyable driving experience.

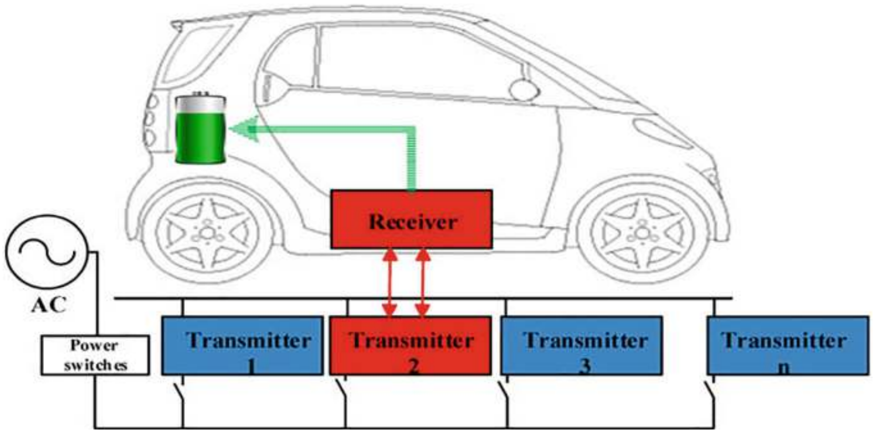


Fig. 29 Wireless EV charging stages

Lower Accident Risk

Charging cables can degrade over time, especially in regions with extreme temperatures. This deterioration poses safety risks to both the vehicle and its owner. Wireless EV charging eliminates the need for cables, reducing the likelihood of damage and eliminating the costly process of cable replacement.

More Convenience

Wireless EV charging offers a more convenient experience, even in its current static form. Imagine the added convenience of dynamic charging, which would allow vehicles to charge while in motion. This technology has the potential to revolutionize the EV charging landscape, providing drivers with unparalleled ease and flexibility.

Save Time

While wireless charging may not offer a significant speed advantage over traditional plug-in charging, it does eliminate the time-consuming process of physically plugging in the vehicle. The convenience of remaining in the vehicle during the charging process can be valuable. Additionally, once dynamic charging becomes a reality, the time savings associated with charging while in motion could be substantial.

8.4 Future Perspectives

Power converters play a vital role in the future of electric vehicles (EVs) and will continue to be a key area of development for several reasons:

1. **Efficiency and Performance**:

- Power converters ensure optimal power flow among the battery, electric motor, and other elements of electrical components in an EV.
- Advanced converter designs will focus on minimizing energy losses during conversion, maximizing the driving range and overall efficiency of EVs.

2. **Multi-voltage Systems**:

- Future EVs might utilize different battery voltages depending on factors like vehicle size and range.
- Power converters will be crucial for regulating voltage and ensuring compatibility between various battery types and the electric motor.
- This flexibility will allow for a wider range of EV designs and cater to diverse consumer needs.

3. **Bidirectional Charging**:

- The concept of vehicle-to-grid (V2G) technology is gaining traction, where EVs can feed power back into the electricity into the grid during periods of peak consumption.
- Bidirectional power converters will be necessary to facilitate bidirectional energy transfer, promoting grid stability and potentially offering economic benefits to EV owners.

4. **Faster Charging and Higher Power Densities**:

- Consumer demand for faster charging times and longer driving ranges will push the development of next-generation power converters.
- These converters will need to handle higher power densities efficiently while maintaining safety and reliability.

5. **Integration with Renewable Energy**:

- As the world transitions toward renewable energy sources like solar and wind, power converters will play a role in integrating these fluctuating power sources with the grid.
- EVs with smart charging capabilities can leverage these renewables, further reducing their environmental impact.

8.5 Future Trends in Power Converters for EVs

The future of power converters in electric vehicles hinges on several key advancements. The adoption of wide-bandgap semiconductors, such as silicon carbide (SiC) and gallium nitride (GaN), will enhance efficiency and thermal performance. Advancements in converter topologies, like multi-level converters, will facilitate higher power densities and reduce switching losses. Moreover, the integration of intelligent control systems will optimize power flow, manage battery health, and enable innovative features like V2G. By focusing on these technological breakthroughs, power converters will continue to play a pivotal role in pioneering the widespread adoption of electric vehicles and ushering in a new era of sustainable mobility.

Conclusion:

In conclusion, power converters are not mere supporting actors; they are pivotal players in the electric vehicle revolution. Their development will directly influence the efficiency, performance, and functionality of future electric vehicles. As the industry pursues faster charging, extended ranges, and integration with renewable energy, innovative power converter designs will be instrumental in unlocking the full potential of EVs and paving charting a course toward a sustainable transportation future.

9 Beyond Efficiency: Power Converters as Enablers of a Sustainable EV Ecosystem

Power converters are much more than just components that ensure efficient energy flow in an EV. They are fundamental enablers for a future-proof electric vehicle ecosystem. Here is why:

- **Unlocking Faster Charging and Wider Adoption:** Imagine pulling into a charging station and topping off your EV's battery in a fraction of the time it takes today. Advanced power converters with high-power density capabilities will make this a reality. This convenience factor will be crucial for widespread EV adoption, encouraging more consumers to switch from gasoline-powered vehicles.
- **Optimizing Range and Battery Health:** Next-generation power converters will not just deliver power efficiently; they will also play a key role in maximizing an EV's driving range. Additionally, these intelligent systems can monitor and regulate battery health, ensuring longer lifespans for these critical EV components.
- **The Gateway to Vehicle-to-Grid Integration:** Imagine your EV not just utilizing power supplied by the grid, but also contributing to it. Bidirectional power converters will pave the way for V2G technology, where EVs can act as distributed energy storage units. This two-way flow of electricity can provide grid stability during peak demand periods and even offer economic benefits to EV owners who participate in such programs.
- **The Green Bridge to Renewables:** The future of transportation is not just electric, it is sustainable. Power converters will act as the bridge between EVs and renewable energy sources like solar and wind. With the ability to handle the unstable nature of these renewable energy sources, converters will enable EVs to charge using clean energy, further reducing their environmental impact.

In essence, power converters are not merely technical components; they are the architects of a cleaner, more sustainable transportation future. By focusing on innovation in power converter design, we can unlock the full potential of EVs and pave the way for a future where electric vehicles are not just the alternative, but the standard.

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