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Review article

A comparative analysis of the efficient coordination of renewable energy and electric vehicles in a deregulated smart power system

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ABSTRACT

Deregulation in the energy sector has transformed the power systems with significant use of competition, innovation, and sustainability. This paper outlines a comparative study of renewable energy sources with electric vehicles (RES-EV) integration in a deregulated smart power system to highlight the learning on system efficiency, effectiveness, viability, and the environment. This study depicts the importance of solar and wind energy in reducing carbon emissions and the challenges of integrating RES into present energy grids. It touches on the aspects of advanced energy storage systems, demand-side management (DSM), and smart charging technologies for optimizing energy flows and stabilizing grids because of fluctuating demands. Findings were presented to show that, based on specific pricing thresholds, hybrid renewable energy systems can achieve grid parity and market competitiveness. Novel contributions included an in-depth exploration of the economic and technical feasibility of integrating EVs at the distribution level, improvements in power flow control mechanisms, and strategies to overcome challenges in decentralized energy systems. These insights will help policymakers and market participants make headway in the adoption of microgrids and smart grids within deregulated energy systems, which is a step toward fostering a sustainable and resilient power sector.

1. Introduction

Renewable energy sources, especially wind and solar, have witnessed tremendous growth in electricity production in the past few years; the global production of power through renewable energy is expected to reach 50 % in 2023, as a clear signal towards cleaner sources of energy solutions (Partha Pratim Dey et al., 2020; Maher et al., 2021; Chauhan et al., 2021). The global energy sector has set ambitious targets for net-zero carbon dioxide emissions by 2050, with the electricity sector leading the transition toward a carbon-free, renewable-based power generation system (Chakraborty et al., 2022). This transition requires significant advancements in grid infrastructure, including the development of more robust and technologically advanced grids that can support increased power generation and improved recovery capabilities. Distributed Energy Resources, which oppose the traditional centralized power generation systems, have been playing an important role in this transition with the introduction of smart grids offering alternative grid architectures designed for the efficient integration of renewable energy sources (RES) (Barik et al., 2021; Das et al., 2022a; Hussain et al., 2020a). The smart grids provide the integration of RES, providing inexhaustible and low-cost energy while reducing greenhouse gas emissions (Farooq et al., 2022; Kumar Singh et al., 2021; Safiullah et al., 2022; Das et al., 2022b; Nayak et al., 2023; Amitkumar et al., 2022; Hussain et al., 2019; Suhail Hussain et al., 2020; Yadav et al., 2021; Dawn et al., 2021). Furthermore, the incorporation of DERs such as solar photovoltaic (PV) panels, wind power plants, energy storage systems (ESS), and demand response mechanisms in solar-integrated microgrids supports local energy independence and improved power reliability, operating either in isolation or in parallel with the main grid (Chauhan et al., 2022; Ranjan et al., 2021; Latif et al., 2021a; Ulutas et al., 2020;

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Sudhanshu Ranjan et al., 2021; Latif et al., 2021b). Advanced communication technologies deployed within smart grids support more efficient management of energy resources, enhance grid resilience, and allow for effective demand-side resource management (Ustun et al., 2022, 2021a; Hussain et al., 2020b; Ustun et al., 2011; Ustun and Hussain, 2020a). However, the increase in connectivity and complexity brought by smart grids is accompanied by risks of cybersecurity attacks, which are necessary to address for the systems to be reliable and resilient (Ustun and Hussain, 2020b; Farooq et al., 2018; Ustun, 2021; Ustun et al., 2020; Farooq et al., 2019). Recent studies have been more focused on devising strategies for improving cybersecurity within smart grids that address these new challenges (Ustun et al., 2021b, 2021c; Unsal et al., 2021; Ustun, 2019; Chawla et al., 2022).

The integration of RES and DERs further facilitates the transformation of power systems toward cleaner, more sustainable practices, driving the overall efficiency of energy management and supporting cleaner power generation (Basu et al., 2022). Off-grid renewable energy systems, particularly in rural and remote areas of developing countries, represent a promising solution for providing electricity in areas with limited access to centralized grids. However, environmental challenges, such as difficult terrain and geographically dispersed communities, are considered significant barriers to the effective installation and maintenance of these systems (Nyarko et al., 2023). Decentralized energy systems, which include microgrids, thus offer a big opportunity for developing more sustainable and resilient infrastructures that integrate renewable energy sources while improving overall grid reliability. Additionally, the integration of smart grid technologies promotes energy efficiency and encourages consumer participation in local energy markets, thereby supporting the shift toward renewable energy adoption and reducing reliance on the main grid (Alanne, 2023). Electric vehicles are another key component in the transition to a sustainable future, offering a zero-emission alternative to traditional internal combustion engine vehicles. When charged with renewable energy, EVs also contribute greatly toward carbon emissions and overall environmental impact. In addition, long-term savings are achieved by lower operating costs and more efficient usage of energy, as they convert about 60 % of electrical energy from the grid into power for the wheels, whereas an internal combustion vehicle converts only 17–21 % of the energy delivered from the pump to the wheels (IEA, 2024).

India has set an ambitious target of sourcing 40 % of its electric power capacity from non-fossil fuel-based sources by 2030, which will help maintain the environmental benefits of EVs. However, the widespread adoption of EVs raises concerns about grid stability and power quality, particularly regarding the increased load on the grid due to the growing number of EVs. One of the promising solutions is decentralizing power systems by utilizing smart, self-sufficient systems that are not as stressful for centralized management of the grid and would allow EV owners the possibility of participating in maintaining stability by providing balancing and regulating services. Besides, a strong public charging infrastructure will be needed to complement the spread of EVs in developing countries such as India, where municipal and regional charging facilities will be important to optimize resources and extend EV adoption (Desai et al., 2023). As a strategy to counter the fluctuations caused by these kinds of renewable energy sources, one key approach for LIBs is its operation in the pulsed mode, wherein the nonlinearities introduced can help stabilize the grid and further dampen the impacts of variable renewable generation in ensuring overall system stability (Qin et al., 2022).

Transition to renewable energy has been the pivotal, urgent priority in modern power systems due to rising global demand to reduce carbon emissions and meet international agreements and national policies for sustainability. With the world trying to intensify efforts to combat climate change, RES integration and increased adoption of Electric Vehicles offer a unique opportunity to overhaul and enhance the existing power grid infrastructure. This shift is crucial for a sustainable, low-carbon energy future, yet it brings along a host of challenges, especially in the context of deregulated energy markets. The integration of RES and EVs into traditional grid systems, with their inherent variability and decentralization, raises complex technical, economic, and operational concerns, especially in deregulated environments where market dynamics and competition among various stakeholders add layers of complexity. In deregulated power markets, the grid is typically managed by Independent System Operators (ISO), and various market participants compete for energy production and consumption. This decentralized structure poses several major challenges that have to be met for the grid to be operated effectively and integrated with other sources of power. Among them are ensuring stability in the grid with fluctuating supply from RES, optimizing the integration of DERs, and increasing electrical demand because of the large number of EVs on the road. Additionally, the explosion of EVs introduces further concerns regarding the strain they place on the grid, requiring advanced methods to balance charging demands and ensure grid stability. These challenges highlight the need for thorough analysis and the development of innovative solutions that can facilitate the seamless and reliable integration of RES and EVs into the existing grid infrastructure. There have been some developments in smart grid technologies which have helped overcome some of the problems mentioned above. One notable area has been the development of advanced control mechanisms to integrate RES more efficiently and reliably into the power grid. Technologies such as Battery Energy Storage Systems (BESS), Vehicle-to-Grid (V2G) interaction protocols, and Demand-Side Management (DSM) strategies are at the forefront of these innovations. For instance, BESS contributes to stabilizing the grid by taking the surplus renewable energy available when demand is low and also discharging it at high-demand moments such that the supply of power to the grid remains constant and dependable. V2G protocols further improve the stability of the grid because EVs not only draw power from the grid but also supply energy back into the grid, providing an added layer of flexibility and resource availability. DSM strategies, on the other hand, focus on optimizing energy consumption patterns by adjusting demand in response to supply conditions to ensure that the grid operates efficiently even with fluctuating renewable generation. In addition, optimization algorithms that use machine learning and metaheuristic methods have improved the efficiency of microgrids in their operations. Such algorithms make the microgrid adaptive and responsive to changes in energy supply and demand, thereby allowing for optimized energy management with reduced waste and increased efficiency. By using real-time data and predictive analytics, such algorithms can improve decision-making processes, enhance system resilience, and optimize the allocation of energy resources within the microgrid.

With a lot of the previous and current literature dealing with the technical integration issues of RES and EVs into the electricity grid, there is a significant lack of material involving research on their economics and environmental impact in deregulated market settings. Most studies fail to examine the intricate interaction between market dynamics, regulatory frameworks, and RES and EV integration, thereby neglecting the economic benefits and challenges that may arise from such integration. Moreover, there is a lack of detailed analysis of the advanced control mechanisms required to ensure grid resilience and profitability in the face of fluctuating energy demand. Most existing studies tend to focus on decentralized energy management systems in a limited capacity, not fully exploring their potential for optimizing grid operations and economic outcomes. This paper aims to address these gaps in the literature by providing a detailed analysis of the integration of RES and EVs in deregulated smart power grid systems. More specifically, it discusses the integration role of several DG technologies, including thermal power, concentrated solar power, and fuel cells, in deregulated power systems. Although RES-based DG units received a lot of attention in terms of research within microgrids, integration of other DG technologies was less explored. Bridging this research gap, this paper aims to better understand the scope of DG technology diversity toward more reliable power supply, fulfilling sustainability goals, and making a power system more resilient and economical in deregulated markets. This work also stresses the need for new approaches to energy management, including the role of advanced controls and optimization strategies in achieving a seamless transition to a more sustainable and efficient energy future. The study focuses on the following key areas:

- This paper explores how deregulated power systems impact the stability and reliability of energy grids, along with the opportunities for technological advancements.
- Furthermore, it investigates how the incorporation of microgrids and smart grids into these deregulated systems can enhance efficiency and optimize overall grid performance.
- While microgrids and smart grids hold promise for fostering sustainable development in the future, it's essential to evaluate the economic and environmental impacts of their implementation.
- This paper also presents actionable recommendations for the integration of microgrids or smart grids into deregulated energy systems, aiming to boost electricity generation, distribution, and profitability for energy providers.

This study aims to fill the existing gaps in research on the integration of renewable energy sources and electric vehicles in deregulated power systems by presenting a comprehensive analysis. Both technical and economic dimensions of this integration have been explored to provide valuable insights into how these technologies have contributed to more sustainable, efficient, and resilient energy systems. The control parameters and variables play a crucial role in optimizing renewable energy systems, smart grids, and electric vehicle integration into deregulated power markets. Parameters that have an impact on the efficiency, stability, and economic feasibility of integrating RES with DG, ESS, and V2G technologies are outlined in the discussion that follows about control parameters and variables in the literature.

1.1. Control parameters in renewable energy integration

Control parameters in renewable energy systems are primarily centered on the management of RES variability, maintaining power balance, and optimization of system performance.

a) ***Grid stability and power flow control parameters:*** To maintain the stability of the grid, voltage profiles must stay within allowable limits, which may be controlled through control techniques employing FACTS devices. Intermittency of renewable energy often causes fluctuations in the grid frequency, and thus, adaptive control methods and Demand Response strategies are used to stabilize the frequency. Additionally, the power factor must fall in a permissible range, which is achieved with control techniques such as reactive power compensation and phase-shifting transformers to achieve optimal grid performance and reliability.
b) ***Optimization-based parameters for RES and DG:*** The Maximum Power Point Tracking (MPPT) algorithms that are applied in PV and wind energy systems include the Perturb and Observe (P&O) and Particle Swarm Optimization (PSO) schemes. The PSO is applied to ensure maximum extraction of power from the energy grid. Overcharging and undercharging limits pose a limitation on power availability in the hybrid energy storage system. Care should be taken by setting appropriate limits to maintain system efficiency. This further refers to the application of economic dispatch strategies in defining cost functions that minimize operational expenses while optimizing the use of Renewable Energy Sources, maximizing their utilization.
c) ***Cybersecurity and communication control parameters:*** The data exchange rates in smart grid systems play a vital role in communication protocols to ensure real-time control and maintain security without cyber attacks. For more protection, machine learning-based security algorithms are deployed to monitor network anomalies, detect possible threats, and prevent cyberattacks from invading the smart grid infrastructure, maintaining its integrity and reliability.

1.2. Control parameters in energy storage systems

Energy storage is an important measure to mitigate RES intermittency, and control parameters are optimized to maximize storage performance.

a) ***Battery management system (BMS) parameters:*** To maximize battery life, careful management of the State of Charge (SoC) and Depth of Discharge (DoD) is important to optimize charging and discharging cycles. Fuzzy logic controllers and reinforcement learning-based BMS are used to enhance the efficiency of these charge cycles. Also, effective temperature management is crucial to prevent thermal runaway and optimize battery performance. This is accomplished through cooling and heating systems and thermally-aware controllers so the batteries always stay within a safe temperature range.
b) ***Hybrid energy storage system (HESS) optimization:*** Supercapacitors are used to handle high-power bursts in HESS, whereas lithium-ion batteries (LIBs) are used to store energy over a long duration. Control strategies are usually deployed to optimize the dispatch of energy from these sources. In V2G systems, the dynamic energy storage unit of electric Vehicles gives feedback power to the grid during peak demand h. To optimize V2G scheduling, DRL-based control algorithms are used, which ensure efficient energy exchange and grid stability.

1.3. Control parameters in smart grid and demand-side management (DSM)

The working of smart grids involves real-time monitoring, automation, and demand-side response mechanisms, which ensure the proper functioning of the smart grid.

a) ***Demand response (DR) and load scheduling:*** The Time-of-Use (ToU) and dynamic pricing signals can be used as incentives for customers to shift energy usage towards off-peak h to balance the demand. Control techniques are applied to support this load shifting through price-responsive Demand Response algorithms. Besides, the Random Forest (RF) and Long Short-Term Memory (LSTM) based techniques on machine learning can boost load forecasting and management. Accurate demand prediction, along with reduced peak loads, ensures better operation and energy distribution through a more efficient grid.
b) **Optimization of power distribution in microgrids:** Techniques like mixed-integer linear programming (MILP) and metaheuristic algorithms, such as genetic algorithms and Particle Swarm Optimization (PSO), are used to optimize energy scheduling in microgrids to manage power dispatch efficiently. Furthermore, grid islanding mode control is ensured with a seamless transition between grid-connected and islanded operations, which uses fast-switching controllers and fault-detection algorithms to ensure stability and reliability during the transition. These strategies enhance the flexibility and resilience of microgrids, allowing for optimized energy management and continuous operation under varying conditions.

1.4. Control variables in renewable energy, smart grid, and EV integration

Control variables are measurable factors in renewable energy systems, smart grids, and electric vehicle integration that are controlled to maximize overall system performance. In renewable energy systems, the direct impact of solar radiation on photovoltaic output requires adaptive power conversion. Wind speed is a variable in wind turbine power generation that must be controlled with pitch angle adjustment for optimal efficiency. Inverters' efficiency is another critical variable that determines the effectiveness of power conversion, and it impacts the overall performance of the system. For battery storage and Vehicle-to-Grid (V2G) systems, the SoC of EVs sets the energy availability for grid support, which is influenced by users' driving patterns, while the charging and discharging rate controls the power flow between EVs and the grid. The State of Health (SoH) of batteries is important because it indicates the degradation levels that can affect long-term system reliability. Economic and market control variables include electricity market prices, which influence energy trading and real-time dispatch optimization decisions, and renewable penetration levels, which impact grid reliability and curtailment strategies. Finally, reduction targets in emissions establish the prerequisites for choosing policy-driven optimization techniques capable of satisfactorily attaining environmental objectives. The control variables in themselves guarantee the reliable, effective, and sustainable integration of renewable energy sources, smart grid technology, and electric vehicles within the energy system.

1.5. Control strategies for RES-EV integration

The latest research concentrated on producing more erudite controlling mechanisms to help improve the sustainability and efficiency of RES-EVs. Machine learning and AI-driven control strategies have been developed based on Deep Reinforcement Learning (DRL) while optimizing real-time power distribution and ensuring grid stability in complex networked systems. AI-driven and supported forecasting models help reduce forecasting errors in determining RES output, EV charging needs, and related energy management performance. In multi-agent and decentralized control frameworks, blockchain-based energy trading enables P2P transactions among microgrids, thus allowing better efficiency in energy exchange. Further, decentralized management of energy for smart homes can maximize demand-side energy consumption through IoT-enabled controllers, providing rapid and efficient usage of dispersed energy resources. These new strategies, as a collective contribution, pave the way for more flexible, reliable, and sustainable energy systems.

2. Global renewable energy status

Investments in clean and sustainable power generation have further stimulated global markets to prioritize renewable energy. This is particularly true in sectors like solar energy and electric vehicles, wherein huge financial investments are made for their growth. Fig. 1 displays the trend of worldwide investment in renewable energy technologies and the market of electric vehicles for 2015–2023 (Nyarko et al., 2023). The data shows a tremendous surge in investments in clean energy technologies, with a clear emphasis on renewable projects and the expanding EV market. This upward trend reflects a global shift towards sustainability, driven by ambitious climate goals and supportive government policies aimed at accelerating the adoption of green energy initiatives. The continued growth of investments in renewable energy, particularly in the context of smart grid technologies, marks a crucial step in the global transition from fossil fuel dependency to a more sustainable energy future. The energy sector is witnessing significant investments in power generation and renewable energy infrastructure, with several drivers behind this, including growing electricity demand, decreasing costs for renewable energy, and government regulation expansion for clean energy. Figs. 2 and 3 outline global fossil fuel versus clean energy investment trends, showing a marked shift towards renewable energy investment. The global renewable energy production capacity stood at a cumulative of 3372 GW by the end of 2022.

Major hydropower sources accounted for most of this capacity, reaching as high as 1256 GW of the total capacity. The remaining capacity, apart from hydropower, comprised solar and wind, amounting to 1053 GW and 899 GW, respectively. Bioenergy contributed 149 GW, geothermal energy had 15 GW, and marine energy added up to 524 MW (Worldwide Renewable Energy Capacity Rises 10% In, 2022, 2023). In 2022, the renewable energy sector increased its capacity by 295 GW, which is a 9.6 % growth. Growth in Solar energy was notable at 192 GW or 22 %, followed by Wind energy, which saw an increase of 75 GW or 9 % growth. The growth of Renewable Hydropower stood at 21 GW or 2 %, while bioenergy grew by 8 GW or 5 %. Geothermal energy rose modestly by 181 MW. Fig. 2 is a comparative chart showing global financial investments in renewable energy sources, including wind and solar technologies, compared with non-renewable energy sources, such as fossil fuels and nuclear power. There is an increasing trend toward investing in renewable energy sources as a result of the global mandate to reduce carbon emissions and mitigate climate change. This is in line with the focus of the study and tends to prove that renewable energy sources are gaining importance in the energy market.

Fig. 4 is a visual representation of global expansion in renewable power capacity. The graph emphasizes significant year-over-year growth in renewable energy capacity because of reduced production costs, technological advancement, and the development of favorable regulatory environments. This growth underscores the growing need for flexible, advanced smart grid systems that can manage the variability of renewable energy sources. These observations resonate with the

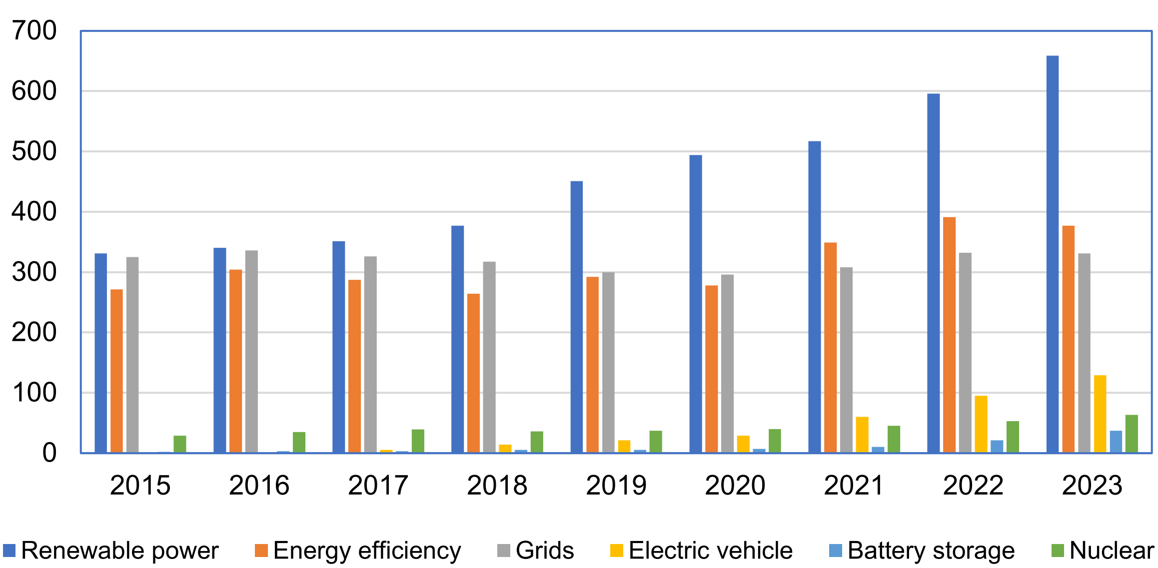

Fig. 1. Global status of clean energy investment (In billion USD).

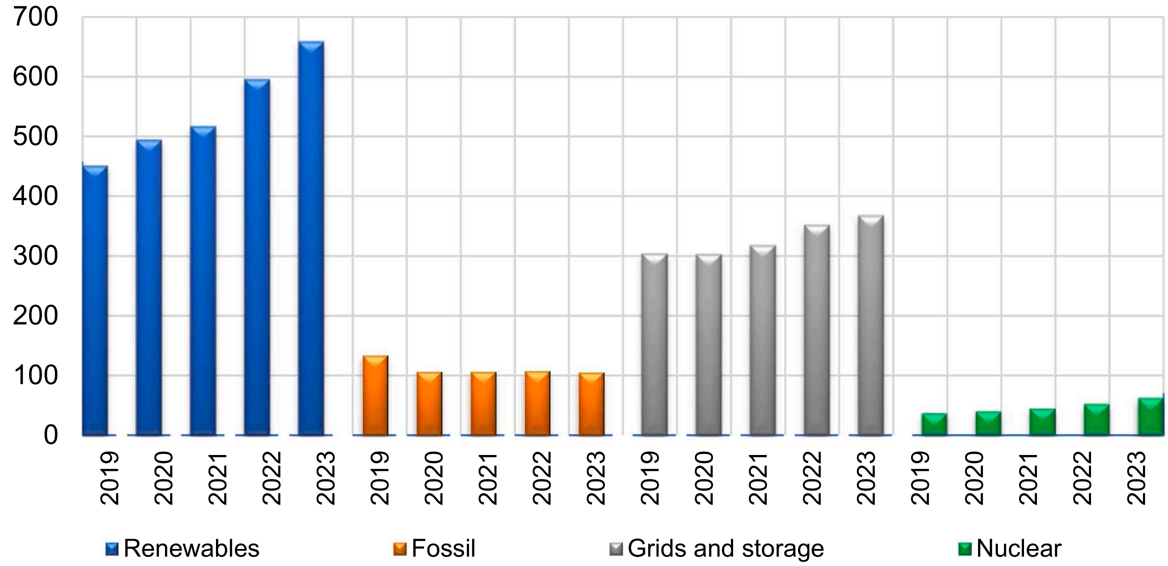

Fig. 2. Comparison between worldwide investment in RES and non-RES (In billion USD).

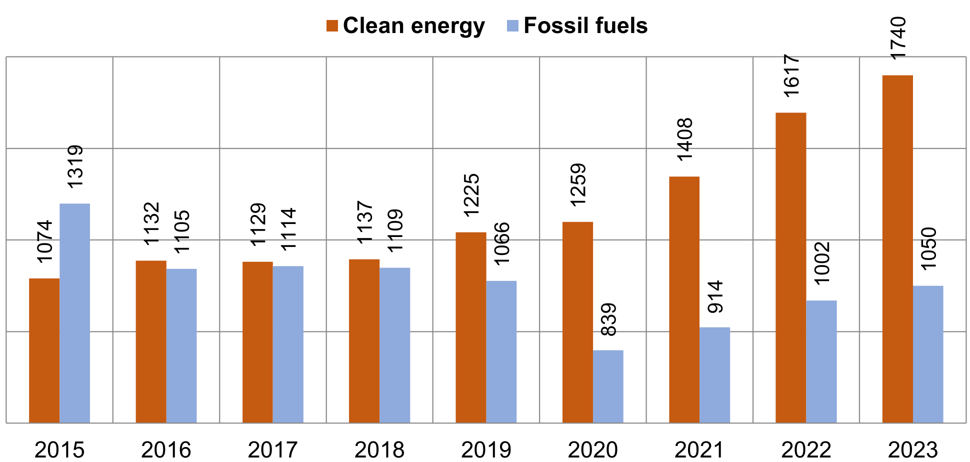

Fig. 3. Global investment in clean energy and fossil fuels (In billion USD) (IEA, 2024).

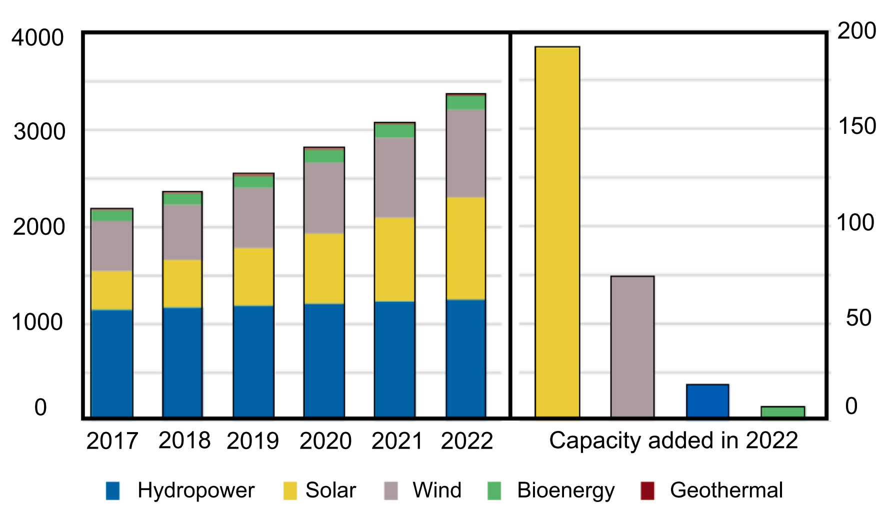

Fig. 4. Global renewable power capacity growth (in GW).

findings of the study on the necessity of integrating smart grid technology with RES to ensure grid stability and efficiency. The growing surge in renewable energy capacity, coupled with declining costs and supportive policies, underscores the critical need for advanced smart grid systems. Such systems are essential for managing the fluctuating nature of renewable energy, ensuring grid reliability, and facilitating the continued integration of renewable energy into modern power systems. In 2022, the global growth of renewable energy surpassed long-term averages, marking a significant milestone in the global energy transition. China and the United States continued to lead this expansion, while many other countries made considerable progress in enhancing their renewable energy capabilities. The share of renewable energy sources in total capacity growth increased to 83 % in 2022, up from 78 % in 2021, which indicates a strong global shift toward cleaner energy.

The share of renewable sources in total generation capacity also increased by nearly two percentage points, climbing from 38.3 % in 2021 to 40.2 % in 2022 (shown in Fig. 4). This acceleration in renewable energy adoption highlights the increasing shift away from non-renewable energy generation, with a concurrent slowdown in the growth of fossil fuel-based energy capacity. The global growth in renewable energy capacity is also driven by the major decommissioning of non-renewable generation units in many regions, although non-renewable capacity kept growing in some parts of Asia in 2022. North America saw considerable decommissioning, while Europe bucked the trend by recording growth in non-renewable capacity. At the same time, there are still some countries leading the way in terms of renewable energy share in the primary energy mix, for instance, Iceland, Norway, Costa Rica, and Austria. The increasing share of renewable energy in global power systems brings several environmental as well as economic benefits and reduces carbon emissions, but integrating RES, including large-scale photovoltaic systems, into the existing infrastructures of the grid produces a set of technical difficulties. The general contribution of renewable energy in worldwide electricity production has remained consistently increasing over the years, mainly because of the increasing capabilities of solar and wind sources of energy (Accelerating transition to secure, sustainable and equitable energy systems, 2023). In the year 2022, renewable energy generated almost about 13 % of the energy generated in the world globally, surpassing nuclear energy for the first time. While the share of coal in global power generation increased slightly in 2022, it was still lower than in any previous year and continued to reflect the global trend toward decarbonization of the energy mix. Fig. 5 shows the growth in global annual additions to power capacity from renewable sources, with continued growth in solar, wind, and other forms of renewable technology. In a similar form, Fig. 6 illustrates the world map of renewable energy, outlining how renewable energy is spread across the world. There also geographical differences across different regions.

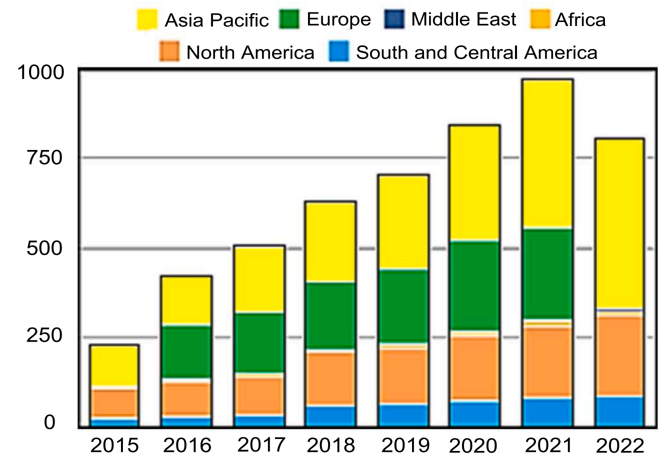

Fig. 6. Global Renewable Energy Consumption (in million tones oil equivalent).

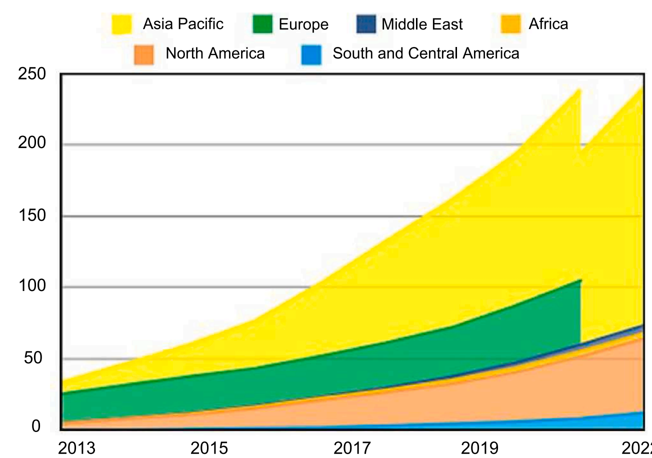

Fig. 7. Global solar energy consumption (in million tones oil equivalent).

Figs. 7, 8, and 9 illustrate renewable energy use as split into different

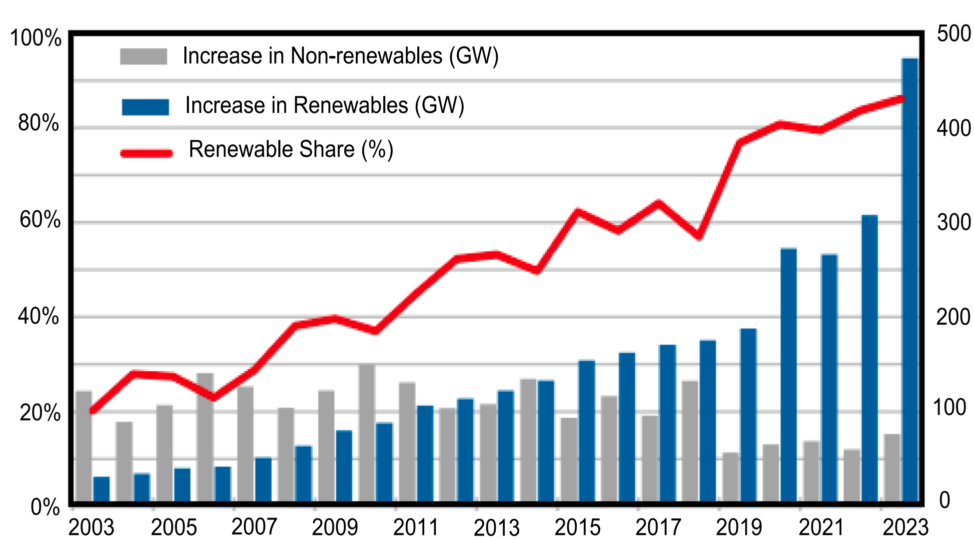

Fig. 5. Annual power capacity expansion on renewable sources.

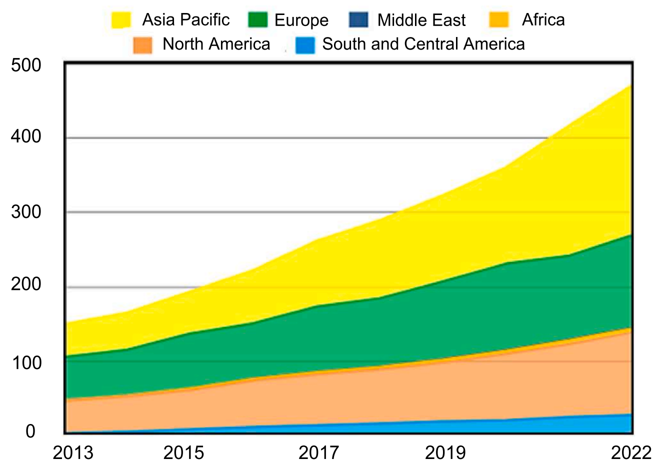

Fig. 8. Global wind energy consumption (in million tones oil equivalent).

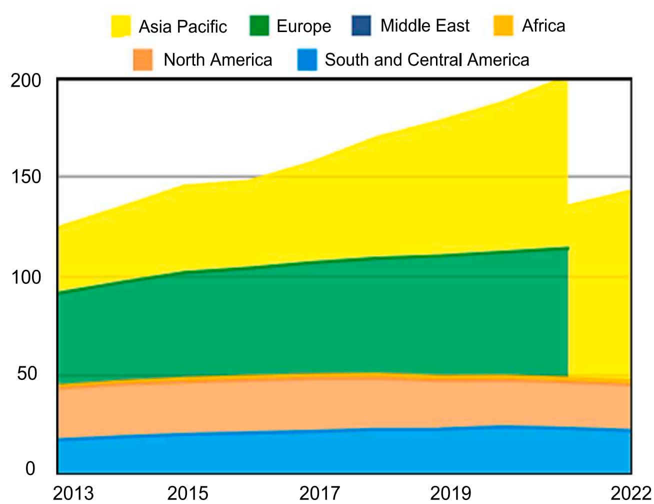

Fig. 9. Geothermal, biomass, and other renewable consumption (million tones oil equivalent).

renewable energies, including solar, wind, and other sources. The integration of RES into microgrids is more challenging because of the variability and intermittency of these sources. A microgrid, usually powered by sources like solar and wind that depend on distributed generation units, has to face variability in supply that depends on the time of day, seasonality, and weather conditions. Such variability in the supply of energy combined with increasing complexities in the demand for loads, as seen in smart load participation and dynamic consumption patterns, could compromise the stability of the grid. Smart load participation adds another layer of complexity to microgrid operations as load demand becomes more dynamic and less predictable. To integrate non-dispatchable distributed generation units within existing utility grids, new control mechanisms must be implemented to overcome the impracticality of islanding—where a microgrid operates independently from the main grid. Coordination between RES, load participation, and the grid operator is critical for balancing the supply-demand relationship and ensuring stability within the grid. Advancements in planning, control strategies, and smart grid technologies must be incorporated in real-time adjustment to generation and consumption patterns.

This movement towards renewable energy is rapidly becoming global, with renewable sources growing significantly in terms of share of global energy production and consumption. However, the incorporation of RES into existing power grids raises a whole set of technical issues that need to be addressed for the achievement of stable and reliable grid performance. Smart grids combined with innovative control mechanisms will be key to ensuring that the increasing share of renewable energy can be seamlessly integrated into the grid. Further research into the stability and operational impacts of high-penetration renewable energy systems will be necessary to support the transition to a more sustainable and resilient energy future.

3. Renewable energy in deregulated power systems

The deregulated power market differs from the regulated environment in which a single body, such as the government, holds control. In contrast, the deregulated power market is characterized by competition between multiple market players, which benefits customers (Jawad and Masood, 2022). However, as shown in Fig. 10, various factors influence the adoption of the deregulated power system.

- **Innovation in renewable energy:** Renewable energy is becoming more accessible, efficient, and cost-effective due to technological breakthroughs. Energy storage is being developed to provide a consistent power supply from unreliable renewable sources. Community-owned deregulated renewable energy projects are on the rise, giving communities more control over their energy supply and strengthening local economies.
- **Customer choice:** Electricity generation and distribution are controlled by monopolistic utilities, leading to price competition among corporations. Power costs for customers vary based on location, even with the same consumption. Deregulated electricity systems allow customers to choose their power provider. This enables comparison of prices and services to find the most competitive option. Customers can benefit from lower rates and better services.
- **Advanced control and monitoring:** Modern control and monitoring systems are essential for optimizing power system operation, improving efficiency, and reducing expenses. These advanced systems use modern algorithms and real-time data to make informed decisions and adjust power flow. This also helps identify and isolate errors, minimizing downtime and improving power supply reliability. A key component of these systems is the Supervisory Control and Data Acquisition (SCADA) system, used for power generation, transmission, and distribution, as well as monitoring and control.
- **Capital risk management:** The utility firm's regulated electricity system transfers investment risks to customers through increased rates. Customers bear all investments and associated risks. In a deregulated power system, competition among energy suppliers is allowed, encouraging efficient and cost-effective investments. This competition incentivizes providers to make wise investments that maximize returns and minimize risk.
- **Challenges and opportunities:** Because of deregulation, market power becomes concentrated, restricting competition and enabling

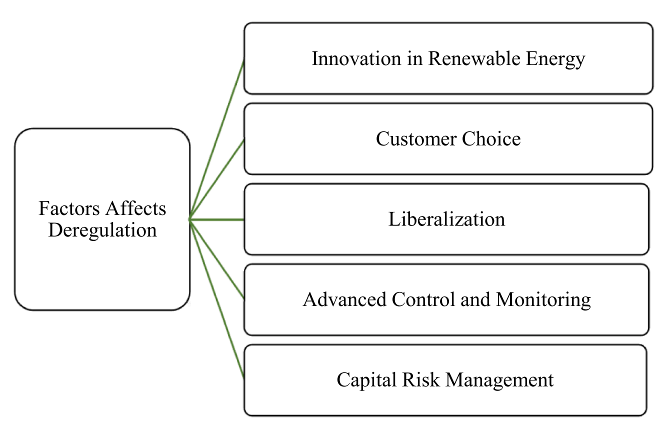

Fig. 10. Factors affecting deregulated power systems.

monopolistic practices. Developing appropriate laws for a deregulated market is complex and necessitates strict scrutiny to maintain fair competition, consumer protection, and market stability. Upgrading infrastructure can be expensive and difficult, particularly in places with old systems. When engaging in a thoughtful analysis of the various infrastructure limitations alongside the inherent risks associated with depending on decentralized systems, particularly in nations that exhibit unpredictable regulatory environments, it is of paramount importance to consider the following points which hold significant relevance:

A. ***Infrastructure limitations:*** A considerable number of nations often encounter significant challenges when it comes to effectively integrating contemporary decentralized systems such as microgrids and various RES, which necessitates that considerable efforts be undertaken to upgrade transmission and distribution networks, a process that can prove to be both prohibitively expensive and extraordinarily time-consuming, thereby complicating the transition to modern energy systems.
B. ***Risk of decentralized systems:*** In deregulated markets, price volatility and the threat of stranded assets can severely impact the functionality and reliability of decentralized systems because the sudden change in the regulations can pose unanticipated financial pressures on the operators, especially in competitive markets where the margins of profitability are already incredibly less.
C. ***Mitigation strategies:*** Governments need to take proactive measures by formulating and implementing stable, clear policies that provide strong incentives for the adoption of renewable energy and the development of decentralized systems, thereby fostering a favorable environment for growth. To address the pressing challenges posed by aging infrastructure, both governmental entities and utility companies must make initiatives.

4. Smart grid system (SG)

A smart grid is an electrical power network that utilizes digital technologies to enhance its reliability, sustainability, and effectiveness. The grid's bidirectional communication among all stakeholders, including grid operators, generators, and consumers, makes this possible. This connectivity allows for real-time monitoring and management of the grid, resulting in increased efficiency and fewer power outages. AMI (Advanced Metering Infrastructure) is a network of intelligent meters that collect and transmit information about electricity usage to the grid operator. This data enables the monitoring of energy consumption, identification of potential issues, and implementation of demand response. ICT (Information and Communication Technologies) data is shared among all participants in the grid. This data not only allows for the monitoring and management of the grid but also enables consumers to receive notifications regarding their energy consumption. Grid optimization involves leveraging data and analytics to enhance the efficiency of the grid. By reducing losses and optimizing the utilization of resources, the effectiveness of the grid can be significantly improved. Demand response programs incentivize customers to reduce their electricity usage during periods of high demand. By participating in these programs, customers can help prevent outages and alleviate the strain on the system.

A standard block diagram of a smart grid is shown in Fig. 11. ICT is crucial for smart grid operation, facilitating data transmission between generators, consumers, and grid operators. It enables monitoring and control to provide consumers with energy usage information. The Internet of Things (IoT) simplifies monitoring, communication, and data processing among smart devices in the SG. IoT technologies enable connectivity and automation throughout the SG network, utilizing IoT devices for monitoring, tracking, and data analysis (Neelofar Shaukat et al., 2023). The process of improving the grid's effectiveness using data and analytics is known as grid optimization. This involves reducing losses and improving resource utilization. A program called demand response encourages customers to use less electricity during high demand to prevent outages and reduce the load on the system. Both demand response and grid optimization are important for improving the smart grid. In EV charging infrastructure, these strategies are used to manage increased energy demand by optimizing charging schedules, load balancing, and integrating renewable energy sources for grid stability (Alavikia and Shabro, 2022). The manuscript's novelty, especially about the modern technologies linked to smart grids and sustainability-focused solutions, is essentially fixed in several innovative dimensions that relate to the smooth integration of EVs and RES in deregulated electricity markets:

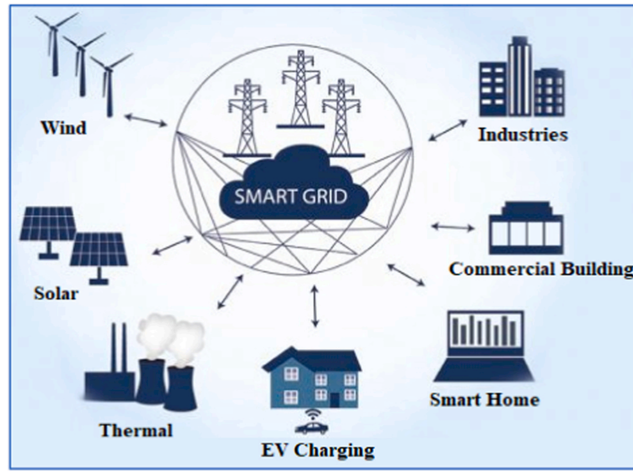

Fig. 11. Typical architecture of smart grid.

- ***Synergistic integration of RES and EVs:*** The manuscript explicates how the incorporation of various RES in conjunction with EVs can enhance the operational efficacy of power systems. This intricate integration not only augments energy efficiency and diminishes transmission losses but also optimally leverages the potential of available renewable resources.
- ***DSM for EV charging:*** One of the pivotal innovations presented in the work lies in the emphasis placed on smart charging technologies and the implementation of DSM strategies, which enable EVs to adeptly respond to abrupt fluctuations in energy demand. By optimizing the charging processes of EVs during peak demand periods, the overall system can effectively maintain operational stability, achieve substantial cost savings, and alleviate the pressure exerted on the grid infrastructure.
- ***Economic viability of HRES:*** In the context of economic analysis, the manuscript provides a comprehensive evaluation of the financial dimensions associated with HRES, illustrating the potential for achieving grid parity within specified pricing parameters. This finding boosts the financial sustainability of the integration of RES and EVs within deregulated energy markets.
- ***Technological and policy implications:*** The research expressed a compelling need for innovations in power flow management methods, as well as a strong advocate for the formation of a strict regulatory framework to support the development and implementation of microgrids and smart grid technologies. The manuscript emphasizes the necessity for policy incentives and the advancement of technological innovations, such as enhanced energy storage solutions and V2G interactions, all of which are critical to healthy grid stability and promoting sustainability in energy systems.

This combination of technology integration, energy management, and incisive economic considerations distinguishes the manuscript's innovative contributions to the field of improving smart grid technologies and supporting sustainable energy solutions.

5. Factors affecting the selection of grid

The electrical grid selection process is heavily dependent on certain key factors.

5.1. Grid characteristics

When choosing a smart grid, it is vital to consider the characteristics of the current grid. If the grid is outdated and inefficient, priority should be given to technology that can improve efficiency. Conversely, if the grid experiences frequent failures, priority should be given to technology that can enhance dependability. The focus of the research (Mohanty et al., 2022a) is to optimize the scheduling of flexible assets in the energy system, specifically energy storage and manageable demand, within a technology park in Spain. This includes integrating battery energy storage in distribution networks to maximize the use of photovoltaic power generation and reduce the negative impacts of EV fast charging (Massana et al., 2022). The present paper highlights grid characteristics toward more efficient and resilient energy systems, especially in deregulated power markets. The important attributes include the following:

- ***Integration of RES:*** RES introduces variability in supply due to dependency on environmental factors such as weather and time of day. Distributed Energy Resources (DERs) in the microgrids involve the integration of on-site renewable sources such as PV panels and wind turbines, thus cutting the reliance upon the centralized grids.
- ***Smart grid technologies:*** The advanced monitoring technologies of the smart grid with the use of AMI as well as SCADA for immediate monitoring and management purposes. Advanced grid communication enables interaction between operators, generators, and consumers to enhance the efficiency of energy distribution.
- ***Demand response and flexibility:*** Smart grids allow for DSM, optimized energy consumption patterns, peak shaving, and reduced strain on the grid.EVs contribute flexibility through V2G technology, acting as energy storage and dispatch systems.
- ***Economic and environmental viability:*** The paper talks about the achievement of economic viability through grid parity and competitive market pricing through the grid. It offers environmental benefits in the reduction of CO_2 emissions and mitigates greenhouse gases with the integration of renewable sources.
- ***Energy storage solutions:*** Battery Energy Storage Systems (BESS), such as Li-ion battery technology, enhance the stability of the grid and provide backup during demand variations.
- These features reflect the grid's maturity toward sustainability and reliability, making it adapt to higher penetration of renewable energy and dynamic consumer demands.

5.2. Market structures and regulations

The choice of a smart grid can be influenced by laws and market dynamics. Utilities may adopt innovations that lower their costs in a deregulated market. Utilities may adopt technology mandated by regulators in a regulated market. Pulsed current LIBs are competitive and provide flexibility for future grids. LIB deployment is expected to reach 20 TWh from a vehicle-to-grid application by 2030 (Lai et al., 2022).

5.3. Reliability and resilience requirements

The choice of smart grid technologies can be influenced by the reliability and resilience needs of a region. For example, regions prone to natural disasters may prioritize technologies that prevent or reduce the impact of power outages. Connecting a large number of DESs to the central grid requires careful evaluation and planning due to the potential impact on the system's frequency (Gbadega and Sun, 2022).

5.4. Future trends and emerging technologies

Renewable energy integration into the grid may be prioritized after its consumption. Utilities may be more willing to accept new technology if it increases grid efficiency or reliability. Advanced monitoring and communication systems, increased storage capacity, and mobile pay-as-you-go metering can all help in the growth of off-grid renewable energy projects.

6. Relative investigation of the technologies in renewable integrated system

The present study has depicted a technological, economic, environmental, and operational comparison of renewable technologies in the key domains of analysis. This investigation aims to examine the impact of a renewable integrated system in a deregulated environment.

6.1. Technological comparison

The research focuses on advancing energy systems through optimization, forecasting, and integration of innovative technologies. The key highlights are as follows:

- ***Micro-inverter technology for solar micro-grids:*** Improved photovoltaic power forecasting is obtained by using micro-inverters to gather individual and total PV panel outputs that support hierarchical energy management with battery-supercapacitor integration. An MINLP model schedules energy storage and appliance use, taking into account load shifting and battery degradation, to minimize costs.
- ***Battery energy storage systems:*** Li-ion batteries improve grid resilience and assist in regulating the voltage of smart grids. Optimization and simulation models are adopted to evaluate the techno-economic viability of PV-battery systems that range from streetlights to household power.
- ***Meta-heuristics and advanced optimization:*** The Honey Badger Algorithm and DE-HSS outperform other approaches in microgrid frequency control and energy dispatch. In hybrid systems, SSA exceeds the performance of conventional techniques in terms of emission minimization and cost reduction. For active-reactive power dispatching, the Canonical Differential Evolutionary Particle Swarm Optimization algorithm allows for cost savings.
- ***Energy storage and hybrid systems:*** Different battery technologies, including Li-ion and flow batteries, are reviewed for their performance in grid-connected renewable systems. Hybrid systems reduce emissions and improve reliability.
- ***V2G and V2μG:*** EVs improve the demand response and load management of grids. Bidirectional charging, intelligent scheduling, and coordination algorithms enhance the stability of the grid and reduce emissions. V2μG systems use BEVs and FCEVs to optimize energy storage and reduce degradation in batteries.
- ***Smart grid control and optimization:*** Distributed control strategies, including bio-inspired emergent methodologies, enhance grid stability. Frameworks that address non-linearity and uncertainties in Micro Smart Sensor Networks include a theory of the Koopman operator as well as Model Predictive control.
- ***Artificial intelligence in energy systems:*** AI-driven optimization techniques are used in PV system sizing to enhance energy storage performance with grid synchronization. Techniques of ResNet can detect with high accuracy solar cell micro-cracks, and DRNN-based schemes can optimize power sharing in microgrids.
- ***Emerging applications:*** Innovations include wind farm micro-siting for profitability, smart EV charging stations for demand response,

and cost-effective microgrid solutions using stochastic and resilient optimization techniques.

These developments point to the integration of AI, metaheuristics, and hybrid system designs to overcome the challenges in renewable energy, grid stability, and cost efficiency that are in line with global sustainability goals. The research (Kallio and Siroux, 2023) examines the micro-inverter technology in solar microgrids to improve photovoltaic power forecasting. This technology allows both individual PV panel outputs and total system output to be collected, improving the accuracy of the forecast. A two-layer energy management system is proposed that integrates a battery and supercapacitor to optimize energy usage while addressing uncertainties in renewable energy.

MINLP is used to compute the optimal schedule of appliances and energy storage over 24 h with load shifting and battery degradation costs (Nadeem et al., 2023). Li-ion batteries are becoming popular for energy storage as they are beneficial for supply-demand balance and integrating renewable sources (Huang et al., 2022). PV-battery systems are techno-economic models, either optimization or simulation models, to evaluate their feasibility (Rouholamini et al., 2022). Several studies, such as in (Hassan et al., 2023), have optimized PV-battery system sizing with experimental data utilizing tools like MATLAB. Optimization of PID control in frequency is made in microgrids using the Honey Badger Algorithm to improve the controller performance (Naderi et al., 2023). Comparative studies show the DE-HSS algorithm had better convergence speed and quality of solutions (Akbari et al., 2022). Other works discuss multi-energy systems; in such studies, deep reinforcement learning has been applied to optimize flexibility in nomadic communities (Li et al., 2022). Other works make use of genetic algorithms in managing flexible assets in energy systems (Caputo et al., 2023). EV battery charging strategies, including bidirectional charging, are also considered for cost optimization and emission reduction (Sharma and Chinnappa Naidu, 2023). The challenges to the broader adoption of such technologies include the lack of standardized testing methods and the need for efficient optimization in metaheuristics (Kong and Karagiannidis, 2016). Research on congestion control in micro smart sensor networks uses Koopman operator theory and extended state observers (ESO) for real-time predictions and compensations (Bianca Pop et al., 2022). In the V2G system, blockchain technology allows secure, anonymous information exchange between EVs and charging stations (Zhou et al., 2021), and the V2μG network concept integrates BEVs and FCEVs for off-grid buildings (Rajasekaran et al., 2022). Research studies about DSM of EVs highlighted research gaps such as inefficient power flow control.

Techniques such as distributed energy systems (DES) play a vital role in sustainable energy, whereby hybrid systems with biogas and renewable sources like wind and PV improve access to energy while reducing emissions (Wang et al., 2022). In smart grid optimization, resilient optimization and stochastic optimization methods deal with uncertainty during the design and operation of smart energy hubs (SEHs) (Modu et al., 2023). Smart inverters, as well as automated testing platforms, are used to make grid integration of renewable energy systems better (Lasemi et al., 2022). A comparison between different algorithms concludes that the Sparrow Search Algorithm (SSA) is superior in reducing microgrid management costs and emissions (Hashimoto et al., 2021). Performance under frequent blackouts is reviewed for energy storage solutions meant for grid-connected systems (Fathy et al., 2022), while distributed control strategies, such as bio-inspired emergent controls, provide optimization of energy coordination in smart grids (Barakat et al., 2022). A hybrid grid system that integrates floating solar and hydropower in Khuzestan, Iran, mitigates power outages and water shortages while reducing emissions (Medina et al., 2023; Deilami, 2018; Rodrigues et al., 2022). Optimization techniques, such as MOHGS, are cost-effective and have high renewable energy usage (Cazzaro et al., 2022). Another application is a V2G system for charging and discharging EVs, using day-ahead scheduling to optimize SOC and minimize costs (Alamaniotis et al., 2015). The C-DEEPSO algorithm improves active-reactive power dispatch in microgrid systems with EVs, achieving cost reduction (Shaker et al., 2021). Finally, deep learning schemes, such as ResNet, improve the accuracy of defect detection in solar cells, and adaptive control scheme improves voltage restoration and achieve power sharing in islanded microgrids (Amamra and Marco, 2019; Marcelino et al., 2022). In situations where the grid is not reliable, research suggests the use of an active damping adaptive control technique for grid-connected inverters. This technique utilizes adaptive control and a Lyapunov-based back-stepping architecture to ensure stability while considering variable impedance (Fan et al., 2022). Research focuses on economically viable distributed stationary micro-storage systems and highlights the benefits of an AC-coupled architecture in terms of modularity and robustness. To prolong the lifespan of batteries, a precise and dynamic battery management system is crucial for determining the State of Charge and state of health (Zhang and Wai, 2022). To offer demand response services, the article proposes a smart Electric Vehicle Charging Station (EVCS) operations structure. This framework improves the operations of the distribution system and provides insights into the advantages of incorporating intelligent EVCS, considering factors such as minimizing losses and capacity limits (Li et al., 2021). Both lead-acid and lithium batteries have made advancements, including improvements in lead-acid peak power handling and battery management. Carbon-enhanced designs have made lead-acid batteries suitable for contemporary utility-scale applications. Batteries, particularly lead-acid and lithium batteries, are widely used in energy storage due to their ability to integrate renewable energy sources and reduce emissions (Hussein et al., 2012). A technological comparison can be found in Table 1 in the literature review. Table 1 is designed to systematically evaluate and compare a wide range of renewable energy technologies along with their specific applications in the realm of microgrids. In this thorough assessment, technologies such as lithium-ion batteries, micro-inverter setups, and demand-side management approaches are carefully examined for their roles in improving grid stability and enhancing the overall efficiency of energy distribution networks. This study precisely investigates the multifaceted impact that arises from the integration of RES and EVs within the context of a deregulated smart power system, with a particular emphasis on critical aspects such as grid stability, economic viability, and the environmental benefits that can potentially be realized. The following detailed steps outline the methodology employed throughout this research:

- ***System modeling:*** A comprehensive model of a deregulated power system is developed, which includes renewable energy sources and electric vehicle charging infrastructure. The optimization of energy dispatch, load balancing, and grid efficiency under deregulation is done using MILP.
- ***Data collection and input parameters:*** This model utilizes historical load profiles, renewable energy generation data, and EV charging patterns that are derived from grid operators, renewable energy reports, and datasets from fleets of EVs. The integration of weather forecasting data will consider the variability of wind and solar generation for realistic simulations of the uncertainties in renewable supply.
- ***Optimization techniques***: Some metaheuristic algorithms used in the optimization of grid efficiency include the Honey Badger Algorithm (HBA) and Genetic Algorithm (GA). Here, the objective is mainly cost minimization, profit maximization, and loss reduction, with the performance being measured based on load dispatching and supply-demand balance.
- ***Economic analysis:*** Economic feasibility is assessed through the Levelized Cost of Electricity (LCOE) and Net Present Value (NPV), considering scenarios with varying renewable energy penetration, EV adoption rates, and policy incentives. Sensitivity analysis examines the impact of factors like battery costs, EV adoption, and electricity price fluctuations on system economics.

Table 1
Technological comparison and analysis.

Ref.	Technology Used	Advantages	Disadvantages	Other Considerations
(Alavikia and Shabro, 2022)	Li-ion Battery Storage	Supply-demand balance, Voltage support	Detailed cost models	Integration of renewable sources, operational flexibility
(Mohanty et al., 2022a)	PV and Battery Techno-economic Models	Optimization, Experimental data	Simulation vs. Optimization	Evaluated using MATLAB tools
(Gbadega and Sun, 2022)	Transient Stability Analysis	Power system dynamics	Complex modeling	Relevance in deregulated power systems
(Kallio and Siroux, 2023)	Microgrid Architecture (PSCAD)	Design flexibility, Control	Complex modeling, Simulation	Utilizes Power System Computer-Aided Design
(Nadeem et al., 2023)	Islanded Microgrid Control	Reduced fluctuations, Stability	PID optimization method	Utilizes the Honey Badger Algorithm
(Akbari et al., 2022)	Micro-Energy Grid Dispatch	Superior performance, Real data	Complex modeling	Utilizes DE-HSS algorithm
(Li et al., 2022)	Multi-energy Supply Systems	SDG7 achievement, Flexibility	Optimization complexity	First-time DRL used in energy access planning
(Caputo et al., 2023)	Grid-Connected PV with Retired EV Batteries	Power flow optimization	Limited participation of EVs	Focus on power flow scenarios
(Sharma and Chinnappa Naidu, 2023)	Optimal Scheduler for Flexible Assets	Energy system management	Complex scheduling	Hourly day-ahead scheduling in a technology park
(Kong and Karagiannidis, 2016)	PHEV Battery Charging Strategies	Cost optimization, Emission reduction	Charging fairness	Maximizes operator costs and profitability
(Bianca Pop et al., 2022)	Metaheuristics for Smart Grids	Low computational time, Low resource overhead	Lack of standard testing methodologies	Addressing decentralized optimization problems
(Zhou et al., 2021)	Data-Driven Congestion Control	Network stability	Real-time modeling errors	Utilizes Koopman operator theory and MPC
(Rajasekaran et al., 2022)	Anonymous Blockchain for V2G Network	Secure information exchange	Computational time	Utilizes blockchain for authentication
(Wang et al., 2022)	(V2μG) Network	Energy storage and integration	Battery degradation	Reduction in lithium-ion battery degradation
(Modu et al., 2023)	Blockchain PV-EV Bidding Model	Distributed storage, Smart contracts	Complex optimization	Utilizes improved particle swarm optimization
(Lasemi et al., 2022)	EV Demand-Side Management (DSM)	Load optimization, Peak shaving	Uncertainty in forecasting	Focus on maximizing profits and user comfort
(Barakat et al., 2022)	DC Microgrid Architecture	Integration of DG, Voltage control	Power electronic converters	Effective connection of energy storage devices
(Medina et al., 2023)	Emergent Control in Smart Grids	Coordination, Renewable prioritization	Distributed control strategies	Development of emergent control approach
(Deilami, 2018)	Smart Inverters Testing Platform	Testing effectiveness, Automation	Increased testing reliability	Supports integration of renewable generators
(Rodrigues et al., 2022)	Sparrow Search Algorithm	Reduced operating costs, Emission reduction	Outperforms other optimizers	Achieves superior performance in MG operation
(Fan et al., 2022)	Distributed Secondary Control	Demand response, Distribution operations	Loss minimization	Incorporates queuing models and optimization
(Zhang and Wai, 2022)	Economically Viable Micro-Storage Systems	Modularity, Robustness	Precise BMS for SOC and SOH	Battery management system (BMS) Importance
(Li et al., 2021)	Smart Electric Vehicle Charging Station	Distribution system improvement	Loss minimization, Capacity limits	Queuing models and optimal operations
(Hussein et al., 2012)	Lead-acid and Lithium Battery Technology	Energy storage, Renewable integration	Regulations, Environmental effects	-

- ***Simulation and validation:*** The model is validated by using empirical data from actual grid operations and market pricing. Comparisons of the simulations with real-world performance metrics are used to evaluate the accuracy of the model. Forecasting methods such as ARIMA and Machine Learning algorithms (e.g., Random Forest) are used to predict renewable energy output and EV charging demand.
- ***Environmental impact assessment:*** The environmental analysis quantifies CO_2 emission reductions associated with integrating renewable energy sources with EVs.

6.2. Economic comparison

PVBA systems become economically viable because the cost of energy production is intensely more competitive than conventional electricity. Techno-economic estimations indicate that microgrid-solar PV plus batteries-systems is the most economical solution to allow residential prosumers access to energy, even off grids surpassing grid supply levels. Seasonal storage becomes economical only in latitudinal regions (Hafez and Bhattacharya, 2018). For hybrid renewable energy systems (HRES), grid parity in Finland is attained at 17–29 €c/kWh. High-cost Level 3 charging infrastructure and maintenance costs are also considered, in addition to economic factors such as charger and battery costs for EV users (McKeon et al., 2014). A comparison of reinforcement learning methods, including the PDDPG method, investigates their effects on EV pricing, aggregator profits, and EV owner costs (Keiner et al., 2023). The CPSO-MPC algorithm is superior to linear programming in minimizing the operation costs and enhancing microgrid performance (Savari et al., 2023).

The SSA algorithm reduces pollutant emissions by 54.76 % in a single-objective problem and 0.118 % in a multi-objective problem (Hashimoto et al., 2021). A comparison between grid-connected hybrid systems (Grid-PV) and standalone PV-Genset systems in Ghana shows that the Grid-PV system is 184 % cheaper than the grid-only system and 24 % cheaper than the PV-Genset system, at a LCOE of 0.0824/kWh compared to 0.309/kWh (Savari et al., 2023). An optimization framework for wind farms suggests that shape optimization can increase profitability by 1.1–2.8 %, corresponding to 46–109 million Euros (Chawla et al., 2022). The paper (Qiu et al., 2020) explores economic techniques in energy trading and auction mechanisms for V2G systems, microgrids, and distribution networks to ensure economic viability. Table 2 provides a comparative analysis of the economic feasibility of different renewable energy systems, examining cost reductions, grid parity, and EV charging infrastructure expenses. It also evaluates various methods for optimizing costs and integrating renewable energy into current systems, contributing to the understanding of the financial dynamics in smart grid operations and renewable energy adoption. A

Table 2
Analysis of economic comparison.

Ref.	Importance in Reducing Energy Costs	Economic Viability of Consumer Systems	Grid Parity for HRES	EV Charging Infrastructure Costs	RL Methods for Profitability	Smart Energy Hubs Economic Aspects	Microgrid Optimization Techniques	SSA for Pollutant Emissions	Grid-Connected vs. Standalone System	Wind Farm Profitability Optimization	Energy Trading Techniques
(Alanne, 2023)			✓								
(Lai et al., 2022)							✓				
(Rouholamini et al., 2022)	✓										
(Modu et al., 2023)						✓					
(Hashimoto et al., 2021)								✓			
(Deilami, 2018)										✓	
(Hafez and Bhattacharya, 2018)	✓	✓									
(McKeon et al., 2014)				✓							
(Keiner et al., 2023)					✓						
(Savari et al., 2023)									✓		
(Qiu et al., 2020)											✓

thorough and effective methodology that integrates state-of-the-art technological advancements, strong regulatory frameworks, and strategically planned market approaches is necessary to effectively address the complex challenges presented by deregulated markets. The following methodical approach supported by empirical data and real-world case studies offers useful insights into its efficacy:

- Regulatory and Market Framework

A. The implementation of innovative real-time pricing strategies is essential for motivating consumers to adjust their electricity consumption habits, thereby shifting usage to non-peak h. This proactive approach not only promotes greater grid stability but also facilitates a more efficient allocation and utilization of renewable energy resources across the energy landscape.
B. The advancement and promotion of microgrids and decentralized energy systems serve to significantly enhance local generation capabilities and consumption patterns. Such decentralized systems effectively reduce the overall stress placed on the larger grid infrastructure while simultaneously improving financial sustainability by minimizing transmission and distribution expenses.
C. The establishment of government policies that offer attractive subsidies and tax incentives for both renewable energy initiatives and grid modernization projects is paramount in alleviating the financial burdens encountered by utility companies, thereby fostering increased investment in essential grid infrastructure developments.

- Real-World Case Studies

A. Germany's Renewable Energy Transition
The ambitious and forward-thinking objective established by Germany, which aims to derive an impressive 80 % of its total electricity supply from renewable energy sources by the year 2030, serves as a compelling illustration of how a deregulated market can operate with remarkable efficiency and effectiveness. This significant endeavor has been boosted by the country's substantial investments in erudite smart grid infrastructure and the seamless integration of renewable energy solutions, all of which are underpinned by robust governmental policies such as the Renewable Energy Sources Act (EEG), which promotes sustainable energy practices.
B. California's Energy Market and Storage Systems

In the state of California, the challenges associated with grid instability, which have arisen as a direct consequence of high levels of renewable energy penetration, have been effectively addressed through the strategic implementation of BESS and demand-response systems, which are responsible for stabilizing the grid. Additionally, the state has adopted time-of-use pricing structures along with DSM strategies, which have collectively alleviated financial pressures on consumers and facilitated better management of the inherent variability associated with solar and wind energy generation.

6.3. Environmental comparison

EVs play a crucial role in reducing fuel consumption and emissions, thus aiding in the fight against global warming. This emphasizes the transport sector's reliance on fossil fuels and the future scarcity of these resources (McKeon et al., 2014). The optimal V2μG network has the potential to reduce carbon dioxide emissions by 515.56 tons compared to traditional off-grid building energy systems that use internal combustion engines (Rajasekaran et al., 2022). AI models can be utilized for energy generation and demand forecasting, as well as demand-side management, leading to more efficient energy usage and a reduced environmental impact. By combining big data techniques with AI, energy and load forecasting can be improved, optimizing energy consumption and minimizing waste (Asamoah et al., 2022).

The proposed SSA method demonstrates its superiority in minimizing pollutant emissions compared to other approaches, achieving significant reductions in both single-objective and multi-objective optimization problems (Hashimoto et al., 2021). The paper (Savari et al., 2023) compares the greenhouse gas (GHG) emissions of two systems. The Grid-PV system emits 12,341.5 kg/yr of GHGs, while the PV-Genset system emits 4775.57 kg/yr. The technology highlights its environmentally friendly nature through the use of solar thermal design and the conversion of heat energy into DC through a reversible thermoelectric effect (Aggarwal et al., 2021). The generator's construction also emphasizes the environmentally conscious approach by utilizing recyclable waste materials. After comprehensive comparisons and analyses of three objectives (minimized system cost, loss of power supply probability, and GHG emissions), the AC-MG is identified as the optimal catalog for the stand-alone microgrid. The AC-MG shows better convergence in terms of system cost and loss of power supply probability, while the GHG emissions have weaker shrinkage (Li et al., 2023). It is believed that integrating distributed energy resources (DERs) like distributed generators and renewables will enhance the security and efficiency of power systems while managing variations in power output. Future power systems are expected to rely heavily on DERs to handle peak loads, improve power quality, maximize operational effectiveness, and alleviate distribution system congestion (Abodunrin and Ofulue, 2022). Table 3 presents the environmental comparison of the literature review. Table 3 illustrates an extensive approach to the multifaceted concept of sustainability by concentrating on critical issues such as the reduction of carbon dioxide emissions along with greenhouse gas emissions, the optimization of fuel consumption, and the minimization of harmful pollutants, all of which are vital for the protection of our environment and are instrumental in achieving the ambitious global climate objectives set forth by various international agreements and initiatives. The discussion highlights the significant advancements in technology, particularly focusing on the application of artificial intelligence in the realm of energy forecasting, the optimization techniques related to system performance and efficiency, as well as the notable progress made in the design of solar thermal systems, all of which collectively underscore the increasingly important role that innovative technologies play in enhancing energy efficiency and promoting sustainability in various sectors. This table serves as an excellent resource that provides a comprehensive overview of the varied contributions made by each reference, clearly demonstrating how they tackle different facets of sustainability, optimization of energy systems, and the innovative technological advancements occurring within the power sector, thereby enriching our understanding of these critical issues.

6.4. Operational and resilience comparison

The article (Li et al., 2021) examines the difficulties and concerns associated with microgrid stability and operation. These include the unpredictable nature of renewable energy resources and the increased complexity of smart load participation. The article presents different strategies and techniques for controlling and optimizing microgrid operation, taking into account factors such as volatility, intermittency, and cost. It emphasizes the importance of accurately predicting PV output in advance for optimal control and energy flow management in a solar microgrid. The use of accurate prediction models, such as artificial neural networks, can improve the system's operational efficiency (Asamoah et al., 2022). PVBA systems have been evaluated in terms of their performance and safety, demonstrating their ability to power various applications effectively (Rouholamini et al., 2022). The proposed solution offers optimal scheduling for controllable assets like the HVAC system, EV charging station, electrolyzer, and hydrogen refueling station. The HVAC system operates based on energy efficiency and economic incentives, shifting its electricity consumption to off-peak h. Load shifting is also implemented for EV charging stations and hydrogen refueling stations (McKeon et al., 2014). The hybrid system suggested includes a combination of a grid-connected Hydropower turbine and floating solar photovoltaic (FSPV) panels. These components work together to increase power generation and decrease water evaporation from a dam. By using this system, emissions can be reduced by approximately 38.5 % compared to a grid-turbine system, resulting in savings of 4.7 M in emissions penalties. Additionally, the hybrid system improves the stability of the electrical system, prevents outages, and reduces water consumption for energy production (Ma et al., 2022). The proposed real-time energy management strategy effectively boosts the integration of EVs while significantly reducing operation time. It achieves this by minimizing the impact of uncertain factors such as travel patterns and load fluctuations and optimizing the charging schedule based on up-to-date information (Ni et al., 2017). The proposed hierarchical game theoretical approach aims to optimize the technical objectives of the system and ensure that the system operates according to predefined criteria. In this approach, the system operator acts as the main decision maker, indirectly controlling the energy scenarios of EVs and EVCSs to meet the technical constraints of the system (Ghasempour et al., 2022; Yang et al., 2022). Table 4 provides an analysis of the system's operation and reliability based on a literature study.

Table 4 presents an extensive overview of energy research methodologies, which thoroughly incorporates a wide array of both technical and environmental dimensions related to energy systems, thereby offering a complete view of the subject matter. Spanning various elements

Table 3
Analysis considering environmental considerations.

Ref.	Importance in Reducing CO_2 Emissions	Role in Minimizing Fuel Consumption	Reduction of GHG Emissions	AI for Energy Forecasting	SSA Superiority in Minimizing Pollutant Emissions	Solar Thermal Design and Environmental Approach	Stand-alone Microgrid Comparison	Integration of DERs in Future Power Systems
(Rouholamini et al., 2022)	✓		✓					
(Rajasekaran et al., 2022)			✓					
(Hashimoto et al., 2021)			✓		✓			
(McKeon et al., 2014)		✓						
(Asamoah et al., 2022)				✓				
(Aggarwal et al., 2021)						✓		
(Li et al., 2023)							✓	
(Abodunrin and Ofulue, 2022)								✓

Table 4
Operation and resilience analysis.

Ref.	Aspects	Control Strategies and Techniques	Operational Performance of PVBA Systems	Solution for Microgrid Control and Scheduling	Hybrid System with Grid-Connected Hydropower and FSPV Panels	Real-Time Energy Management Strategy for EVs	Hierarchical Game Theoretical Approach for System Optimization
(Jawad and Masood, 2022)	Challenges	✓					
	Presented Solutions	✓		✓	✓		
	Emphasis	✓					
	Benefits	✓			✓	✓	
(Mohanty et al., 2022a)	Controllable Assets			✓			
	Operation			✓			
	Load Shifting			✓			
(Kallio and Siroux, 2023)	Emphasis	✓					
(Rouholamini et al., 2022)	Evaluation		✓				
	Applications		✓				
(Ma et al., 2022)	Components				✓		
	Function				✓		
	Environmental Impact				✓		
	Electrical System Stability				✓		
	Water Usage Reduction				✓		
(Ni et al., 2017)	Strategy					✓	
	Reduction of Uncertainties					✓	
	Charging Optimization					✓	
(Ghasempour et al., 2022)	Decision Makers						✓
	Control of Energy Scenarios						✓
	Superior Performance						✓
	Test System						✓

from the development of control strategies to the intricate processes of system optimization, it effectively illuminates the numerous and complex challenges that contemporary energy systems encounter in their operational landscapes. There exists a pronounced emphasis on the vital integration of RES within existing frameworks, the enhancement of hybrid system performance metrics, and the pursuit of greater operational efficiency across the board. The incorporation of modern optimization methodologies strongly emphasizes the urgent necessity for adopting more erudite and innovative strategies in the realm of energy management, especially within the context of complex and decentralized power grid systems. Many of the references direct attention toward the forthcoming evolution of energy systems, placing a strong emphasis on the integration of innovative technologies that include EVs, hybrid RES, and advanced optimization methodologies. These crucial elements will serve as foundational components as the global community transitions towards more decentralized energy systems that are primarily based on renewable sources. In this section, an extensive analysis of a variety of technologies and methodologies is conducted to thoroughly compare and understand the significant impact that an integrated renewable energy system has within a deregulated market environment. Drawing upon the insights and findings presented in this chapter, the ranking of the most critical methodologies can be systematically classified in the following manner:

- The utilization of micro-inverter technology has been identified as a pivotal advancement that enhances the precision and accuracy of photovoltaic power forecasts, thereby contributing to more reliable energy generation projections. The integration of battery systems alongside supercapacitor technologies serves as a fundamental approach for energy storage solutions, which not only optimizes energy usage but also effectively addresses and manages the uncertainties associated with renewable energy production.
- The economic evaluations presented in this section primarily concentrate on the techno-economic models that are employed for both photovoltaic and battery systems, precisely assessing the delicate balance between the incurred costs and the achieved efficiency of the system. This analysis includes the optimization of system sizing as well as the formulation of cost models, all aimed at ensuring the economic feasibility of these technologies in a competitive marketplace.
- The implementation of lithium-ion batteries plays a crucial role in sustaining the delicate balance between supply and demand while also providing essential operational flexibility that encompasses voltage support and various other grid services, which are deemed indispensable for guaranteeing the resilience of the electrical grid within a deregulated setting.
- The significance of DSM, specifically concerning EV integration, is highlighted as a paramount method for optimizing load, facilitating peak shaving, and ensuring seamless energy market integration, which collectively contributes to the effective management of energy consumption in a deregulated renewable energy framework.

7. Integration approaches

AI and data analytics can be utilized to apply hybrid methods in smart energy management systems, merging various algorithms to enhance efficiency and performance. Hybrid deep reinforcement learning methods, like the Deep Q-Network (DQN), can be employed to take into account energy production and consumption in microgrids, combining the concept of actions and rewards from Q-learning with neural networks (Asamoah et al., 2022). The paper analyzes a hybrid green microgrid system that is connected to the grid. This system includes various resources like solar, wind, hydro, battery, and the utility grid. The study identifies the most optimal configuration for the microgrid, which is found to be a solar-wind-hydro-based utility grid-connected network with a low Levelized Cost of Energy (LCOE) of 0.056 $/kWh. Simulation results demonstrate that the efficient use of renewable energy sources in the microgrid has proven to be a cost-effective and reliable solution for power supply in remote communities (Shakerighadi et al., 2018). The integration of power can help during uncertain times and make up for power outages from the main grid, which can improve the reliability and strength of the energy system (Fathy et al., 2022). The coordination of energy production, transmission, distribution, and consumption is called integrated energy management (IEM), and it is done to enhance the efficiency, reliability, and sustainability of the energy system. Smart grids can include microgrids through IEM. Integrating renewable energy sources with EV charging systems has numerous advantages. It helps in reducing air pollution, minimizing fuel consumption, and lowering emissions. Additionally, it brings potential opportunities for the power network through V2G and Vehicle-to-Building (V2B) modes. The integration of microgrids into smart grids faces various challenges. These include technical compatibility, interoperability, and the standardization of communication protocols. Additionally, regulatory and policy barriers, such as outdated regulations and a lack of incentives, can hinder the integration process. Financial constraints, such as high upfront costs and uncertain return on investment, also pose challenges. Another obstacle is the interoperability of different microgrid components and technologies, which need to be standardized and made compatible.

India has achieved a remarkable feat in the automotive industry. As of 2023, it proudly holds the title of the third-largest automobile market in the world based on sales figures. This is a testament to the country's growing influence and economic strength. In 2022, India made another significant stride by securing the fourth spot globally in terms of the valuation of its automotive industry. This industry is valued at an impressive US$100 billion, highlighting its immense worth. The Indian automotive sector not only contributes significantly to the nation's economy but also plays a vital role in its overall economic structure. It accounts for 8 % of India's total exports, showcasing its impact on the export industry. Additionally, the automotive sector contributes 7.1 % to the country's GDP, further solidifying its importance (Anon, 2023). Despite the relatively modest share of EVs in the overall automobile narrative, there has been a positive trend toward their adoption in recent times. The prospects for EVs in India are promising, with a growing interest and significant potential for growth on the horizon. Transportation in India contributes a substantial 14 % of CO_2 emissions, as reported by the ICCT in 2022. This data highlights the significant environmental impact of the transportation sector in terms of carbon dioxide emissions. Additionally, it's worth noting that a staggering 90 % of the energy used in India is attributed to road transport. This statistic emphasizes India's heavy reliance on road transport and the subsequent energy consumption associated with it. The incorporation of renewable energy sources and EVs into existing power grid systems presents numerous complex technical, regulatory, and economic challenges.

- ***Grid stability and compatibility:*** The integration of renewable sources poses significant challenges to maintaining grid stability due to the unpredictable nature of the energy supply. In power grids that are heavily occupied with EVs, these fluctuations are further intensified as a substantial number of vehicles engage in simultaneous charging activities, which can lead to detrimental consequences that threaten the reliability of the entire grid infrastructure.
- ***Demand-side management and smart charging:*** The successful integration of EVs necessitates the deployment of DSM strategies and smart charging systems designed to optimize the overall charging process, mitigate peak demand levels, and ensure that the timing of vehicle charging is synchronized with periods of renewable energy production. In the absence of effective demand-side management techniques, large-scale EV charging operations have the potential to overwhelm the grid during peak demand periods.
- ***Regulatory and policy barriers:*** The presence of outdated regulatory frameworks and a notable deficiency in incentives aimed at promoting the integration of RES and the adoption of EVs presents additional obstacles. Policymakers must evolve and adapt existing regulations to incorporate incentives that would facilitate the development of smart grid infrastructure, the seamless integration of electric vehicles into the power system, and the channeling of investments into renewable energy technologies.
- ***Financial and infrastructure costs:*** The substantial initial financial outlay required for the establishment of smart grid infrastructure, the installation of EV charging stations, and the development of ESS render the widespread adoption of these innovative technologies particularly challenging, especially in regions characterized by developing economies.
- ***V2G systems:*** Although V2G technologies present promising solutions for enhancing grid support by enabling EVs to discharge energy back into the grid, they simultaneously introduce a range of challenges that include concerns related to battery degradation, complexities in communication protocols, and the need for augmented infrastructure capabilities. The implementation of V2G systems requires advanced levels of coordination to ensure the smooth and reliable bidirectional flow of energy between electric vehicles and the power grid, which is essential for maximizing the benefits of this innovative technology.

These complex challenges underscore the critical necessity for comprehensive planning, the adoption of advanced technological solutions, and the imperative for policy reforms aimed at facilitating the efficient integration of renewable energy sources and EVs within deregulated power market frameworks. A comprehensive comparison of EVs within renewable systems in India, alongside comparable data from another country, necessitates the examination of several key areas that will yield a detailed understanding.

a) EV Adoption and Growth

India: In 2023, India has established an exceptionally ambitious and forward-thinking target to achieve an impressive 30 % adoption rate of EVs by the year 2030. Furthermore, the country has experienced a remarkable surge in the growth of electric two-wheelers and three-wheelers, resulting in approximately 1.3 million EVs currently navigating the roads of India. The faster adoption and manufacturing of the Hybrid and Electric Vehicles (FAME) initiative, in conjunction with various state-level policies and incentives, has played a pivotal role in significantly enhancing the adoption rates of electric vehicles across the nation. Additionally, India has set its sights on realizing an ambitious goal of sourcing 40 % of its total electricity capacity from renewable energy resources that are not based on fossil fuels by the year 2030, a target that is critically important for the establishment of a robust green infrastructure for EV charging.

Germany: Germany has emerged as a frontrunner in the field of EV integration, boasting over 1 million EVs on its roads as of the year 2023 while simultaneously targeting an impressive range of 7–10 million EVs by the year 2030. The nation's Renewable Energy Sources Act (EEG) sets forth an ambitious objective that aims for an astounding 80 % of its electricity supply to be derived from renewable energy resources by the year 2030. The successful integration of EVs with RES is heavily supported by the presence of advanced charging infrastructure and innovative V2G technologies, which enable electric vehicles to return electricity to the grid during periods of peak demand.

b) Renewable Energy Integration

India: In the year 2022, India's renewable energy capacity was recorded at an impressive 165 GW, with a target in place to reach a substantial 500 GW by the year 2030, reflecting the nation's commitment to expanding its renewable energy capabilities. Solar and wind energy have emerged as the primary sources contributing significantly to the charging infrastructure for electric vehicles, and India has been actively working on the integration of EVs with RES, with a particular focus on establishing solar-powered charging stations in both rural and urban regions. Moreover, India has initiated the development of Green Energy Corridors, which are designed to facilitate the integration of large-scale RES into the electrical grid, ultimately supporting the charging needs of EVs through these RES.

Germany: As of the year 2022, Germany's renewable energy capacity exceeded 140 GW, with the majority of this capacity being generated from wind and solar power, positioning the country as a leader in renewable energy generation. Germany has been at the top of integrating EVs with solar PV systems, where a considerable number of electric vehicle owners leverage home-based solar power for charging their vehicles. Additionally, the implementation of V2G technology allows these EVs to function as decentralized energy storage systems, adding further value to the energy ecosystem.

c) Charging Infrastructure

India: In the year 2023, India boasts approximately 6,000 public EV charging stations, and the country has set a goal to establish a total of 46000 charging stations by the year 2030, a move that will be crucial for supporting the expansion of its burgeoning EV market. The FAME II policy implemented by India places a strong emphasis on the deployment of charging infrastructure strategically located along highways, within urban centers, and at places of work, coupled with a robust initiative to promote solar-powered EV charging solutions.

Germany: Germany is recognized for having one of the most advanced EV charging infrastructures globally, with a remarkable 80,000 public charging points operational as of the year 2023, and the country aims to achieve an astounding 1 million charging points by the year 2030. The charging infrastructure in Germany is intricately integrated with RES, which is further enhanced by the incorporation of smart grid and smart metering technologies designed to optimize energy consumption and minimize grid overload during peak periods of EV charging.

d) Policy and Incentives

India: The FAME II scheme implemented by India serves as a significant initiative that not only offers various subsidies aimed at encouraging the purchase of EVs but also provides substantial incentives for the development and expansion of a comprehensive charging infrastructure, thereby facilitating a smoother transition to electric mobility. Furthermore, this initiative actively promotes the integration of RES into the EV charging networks, which is crucial for achieving sustainable energy goals. The National Electric Mobility Mission Plan established by India is designed with the primary objective of significantly reducing the country's dependence on fossil fuels while simultaneously promoting energy security, and it particularly focuses on the incorporation of RES for charging EVs.

Germany: In Germany, the government offers remarkably generous subsidies for the purchase of EVs, which can amount to as much as €9000 for each vehicle, alongside various tax incentives that are specifically tailored to encourage and support EV ownership among the population, thereby fostering a more environmentally friendly transportation sector. Additionally, the German government provides a range of incentives aimed at promoting the installation of solar panels that can be utilized for charging EVs in residential homes, commercial businesses, and public spaces, which significantly contributes to the broader integration of RES within the transportation sector.

To compare the integration of EVs with RES in the power sector, especially between India and other leading nations, a few key metrics are essential:

e) ***EV Adoption rates:*** Total number of EVs and share in total vehicle population.
f) ***Renewable energy share***: Percentage of energy from RES in the national energy mix.
g) ***Charging infrastructure:*** Number of public charging stations per capita per EV.
h) ***Energy storage:*** Installed capacity for energy storage that supports EV charging and supply-demand balancing.
i) ***Government policies and incentives:*** EV subsidies, tax benefits, and promotion policies for RES.

These metrics can offer an all-around comparison of the performance and progress made by each country in EV and renewable energy integration. Here's a statistical comparison table that delineates the integration of EVs with renewable systems across the power sectors of India and several other leading nations, which is illustrated in Table 5.

- ***India:*** While India is making notable strides in advancing its renewable energy capacity, currently boasting a 42 % share in its energy mix, the adoption rate for EVs remains relatively modest at just 1.2 %. The nation has set forth ambitious goals for the integration of RES, and while development in energy storage systems is actively underway, it continues to lag in comparison to global leaders.
- ***China:*** China holds a dominant position in both the adoption of EVs and the capacity for energy storage, supported by aggressive governmental policies that bolster both sectors.
- ***United States:*** The rate of EV adoption in the United States is experiencing rapid growth; however, when compared to leading nations like Norway, the share of renewable energy and the development of storage infrastructure remain relatively modest and underdeveloped.
- ***Norway:*** As a leader on the global stage, Norway distinguishes itself through its impressive EV adoption rate of 20.8 % and an extraordinary renewable energy share of 98 %, showcasing the effectiveness and success of its long-term policies geared towards both RES and EV integration.
- ***Germany:*** Germany exemplifies the strong integration of EVs with RES, facilitated by the presence of energy storage systems and driven by ambitious targets aimed at reducing carbon dioxide emissions across the transportation and energy sectors.

Fig. 12 compares key metrics on EV integration with RES across India and other leading nations. China leads in EV adoption, followed by the U.S., while India is making notable progress. Norway stands out for its high renewable energy share and charging infrastructure, with India showing room for growth in public EV chargers. China excels in energy storage capacity, a crucial area where India has potential for expansion. The EV industry of India holds much promise, with over 1.2 million units sold and $200 billion worth of investments likely by 2030. The government plans to have 30 % penetration in private cars, 70 % in commercial vehicles, and 80 % in two- and three-wheelers by 2030. The

Table 5
EV integration status with renewable energy systems in power systems.

Metric	India	China	USA	Norway	Germany
EV Adoption in 2023	2.4 million	9.8 million	3.5 million	610,000	1.2 million
EV Percentage of Total Vehicles	1.2 %	4.2 %	2.7 %	20.8 %	3.5 %
Renewable Energy Share in 2023	42 %	30 %	22 %	98 %	46 %
Public EV Chargers per 1000 EVs	4	14	6	24	12
Energy Storage Capacity (GW)	5 GW	40 GW	22 GW	2 GW	7 GW
CO_2 Emission Reductions (due to EV + Renewables)	12 %	18 %	10 %	45 %	20 %

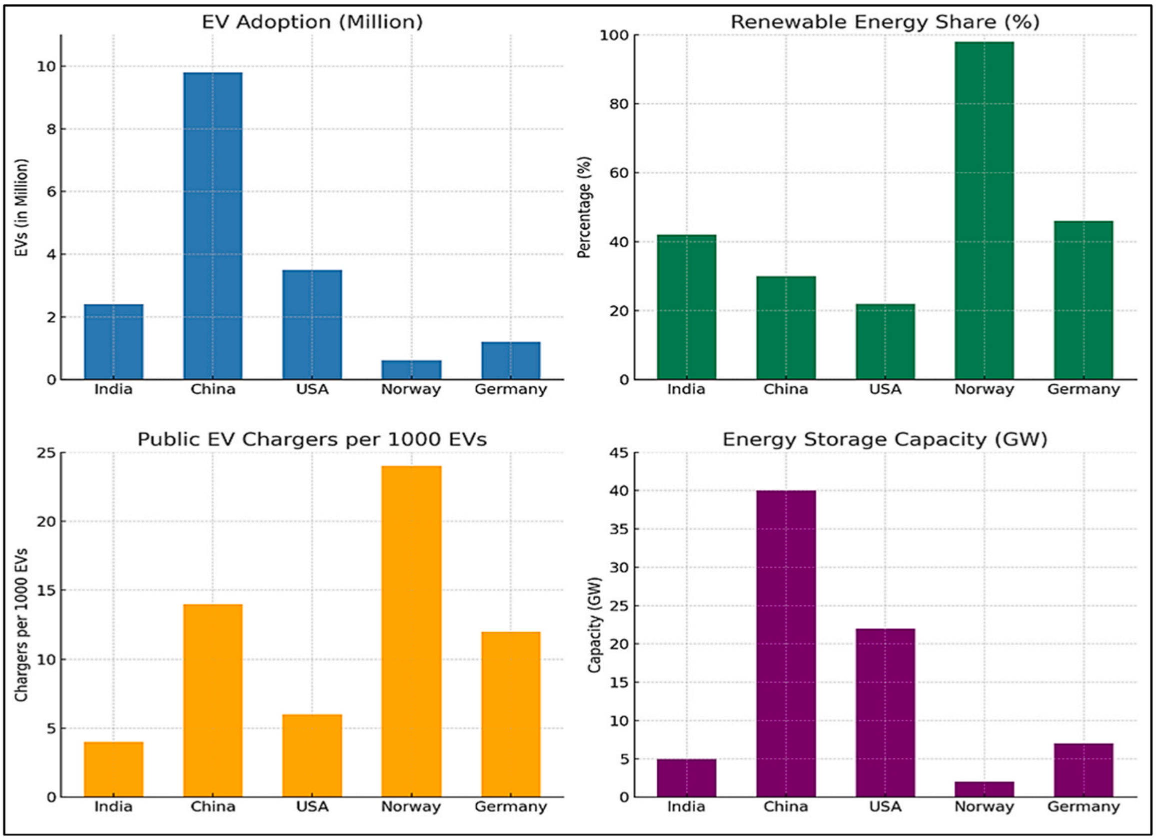

Fig. 12. Comparison of Key Metrics for EV Integration with Renewable Energy System.

growth is led by the FAME scheme and battery and charging technology advancements. Markets of Electric Three-Wheelers (E3Ws) and Electric Two-Wheers (E2Ws) are growing as both E3Ws and E2Ws are more economical vehicles to own than an ICE vehicle. There is growing growth in the Electric Four-Wheeler (E4W) market, as 10,000 electric buses will be operated across 169 cities in India. Government support, increased consumer awareness, and developing infrastructure are pushing the nation's success towards sustainable transportation for a future green earth.

Review on Integration of EV in Renewable System

The paper (Ferro et al., 2018) develops an optimization model for smart grid EV charging scheduling with considerations of energy costs, customer demand delays, and income generation from vehicle services. It proves that smart charging strategies reduce peak demand by up to 40 %, thereby decreasing the need for grid upgrades and extending equipment lifespan. Paper (Hudson et al., 2024) discusses home charging strategies that minimize costs and emissions. The study in (Ohanu et al., 2024) discusses integrating RER into smart grids by addressing problems and solutions. Reference (Mohanty et al., 2022b) discusses the integration of EVs with DSM in smart grids, making suggestions to optimize the functioning of EVs. Paper (Yang, 2024) discusses cybersecurity issues of EVs, proposing blockchain and fuzzy machine learning for better security. Hydrogen fuel cell vehicles are evaluated in (Kapetanovi et al., 2023) for carbon-neutral train operations, focusing on the vehicle-to-grid application. Paper (Jimenez et al., 2024) addresses renewable energy integration into isolated systems; it is demonstrated that renewable energy-based electrification of passenger cars can reduce oil consumption and CO2 emissions. Paper (Saadatmandi et al., 2024) presents an intelligent charging approach for EVs with solar power to minimize energy wastage and enhance grid security by blockchain. The work in (Secchi et al., 2023) presents an optimization algorithm for EV charging to minimize power ripples with V2G benefits. Paper (Jiang et al., 2024) presents a hierarchical deep Q network for the navigation of EV charging. Paper (Barman et al., 2023) discusses renewable energy sources for EV charging and the associated integration challenges. Paper (Hashemi Dezaki et al., 2017) discusses smart grid reliability under uncertainty from PHEVs and distributed generation. The paper (Rehman, 2022) proposes an algorithm using V2G technology to integrate EVs into smart grids, optimizing load scheduling and stabilizing voltage and frequency. Paper (Khalid, 2024) presents the challenge of renewable energy integration into smart grids based on security and flexibility of operations (Oad et al., 2023). illustrates decentralized methods of supply and demand management in V2G smart grids. Paper (Francesco Calise et al., 2021) presents demand management of energy demand in private transport and buildings as a way to minimize energy consumption and CO2 emissions. Recent works are (Alharbi and Bhattacharya, 2023), which optimizes the integration of EV and DER in smart grids, and (Asija and Viral, 2021), which reviews challenges in renewable energy integration into deregulated markets. Research (Nguyen et al., 2014) explores the role of smart EV charging in stabilizing grids with high renewable penetration. Paper (Feng et al., 2022) discusses strategies to enhance power system flexibility with EVs and storage. Study (Chatuanramtharnghaka et al., 2024) presents a coordinated strategy for integrating renewable energy and demand response (Goia et al., 2022). presents the role of virtual power plants in smart grid optimization, while (Tan et al., 2016) reviews the state of the art in V2G technology. Research (Thenmozhi et al., 2022) proposes a hybrid energy management system for microgrids to optimize the integration of EVs and renewables, and (Chandra et al., 2024) investigates the synergy of EVs with energy storage systems to balance renewable generation. Papers (Ullah et al., 2024; Srihari et al., 2024; Gu et al., 2013; Hu et al., 2016) emphasize the importance of flexibility in deregulated systems with coordinated control of EVs and renewables. In summary, recent research focuses on the optimization of EV integration, enhancement of grid flexibility, improvement of smart grid reliability, and challenges in renewable energy and EV coordination. The set of papers advances the field of smart grids, renewable integration, and electric vehicle coordination in deregulated power systems. The recent research collectively examines the complex challenges and opportunities linked to the incorporation of RES and EVs within deregulated systems and smart grids, providing significant insights into the interaction of technology, economics, and pertinent policy factors. The following is a critical analysis of the review:

a) ***System efficiency:*** The comprehensive investigation conducted within the confines of this study underscores the notion that the synergistic integration of RES alongside EVs into a smart grid framework has the potential to significantly optimize the overall profitability and operational efficiency of the power system. This compelling finding implies that there is an opportunity for substantial long-term enhancements not only in environmental sustainability but also in various economic dimensions that are crucial for universal development.
b) ***Market incentives:*** The intrinsic competitive characteristics inherent in deregulated market structures are prominently highlighted as pivotal elements that serve to foster innovation, facilitate the provision of high-quality electrical power at competitive pricing levels, and subsequently stimulate the widespread adoption of advanced clean energy technologies. Within this dynamic, independent system operators (ISOs) assume an indispensable role in the intricate management of supply bids, thereby ensuring the reliability and stability of the electrical grid amidst the fluctuating demands and supplies characteristic of these markets.
c) ***Environmental impact:*** The findings of this research robustly illuminate the various environmental advantages that arise from the integration of RES, particularly emphasizing the substantial reduction of CO_2 emissions, the promotion of sustainability practices, and the overall contribution towards the attainment of global net-zero objectives that have become increasingly critical in contemporary discourse on climate change.

8. Optimization methods for coordination of RES and EVs in a deregulated system

The increasing penetration of renewable energy sources like wind, solar, and hydroelectricity into the electric grid, along with the increasing penetration of electric vehicles, has necessitated the development of optimized coordination mechanisms. One of the significant challenges is balancing energy demand and supply in a deregulated power system, which is characterized by market-driven dynamics, multiple stakeholders, and the uncertainty of renewable energy generation. With high power integration from EVs and RES, effective optimization methods shall be crucial to maintain the stability, reliability, and sustainability of the power system. The coordinated control optimization methods are as follows:

a) ***Stochastic optimization***
Stochastic optimization techniques handle the uncertainty associated with renewable energy generation and the charging patterns of EVs. In a deregulated power system where the supply and demand balance occurs in real time, stochastic models help system operators plan for several possible outcomes. Gino Zanvettor et al. (2024a). developed a stochastic optimization model that incorporates the uncertainty of renewable power generation and user EV charging behaviors, showing improved energy dispatching and stability. Kabli et al. (2020). explored the use of stochastic mixed-integer programming (SMIP) to manage the integration of EVs and RES in the grid, addressing the challenge of managing uncertain demand and renewable output.
b) ***Multi-objective optimization***
In real-world systems, multiple objectives must be optimized simultaneously, such as minimizing energy costs, maximizing renewable usage, and ensuring grid stability. Multi-objective optimization considers trade-offs between conflicting objectives. Study (Mei et al., 2022) proposed multi-objective optimization using genetic algorithms to optimize the scheduling of EV charging to maximize the usage of renewable energy, which was shown to have a potential role in smart grids. On the other hand, Das et al. (2024). designed a multi-objective optimization framework for integrating EVs into the smart grid by achieving efficient distribution of energy by minimizing operational costs and emissions.
c) ***Bi-level optimization***
In bi-level optimization, two hierarchical problems are solved together. The upper level normally optimizes system-wide objectives, for example, cost minimization or grid balancing. The lower-level problem typically takes care of individual participants' behaviors, such as the charging preferences of EV owners. Meng et al (Meng et al., 2024). proposed a bi-level optimization model for coordinating RES and EVs, considering the interaction between utility operators and individual consumers in deregulated electricity markets. Studies (Yang et al., 2021) have developed a bi-level model where the uncertainty from renewable energy can be integrated with flexible demand response from EVs to stabilize the grid in deregulated environments.
d) ***Real-time distributed optimization***
Real-time distributed optimization is about decentralized decision processes, making it possible for different entities (that is, EV owners, RES producers, or system operators, among others) to make real-time decisions affecting the system in any way. Cheng et al (Cheng and Ching, 2024). proposed an RTDO framework for coordinating EVs with renewable energy systems to reduce congestion and improve stability in the distribution grid. Ref (Rahman et al., 2022). presented a distributed control strategy with the integration of low-voltage grids to accommodate electric vehicles, using real-time knowledge of the grids for efficient charging and discharging.
e) ***Stochastic incentive-based demand response***
Incentive-based demand response programs offer incentives to consumers to change their energy consumption behavior. For EVs, this might be charging the EVs when there is excess renewable generation. Roy et al (Roy and Das, 2024). presented a stochastic incentive-based demand response strategy for virtual power plants by integrating solar power, battery storage, EVs, and flexible demand loads for efficient energy management. Zanvettor et al (Gino Zanvettor et al., 2024b). designed a stochastic incentive-based demand response framework aimed at harmonizing EV charging with renewable generations to optimize the operation of the grid with improved holistic efficiency of the system.
f) ***Adaptive control techniques***

Adaptive control techniques vary system parameters based on the dynamics of the system. These techniques are very useful when the behavior of EVs and renewable energy sources is not easily predictable. Singh et al (Singh et al., 2024). applied adaptive control to optimize the charging and discharging schedules of EVs, ensuring stability in grids with high levels of renewable energy. Choi et al. (2018) used adaptive robust optimization to handle the uncertainty in both renewable energy output and EV charging behaviors in smart grid systems.

- Key Considerations in Optimization

a) ***Grid stability:*** The coordination of RES and EVs is critical to the maintenance of grid stability. Optimized charging and discharging strategies can balance the supply and demand fluctuation, especially at high renewable energy generation and low demand periods.
b) ***Regulatory frameworks:*** Optimization methods for deregulated power systems need to consider market mechanisms and regulatory constraints. With the increasing number of market participants,

optimization methods must be developed with multiple regulatory requirements and fair competition in mind.

c) ***User preferences:*** Consumer-centric optimization methods are of recent interest as consumers have preferences over when and how they want to charge their EVs. This needs to be considered for broad adoption and participation in the optimization programs.

The integration of EVs and RES into a deregulated smart power system poses grave challenges due to the variability of renewable energy generation and the diverse behaviors of consumers. However, optimization methods such as stochastic programming, multi-objective optimization, and bi-level optimization promise rather interesting solutions. These techniques enable better energy management, reduction of costs, and sustainability while ensuring grid stability.

9. Limitations of renewable energy and electric vehicles (EVs)

Even though RES and EVs are central enablers of the transition toward sustainable energy, they share several technical, economic, infrastructural, and regulatory limitations obstructing the transition to widespread adoption.

9.1. Limitations of renewable energy

a) *Intermittency and Reliability Issues*
- *Weather dependence:* Solar and wind power generation hinges on the availability of sun and wind, causing variability in power generation.
- *Uncertainty:* Although there are good forecasting models, rapidly changing weather conditions may put grids in danger situation.
- *Grid instability issues:* With high penetration of RES, energy storage and demand response measures must be implemented to maintain equilibrium between supply and demand.

b) *Limitations of energy storage*
- *Expensive storage systems:* The batteries (lithium-ion, flow batteries) are costly; their economic viability is an issue.
- *Low energy density:* High capacities cannot be achieved by the battery technologies currently in use. They do not allow for long durations of efficient storage of energy.
- *Deterioration of battery performance:* Because the performance of energy storage systems deteriorates with multiple charge-discharge cycles, they do not last long.

c) *Infrastructure and integration challenges*
- *Grid modernization requirements:* Traditional power grids are not designed for high RES penetration, requiring expensive upgrades.
- *Transmission and distribution losses:* Distributed energy resources (DERs) require efficient power flow management to minimize losses.
- *Land and space constraints:* Large-scale solar and wind farms require significant land, which is limited in urban areas.

d) *Economic and market barriers*
- *High initial capital investment:* RES projects have significantly high capital costs for infrastructure, installation, and grid integration.
- *Economic viability and grid parity:* In some regions, many RES technologies are not yet economically viable compared to fossil fuels.
- *Energy market volatility:* Unstable electricity prices result in uncertainty about the financial feasibility of investments in renewable energy.

e) *Policy and regulatory challenges*
- *Unclear or inconsistent government policies:* There are few countries with long-term policies to incentivize RES deployment.
- *Subsidy dependence:* Many renewable projects are dependent on government subsidies, which are not likely to be sustainable in the long term.
- *Slow regulatory adaptation:* The market rules and grid codes do not always reflect the needs of renewable energy integration.

9.2. Limitations of electric vehicles (EVs)

a) *Battery technology and range anxiety*
- *Limited driving range:* EVs have a much shorter driving range than ICE vehicles, which leads to range anxiety.
- *Long charging times:* Even with fast-charging technologies, EVs take much longer to charge than refueling ICE vehicles.
- *Battery degradation:* Lithium-ion batteries degrade over time, reducing vehicle performance and increasing replacement costs.

b) *Charging infrastructure challenges*
- *Insufficient charging stations:* There are not many areas where public charging networks are available everywhere; hence, long-distance travel is not possible through a vehicle.
- *Grid demand and overloading:* Locally, increased penetration of EVs brings congestion to the grid and peak demand issues.
- *Standardization issues:* Different manufacturers of EVs use various charging connectors and protocols, thereby limiting interoperability.

c) *High initial cost and economic barriers*
- *Costly batteries:* The cost of EV batteries is still too expensive but is improving gradually. The cost of purchasing an EV is higher as compared to conventional vehicles, mainly because of the cost of the battery and technology.
- *Depreciation over time and resale value:* Since these batteries have rapid technological advancement, uncertainty prevails in the long-term depreciation and resale of EVs.

d) *Environmental and supply chain concerns*
- *Extraction of raw materials for EV batteries:* Lithium, cobalt, and nickel mining for EV batteries has strong environmental and ethical implications.
- *Recycling and waste management for EV batteries*: There is a lack of proper recycling infrastructure, which results in poor waste management.
- *Source of energy for charging EVs:* If EVs are charged by electricity from fossil fuel sources, the benefits of EVs to the environment are compromised.

e) *Policy and market limitations*
- *Lack of EV-friendly policies:* Many regions do not have strong incentives for EV adoption.
- *Limited consumer awareness and adoption:* Many potential buyers are still unfamiliar with EV benefits and maintenance requirements.
- *Fleet electrification challenges:* Transitioning commercial and heavy-duty transport fleets to EVs is challenging due to range and charging limitations.

9.3. Solution for overcoming these limitations

a) *Solutions for renewable energy challenges*
- *Hybrid renewable energy systems (HRES):* Hybridization of solar, wind, and energy storage can enhance reliability and mitigate intermittency issues.
- *Advanced energy storage technologies:* Next-generation batteries, such as solid-state, sodium-ion, and hydrogen storage, can be developed to improve energy storage.
- *Smart grid development:* AI-driven forecasting, demand response mechanisms, and decentralized grid control can be deployed to optimize renewable integration.
- *Regulatory and policy reforms:* Long-term incentives from governments, changing grid codes, and carbon pricing will be promoted to encourage renewable adoption.

b) *Solutions for EV challenges*

- *Battery technology advancements:* Innovations such as solid-state batteries, fast-charging ultra-capacitors, and V2G systems will enhance the adoption of EVs.
- *Expansion of charging infrastructure:* Governments and private sectors must work together to roll out fast chargers and wireless charging to reduce both behavioral and physical limitations to range.
- *Cost reduction through mass production*: Economies of scale and rationalization of the supply chain will decrease the price of EVs.
- *Recycling and second-life applications:* The development of efficient battery recycling programs and reusing used batteries in grid storage will make EVs more sustainable.

Renewable energy and electric vehicles are central to the energy and transportation sector decarbonization process, yet they face major technical, economic, infrastructural, and regulatory limitations. Overcoming these challenges is going to depend on technology advancements, policy support, grid modernization, and consumer awareness. Further research should then focus on the next generation in energy storage, smart grid optimization, and sustainable battery supply chains to ensure that the transition goes smoothly toward a cleaner, electrified future.

10. Key performance indicators (KPIs) in the evaluation process of microgrid

.

- *System efficiency:* It refers to the quantitative analysis, which determines the percentage or degree to which energy resources are utilized effectively and efficiently in a microgrid environment. It significantly enhances the processes of energy distribution and consumption by substantially minimizing losses that occur during the phases of power generation, storage, and transfer, thus promoting a more efficient energy cycle. It also enables the smooth and improved integration of RES, which in turn results in a significant reduction in dependency on traditional non-renewable power generation methods. It also actively supports innovative, dynamic DSM strategies to ensure that there is an optimal balance maintained between the supply of energy and the demand for it, which is critical for the overall performance of the microgrid.
- *Grid stability:* It refers to the overall strength of the grid to ensure consistency in its operations irrespective of variations occurring concerning changes in patterns of production and fluctuations in demand on consumers' sides. It is critically important for renewable energy to gain integration successfully, as source variability is naturally associated with phenomena like wind and solar. Additionally, it helps to improve the strength of the grid against any kind of potential disturbances that might appear as voltage fluctuations, overloading of lines, and even the event of blackouts. Also, it assists in the integration of two-way energy flow systems like V2G technology so that smooth and consistent grid performance is ensured both at peak and off-peak times. Energy reliability cannot be obtained if this does not occur.
- *Cost optimization:* It monitors and quantifies the cost competitiveness involved during every stage of energy production, transmission, and storage that is executed through the operating system of the microgrid. It primarily aids in curbing operational expenditures with the help of appropriate exploitation of erudite energy management systems and predictive analytics to make better judgments. In addition to this, it promotes the transition towards hybrid renewable energy systems, which are designed to reach grid parity for achieving financial sustainability in energy markets.
- *Environmental benefits:* This assessment quantifies the decrease in environmental impact resultant from the implementation of cleaner energy production methods and the rational utilization of available resources. It reduces greenhouse gas emissions through its effective role in mitigating global warming, as it maximizes the penetration of renewable energy in the energy mix. In addition, it encourages sustainable practices and, therefore, might include the use of smart grid technologies and decentralized energy systems that help to contribute to efficiency.

This combination of KPIs represents a strong and comprehensive framework for the proper evaluation and continuous improvement of the dynamic coordination processes governing microgrids and ensuring such systems could make effective contributions to sustainable, resilient energy ecosystems benefiting all those concerned. The study (Mbungu et al., 2022) contributes to sustainable energy management by utilizing the flexibility of EV batteries and integrating them into home energy systems to optimize energy utilization and promote environmental sustainability. Research (Mbungu et al., 2024) developed a practical nanogrid model, integrating solar panels, battery storage, and the utility grid. It focused on residential applications to optimize energy generation, storage, and consumption. A new framework has been introduced to coordinate multiple independent, interconnected, and autonomous microgrids using the optimal energy management system (EMS) in reference (Mbungu et al., 2025). It has taken an integrated photovoltaic system, battery energy storage systems, and utility grid to balance power flow dynamically. These studies together work toward advancing intelligent energy management in residential and microgrid applications, improving energy efficiency, cost-effectiveness, and environmental sustainability. Some important topics about the smart grid and microgrid integration with renewable energy sources are as follows:

a. ***Grid characteristics***

The modern electricity grid is fashioned with an excess of features that greatly enhance the efficient integration of RES and EVs, marking the changing face of consumption and production. The traditional electricity grids have uniqueness characterized by the centralization of the power generation system where power is supplied unidirectional from power generation facilities directly to the end users. Besides this, these grids are characterized by the least communication capabilities, which results in reliance on reactive strategies of maintenance that are not proactive; as a result, they exhibit significant inflexibility and are ill-equipped to handle the demands posed by variable loads and the integration of distributed generation systems becoming increasingly prevalent in modern energy landscapes. In contrast, modern smart grids are marked by an ability to add DERs, which can range from solar and wind energy resources to microgrid systems, enhancing the overall resilience of the grid while introducing variability requiring advanced management. Additionally, these advanced grids facilitate a bidirectional flow of electricity, allowing consumers, who are often referred to as prosumers, to inject surplus energy back into the grid through mechanisms such as V2G technology or small-scale generation systems that contribute to the overall energy supply. Further, advanced technologies such as AMI, SCADA, and the IoT have made modern smart grids use real-time monitoring and predictive analytics for optimization of grid performance and reliability.

b. ***Power electronic circuit topology***

To interface effectively the RES or EVs with the electricity grid, there is a need to ensure compatibility, optimize efficiency, and maintain precise control over the flow of energy by using specific power electronic devices. The inverters are crucial for the conversion of DC produced by solar panels or stored in EV batteries into AC compatible with the grid infrastructure, hence enabling the integration of renewable energy into the existing electrical structure. The centralized inverters used in large solar farms or applications requiring high capacity, these inverters are designed to handle large energy loads efficiently. The string and micro-inverters are smaller-scale inverters meant for distributed systems, such as a rooftop solar installation, whereby individual solar panels can feed the energy directly into the electrical grid, optimizing their energy conversion. The DC-DC converters are essentially crucial components used to maintain the required voltage levels during charging an EV, increasing overall efficiency in charging the vehicle and ensuring safety while charging. The standard electric vehicle chargers usually use unidirectional converters, which allow the flow of power in only one direction, from the grid to the vehicle. The bidirectional converters are necessary for supporting V2G operations, allowing energy to flow in both directions, thus enabling EVs to contribute energy back to the grid when needed. The energy storage integration utilizes power converters to properly handle charging and discharging cycles in energy storage systems for better integration of batteries with the grid while maintaining better stability in the overall grid. The multi-level converters improve efficiency and significantly reduce harmonic distortion levels, especially when they operate at high voltage levels.

c. ***Problems with grid integration***

There are several technical challenges brought about by integrating renewable sources and electric vehicles with the already developed electricity supply systems, basically because they are intrinsically in-and-out irregular and varied in character.

- Important issues of frequency control arise due to the intrinsic variable and volatile nature of some renewable resources, including the possible appearance of an inherent grid-destabilizing phenomenon of an intermittent kind caused by fluctuating renewables. Example: A sudden significant decrease in wind energy output causes a decrease in the overall amount of energy supply, resulting in a decrease in grid frequency, which may bring instability to the electrical system.
- ***Voltage regulation:*** This is most often caused by rapid changes in the renewable sources' outputs or the variability in loads when electric vehicles are charged in a way that requires dynamic management strategies for ensuring that voltages are maintained at reasonable levels.
- ***Voltage ride through:*** It is such a vital mechanism that during sagging periods, the grid will be enabled to tolerate them and continue to regain normalcy to avoid stability conditions during fluctuations.
- ***Power quality issues:*** Harmonics produced by inverters or electric vehicle chargers may interfere with sensitive electrical equipment, reducing their efficiency and increasing operational losses, thereby complicating the integration process.

d. ***Control strategies***

Modern control systems and algorithms are employed to effectively counter all those challenges because grid integration efficiently optimizes the general performance of the grid and meets energy demands now and forever. Some key strategies are as follows:

- ***DR:*** This approach actively forces consumers to shift their use of energy according to periods of peak demand, therefore relieving a lot of stress on the grid as well as providing overall improvement in efficiency.
- ***Dynamic pricing models:*** These models are programmed in a way to offer the customer some economic incentives to use more energy during off-peak h, thus better-balanced energy usage throughout the day.
- ***Energy management system:*** These systems are the modern systems that optimize the scheduling and dispatching of resources while integrating advanced forecasting models of renewable energy sources as well as charging demands for electric vehicles. Mechanisms such as Frequency-Watt Control are used to regulate output from renewable energy sources to maintain the stability of frequencies within the grid. Furthermore, Voltage-Reactive Power Control is used for voltage deviations and operated by the precise working of inverters.
- ***Advanced optimization algorithms:*** The use of AI and ML techniques enables the prediction of energy fluctuations and optimization of dispatch strategies, while metaheuristic methods are applied to enhance the operational efficiency of DERs under conditions of uncertainty, ensuring a resilient and responsive energy system.

e. ***Required control parameters***

The control parameters have the important role of keeping in check the adherence to established regulatory frameworks and grid. The key parameters are as follows:

- ***Frequency setpoints:*** It is crucial to keep the grid frequency within a narrow band of $\pm$ 0.5 Hz relative to the nominal operational values, which are typically 50 or 60 Hz, depending on regional electrical standards.
- ***Voltage levels:*** It would be necessary to carefully control the grid voltage so that it could maintain an acceptable tolerance level within $\pm$ 5 % of maintaining constant power.
- ***Limits on harmonic distortion:*** It would be imperative that the Total Harmonic Distortion (THD) should not exceed 5 % because this factor ensures that there is no decrease in power quality, thereby degrading both equipment and the system as a whole.
- ***State of charge (SOC) and state of health (SOH):*** The performance metrics of the Energy Storage System (ESS) need to be monitored continuously to ensure a better performance and longer lifespan of the system.

11. Importance of green hydrogen as a renewable energy

Green hydrogen, produced from the electrolysis of water through renewable energy sources, has become a very prominent sustainable energy carrier that can contribute to the decarbonization of industry, transport, and even power generation. This section describes the current status of green hydrogen research, methods of production, integration strategies, economic considerations, and prospects. The main source of green hydrogen is through water electrolysis powered by renewable sources like wind, solar, and hydropower. Electrolysis splits water into hydrogen and oxygen using an electric current. Its efficiency and feasibility are impacted by various factors, like the type of electrolyzer, for example, proton exchange membrane, alkaline, or solid oxide, as well as availability and variability in renewable energy, among others, along with electrolyzer technology developments. Recent research findings have presented advancements in the performance of electrolyzers along with the decreasing cost; this has enabled green hydrogen to compete with more traditional methods of producing hydrogen (Kyriakopoulos and Aravossis, 2022).

To integrate green hydrogen into existing energy systems is an opportunity but also a challenge. Hydrogen can act as a storage medium for excessive renewable energy, thus improving the stability of the grid and allowing supply-demand balancing. Hydrogen can be used in transport in fuel cells, injected into natural gas pipelines, or converted to ammonia for use in diverse industrial applications. If it is to be efficiently integrated, infrastructure for the production, storage, distribution, and utilization of hydrogen, alongside policies and legislation favorable to the use of hydrogen, must be developed (Maka and Mehmood, 2024). The economic feasibility of green hydrogen is yet another aspect that determines its use. Indeed, though production costs have dropped because of technological advancement and economies of scale, green hydrogen is still more expensive than one produced from fossil fuels. These include the cost of renewable electricity, electrolyzer capital and operational costs, and the scale of production facilities. Policy interventions such as carbon pricing and subsidies can bridge the cost gap and support green hydrogen deployment (Franzmann et al., 2023).

One environmental benefit of green hydrogen is offering zero-emission fuel in fossil fuel, thereby reducing overall greenhouse gas emissions and contributing toward mitigating the impacts of climate change. Although green hydrogen involves low greenhouse gas emissions in both production and usage, the impacts depend on sustainability issues related to renewable energy and lifecycle emissions issues from electrolyzers, manufacturing processes, and other infrastructure development efforts. Therefore, it is pertinent to conduct wide-ranging lifecycle assessment studies to positively impact environmental sustainability (Odenweller and Ueckerdt, 2025). Although green hydrogen has significant potential, it faces several obstacles to its mass adoption. High production costs, technological limitations, infrastructure deficits, and regulatory uncertainties are some of the major hurdles. Current research is focused on improving electrolyzer efficiency, scalable storage solutions, and robust supply chains. Government, industry, and research institution collaboration are vital to overcome the challenges and fully realize the promise of green hydrogen as a cornerstone of a sustainable energy future (Stöckl et al., 2021).

- ***Survey on green hydrogen as a renewable energy***

Green hydrogen, produced through the electrolysis of water powered by renewable energy sources, is gaining increasing attention as a promising alternative to fossil fuels. As countries strive to meet their climate goals, green hydrogen is seen as a potential solution for decarbonizing energy-intensive sectors, such as transportation, industry, and electricity generation (Hassan et al., 2024). The following literature review examines recent studies on green hydrogen, including its production, applications, challenges, and prospects.

Green hydrogen production is primarily based on water electrolysis, where electricity generated from renewable sources like solar, wind, and hydropower is used to split water into hydrogen and oxygen (Kourougianni et al., 2024). Several studies have focused on improving the efficiency and cost-effectiveness of electrolysis technologies. For instance, Kumar et al (Kumar and Lim, 2023). reviewed the advancements in proton exchange membrane (PEM) electrolyzers, highlighting their ability to operate efficiently under intermittent renewable energy supply conditions. Another key area of research is the development of efficient catalysts for electrolysis. Wang et al (Wang et al., 2021). explored novel catalysts based on transition metals to reduce the energy required for water splitting. They emphasized that the optimization of these catalysts could significantly lower the cost of hydrogen production and improve the scalability of green hydrogen systems. One of the key advantages of green hydrogen is its potential role in energy storage. As a flexible energy carrier, hydrogen can be stored and transported to balance supply and demand in power systems dominated by intermittent renewable energy (Ghirardi et al., 2023). According to the study by Islam et al. (2024), green hydrogen can be used in combination with large-scale storage systems to provide grid stability during periods of low renewable generation.

Further research by Kwon et al. (2024) explored the integration of green hydrogen with advanced battery storage systems, illustrating the synergy between hydrogen and batteries in maintaining a stable and sustainable energy grid. Their findings suggest that this integration can help overcome the intermittency challenges of renewable power sources. The use of green hydrogen in transportation is another rapidly growing area of research. Hydrogen fuel cells are being developed to replace conventional internal combustion engines in heavy-duty vehicles such as trucks, buses, and trains (Sadeq et al., 2024). In their study, Camacho et al (Nieves Camacho et al., 2022). investigated the performance of hydrogen fuel cell-powered vehicles in comparison to electric vehicles and found that hydrogen fuel cells offer a better range and faster refueling time for long-distance transportation. Additionally, green hydrogen is seen as a key enabler in decarbonizing industrial sectors such as steel, cement, and chemicals (Griffiths et al., 2021). A study by Bade et al. (2024) assessed the potential of hydrogen in replacing coke in blast furnaces, and their results indicated that green hydrogen could significantly reduce carbon emissions in the steel industry.

Despite its potential, the widespread adoption of green hydrogen faces several challenges, including high production costs, infrastructure limitations, and technological barriers. One of the main hurdles is the high capital cost of electrolyzers and renewable energy infrastructure. According to several reviews, government support and policy interventions are essential to scale up green hydrogen production and make it competitive with conventional hydrogen production methods, such as gray and blue hydrogen. The need for an extensive hydrogen infrastructure, including storage, transportation, and refueling stations, is another critical challenge. A report by the International Energy Agency (2022) highlighted the lack of a global hydrogen supply chain as one of the significant barriers to green hydrogen's widespread deployment. The future of green hydrogen depends on continuous technological advancements, cost reductions, and supportive government policies. In a recent study, Islam et al. (2024) reviewed various policy frameworks aimed at accelerating the development of green hydrogen, such as subsidies for renewable energy, tax incentives for green hydrogen producers, and investment in hydrogen infrastructure.

Green hydrogen will play a central role in the world's transformation into a low-carbon energy system. Even so, although good progress has been made regarding both efficiency and economy of production and applications, important challenges lie ahead. Unlocking the full potential of green hydrogen will thus depend on the fruits of further research and effective cooperation between industry, academia, and policymakers.

12. Review on hydrogen vehicles as a renewable energy source

Hydrogen vehicles, particularly those powered by hydrogen fuel cells, are emerging as one of the most promising solutions for reducing carbon emissions from the transportation sector. With the global push towards sustainability and decarbonization, hydrogen vehicles offer an alternative to conventional gasoline and diesel-powered vehicles, especially for sectors like heavy-duty transportation, where battery-electric vehicles might not be as effective due to range and weight constraints. This review explores the recent advancements in hydrogen vehicles, including the progress in fuel cell technologies, challenges in infrastructure development, and policy support.

- Hydrogen vehicles function based on hydrogen fuel cells, which transform hydrogen into electricity and use this electricity to drive an electric motor; the only product is water. Much of recent research has involved optimizing hydrogen fuel cells' performance, efficiency, and longevity. Ephraim et al (Agyekum et al., 2024). noted that better membrane electrode assemblies and catalysts are significant areas of improvement that enhance hydrogen fuel cell efficiency. Their study suggests that optimizing MEA design and improving platinum-based catalysts can significantly reduce the cost and increase the efficiency of hydrogen fuel cells. Recently, improvements in the proton exchange membrane (PEM) fuel cell systems have also been highlighted.
- The efficiency and performance of the hydrogen-powered vehicle depend greatly on the fuel cell stack and the storage systems deployed in the vehicle. Mori et al (Mori and Hirose, 2009). emphasized how efficient hydrogen storage solutions like high-pressure tanks and the storage of liquid hydrogen would improve the hydrogen vehicles' range and safety. Their work indicates that the storage systems must be lightweight, cost-effective, and capable of safely storing hydrogen at high pressures. Another significant area of research is the integration of hydrogen vehicles with renewable energy sources. As solar and wind energy are intermittent, combining hydrogen vehicles with renewable generation sources provides a mechanism for decarbonizing transportation and electricity sectors simultaneously.
- While hydrogen vehicles hold immense potential, several challenges remain that could impede their widespread adoption. One of the

most significant barriers is the lack of infrastructure for hydrogen refueling stations. A study by Apostolou et al (Apostolou and Xydis, 2019). assessed the global hydrogen refueling infrastructure and highlighted that limited refueling stations restrict the adoption of hydrogen vehicles, especially in remote areas. Another significant challenge is the high cost of hydrogen production, mainly from electrolysis powered by renewable energy. According to Akyuz et al (Serhat Akyuz et al., 2024)., the cost of green hydrogen production needs to be drastically lowered for hydrogen vehicles to be comparable with electric vehicles in terms of costs. This will be through innovations in the technology of electrolysis systems and increased production of renewable energy.

- Hydrogen vehicles are considered environmentally friendly because they emit zero tailpipe emissions, with water vapor being the only byproduct. However, the environmental impact of hydrogen vehicles depends largely on how the hydrogen is produced. In a comprehensive review, Aidin et al (Teimouri et al., 2022). analyzed the lifecycle emissions of hydrogen vehicles, concluding that when hydrogen is produced from renewable energy, hydrogen vehicles can significantly reduce carbon emissions compared to conventional vehicles. Economically, hydrogen vehicles offer long-term cost benefits, particularly in heavy-duty transportation, where the range of battery-electric vehicles might be limited.
- Policy support and government incentives are crucial for the development and adoption of hydrogen vehicles. According to Atul et al (Rawat et al., 2024)., governments worldwide are increasingly introducing subsidies, tax credits, and regulatory frameworks to promote the production and use of hydrogen vehicles. Their study examined the policies in Europe, Japan, and North America, noting that collaborative efforts across these regions could accelerate the establishment of a global hydrogen vehicle market. Paper (Ali et al., 2024) highlighted the importance of hydrogen in helping to meet the climate targets; it indicates that the transport sector needs low-emission alternatives in the form of hydrogen-based automobiles to be aligned with the requirements of the Paris Agreement.
- Ongoing technological advances, infrastructure developments, and policy frameworks will help shape the future of hydrogen vehicles. As discussed by Mendez et al. (2023), it is only by continuous innovation of hydrogen fuel cell technology, production methods, and refueling infrastructure that hydrogen vehicles can be accepted as a widespread solution for environmentally friendly transportation. Cost reductions for fuel cells and hydrogen production technologies are likely to make hydrogen vehicles progressively competitive compared with conventional ones.

Hydrogen vehicles represent a promising pathway to decarbonizing the transportation sector. However, significant challenges such as high costs, limited infrastructure, and the need for large-scale hydrogen production must be addressed to realize their full potential. Continued research, policy support, and technological advancements are essential for overcoming these barriers and achieving the widespread adoption of hydrogen vehicles as a sustainable, renewable energy solution.

13. Contribution to new knowledge

The manuscript exhibits a remarkable focus on the intricate integration of RES and EVs within the dynamic framework of deregulated smart grids. The manuscript exemplifies a high degree of scientific rigor by consistently citing recent data and cutting-edge research that is relevant to the topic at hand. It also presents a comprehensive comparative study that is vital for grasping the distinctions and advantages associated with various technologies, including microgrids, smart grids, and the integration of renewable energy sources. Moreover, it offers in-depth discussions that cover technological, economic, and operational comparisons across diverse grid configurations and energy storage methodologies, which enriches the reader's understanding. The use of advanced algorithms and models, such as MINLP and DSM, is employed to propose innovative solutions aimed at addressing challenges related to grid stability and the integration of RES. Additionally, the incorporation of quantitative analyses, which include assessments of economic viability and the environmental repercussions of these systems, further fortifies the robustness of the manuscript. The manuscript makes a substantial contribution to the body of knowledge by providing fresh insights into the optimization processes involved in the integration of RES and EVs within the context of deregulated power systems, particularly emphasizing the significance of microgrids and smart grids in achieving these objectives. The various advanced technologies offer invaluable insights that are crucial for policymakers and industry stakeholders alike, particularly concerning the complex integration of renewable energy sources, commonly referred to as RES, along with EVs, into the increasingly prevalent framework of deregulated power systems. The subsequent key points delineate their profound impact on the energy landscape:

A. **Sustainability and environmental impact**

The innovative technologies discussed herein facilitate a remarkable and substantial reduction in overall carbon emissions through the strategic integration of renewable energy sources, such as solar power and wind energy, into advanced smart grids and microgrids. This transformative process significantly promotes the establishment of cleaner energy systems, which, in turn, assists countries around the globe in meeting their ambitious climate targets and ultimately achieving the coveted goal of net-zero emissions. Furthermore, by fostering the widespread adoption of EVs and effectively integrating them within these modern energy systems, it can realize even greater reductions in fuel consumption and harmful emissions, thereby contributing positively to the global efforts aimed at mitigating the adverse effects of climate change and global warming.

B. **Grid stability and efficiency**

The implementation of smart grids that incorporate both renewable energy sources and EVs serves to markedly enhance the resilience and reliability of the electrical grid by utilizing advanced control systems, which include DSM strategies and BESS. These technologies are instrumental in optimizing grid efficiency by improving energy flows and minimizing energy losses, particularly during periods of peak demand, which is of paramount importance for preserving the stability and viability of deregulated energy markets. Additionally, the advent of smart charging technologies for electric vehicles ensures that these vehicles can dynamically adapt to the ever-fluctuating energy demand, which significantly alleviates stress on the overall grid infrastructure.

C. **Economic viability**

For policymakers, the insights presented in this paper emphasize that innovative technologies, such as HRES, have the potential to achieve grid parity within specific and favorable electricity pricing thresholds, thereby rendering them economically sustainable and viable within deregulated energy markets. On the other hand, for industry stakeholders, the adoption of these transformative technologies results in a notable reduction in operational costs, an increase in overall profitability, and the provision of competitive advantages in markets that are increasingly driven by investments in clean energy solutions.

D. **Market innovation and participation**

The framework of deregulated energy systems inherently promotes greater levels of competition and innovation by facilitating the involvement of multiple market participants in both energy generation and distribution processes. Policymakers are strongly encouraged to develop and implement policies that create incentives for the adoption of renewable energy sources and the integration of electric vehicles to foster a culture of innovation. This competitive environment has the potential to drive down costs significantly while simultaneously encouraging the ongoing development of new and innovative energy technologies, which ultimately benefits both consumers and businesses alike.

E. **Technological gaps and opportunities:**

The analysis presented in the paper highlights several critical areas where there exists a pressing need for further research and development, particularly in the realms of enhancing power flow control mechanisms and bolstering the participation of electric vehicles at the distribution level. These valuable insights are essential for policymakers as they seek to address existing gaps within current energy policies while also serving as a guiding beacon for industry stakeholders who are looking to invest in technological advancements that enhance both system efficiency and sustainability in the energy sector.

The technologies discussed within this paper contribute significantly to the establishment of a more sustainable, reliable, and economically viable energy system, thereby supporting and accelerating the transition toward the adoption of renewable energy sources and electric vehicles within the increasingly complex landscape of a deregulated market environment.

Here are some extensive case studies, along with practical examples, of the deregulated energy markets that have emerged in various countries around the world, drawing from a comprehensive analysis of the prevailing trends and the key factors that are significantly influencing these markets:

- ***United States***

  The process of deregulating the energy market in the United States commenced during the 1990s, a pivotal era that allowed consumers residing in numerous states to exercise their right to select their electricity providers freely. This shift towards deregulation not only fostered an environment of competition among energy suppliers but also catalyzed technological advancements and resulted in more competitive pricing structures for consumers. Some of the prominent features that characterize this transformation include:

  - Texas: Texas operates an independent electric grid that is not only robust but also features a variety of competitive retail electricity providers (REPs) alongside dynamic wholesale energy markets. Moreover, Texas boasts a significant capacity for wind energy generation, positioning the state as a leader in the production of renewable energy resources across the nation.

  - California: The state of California represents a scenario of mixed outcomes in the realm of energy market deregulation. During the early 2000s, the complications arising from deregulation policies led to a series of rolling blackouts and unexpected spikes in electricity prices. However, following a comprehensive restructuring of the energy market, California has managed to maintain its status as one of the largest energy markets, with a strong focus on the integration of renewable energy sources, particularly solar and wind technologies.

- ***Europe***

Several countries throughout Europe have actively embraced the concept of deregulated energy markets, leading to significant advancements in energy supply and consumption:

- United Kingdom: The United Kingdom took decisive steps to deregulate its energy market in the latter part of the 1990s, which empowered consumers to choose from a multitude of suppliers available in the market. This competitive environment has not only encouraged a surge in investments related to renewable energy, particularly in the offshore wind sector, but has also fostered a broader commitment to sustainability within the energy landscape.

- Germany: As a recognized global leader in the deregulation of energy markets, Germany has implemented its ambitious Energiewende (Energy Transition) initiative, which prioritizes the advancement of renewable energy sources and sustainability practices. The country has set an impressive target of deriving 80 % of its electricity from renewable sources by the year 2030, and it has successfully integrated advanced technologies such as V2G systems and BESS into its energy infrastructure.

- ***Developing countries***

In addition to advancements made by developed nations, several developing countries have also made noteworthy progress in the deregulation of their energy markets, some of which have begun to adopt smart grid technologies while emphasizing the importance of renewable energy integration:

- India: In the case of India, the energy market operates on a semi-deregulated basis, where both state-run and private utilities function concurrently within the same framework. The Indian government has established ambitious objectives to ensure that 40 % of the nation's electricity is generated from non-fossil fuel sources by the year 2030. Furthermore, the deregulation initiatives implemented in states such as Delhi have opened the market to private sector participation, thereby enhancing competitive dynamics and promoting greater integration of renewable energy sources.

- Kenya: Within Kenya, a progressive hybrid Distributed Energy System (DES) model has been introduced, utilizing renewable energy sources such as biogas, wind, and solar power to provide support not only to urban areas but also to remote locations that have historically faced energy access challenges. The country's proactive efforts to encourage deregulation have enabled private entities to enter the energy market, thereby improving grid stability and significantly increasing access to electricity for its citizens.

These illustrative examples shown in Table 6 serve to underscore how deregulated energy markets have fostered innovation, stimulated competition, and facilitated the integration of renewable energy sources within both developed and developing economies. Here is a comprehensive comparative breakdown of the various deregulated energy markets that exist across different regions, including the United States, Europe, and developing countries such as India and Kenya.

14. Problem-solving flowchart

The step-by-step breakdown for the problem-solving methods present in this work is as follows:

a) ***Introduction***

- Define the problem of RES and EV integration in deregulated markets.
- Identify challenges related to grid stability, economic feasibility, and optimization of resources.

b) Problem Identification

Recognize key issues affecting RES-EV integration in deregulated markets:

- ***Grid stability issues:*** Voltage fluctuations, frequency regulation.
- ***Economic viability:*** High initial investment, energy pricing models.
- ***Market complexity:*** Decentralization, competition among generators.
- ***Environmental concerns:*** CO_2 emissions, need for sustainable energy sources.

c) ***Data collection & input parameters***

Collect data for modeling and optimization:

- Data related to the generation of renewable energy, preferably based on solar and wind power.

Table 6
Key metrics comparison for EV integration and renewable energy system.

Details	United States	Germany	UK	India	Kenya
Market Structure	Highly deregulated, competitive retail markets	Deregulated, ambitious renewable targets	Fully deregulated retail and wholesale markets	Semi-deregulated, mixed state/private	Semi-deregulated, focus on off-grid
Renewable Energy Share (as of 2023)	~20 % (Wind, Solar)	50 % (Wind, Solar, Biomass)	40 % (Wind, Solar)	25 % (Solar, Wind)	90 % (Hydropower, Solar)
Technological Innovation	Advanced battery storage, V2G, EV integration	Leading in battery storage, V2G	Smart grids, energy storage expansion	Focus on solar microgrids and wind farms	Off-grid solar microgrids in rural areas
Pricing Mechanism	Dynamic pricing (based on demand-supply)	Renewable energy surcharges, subsidies	Competitive pricing with green tariffs	Subsidies, cross-subsidization	Feed-in tariffs, pay-as-you-go models
Policy Support	Strong federal & state-level policies	Energiewende driving 80 % renewables by 2030	Climate Change Act targets	National Solar Mission, FAME II initiative	Energy Act promoting renewable energy
EV Infrastructure	Widespread EV charging infrastructure	Strong V2G integration and charging network	Growing EV infrastructure, incentives	Growing EV adoption with government incentives	Limited EV infrastructure

- Electric vehicles' charging patterns and mobility data.
- Historical load profiles from smart grid operators.
- Market structures and regulatory policies under deregulated power markets.
- Weather forecasting data for associated variability in solar and wind energy.
- Battery Energy Storage System parameters, including SoC and DoD.

d) ***System modeling & optimization***

Develop a mathematical optimization model for RES-EV integration:

- ***Mathematical formulation:*** Use Mixed-Integer Linear Programming (MILP).
- ***Metaheuristic algorithms:*** Honey Badger Algorithm (HBA), Genetic Algorithm (GA) etc.
- ***Energy dispatch optimization:*** Load balancing strategies.
- ***Smart grid control strategies:*** FACTS devices, Demand Response, and V2G models.
- ***Demand-side management (DSM):*** Schedule EV charging in off-peak h

e) ***Economic & environmental analysis***

Conduct cost-benefit analysis for RES-EV integration:

- ***Levelized cost of electricity (LCOE):*** Calculate the cost-effectiveness of RES integration.
- ***Net present value (NPV):*** Analyze the long-term profitability of RES-based power systems.
- ***CO_2 emission reduction:*** Evaluate environmental benefits from RES integration.
- ***Energy trading analysis:*** Economic impact of integrating microgrids in deregulated markets.

f) ***Validation & case studies***

Compare findings with real-world case studies to validate the model:

- ***Germany's renewable energy transition:*** 80 % RES target by 2030.
- ***California's smart grid & BESS systems:*** Managing high RES penetration.
- ***India's EV and RES market growth:*** Challenges in Developing Smart Grids.
- ***Sensitivity analysis:*** Impact of varying electricity prices, battery costs, and grid limitations.

g) ***Recommendations & future work***

Develop policy and technology recommendations:

- ***Policy incentives:*** RES and EV adoption incentives in deregulated markets.
- ***Infrastructure upgrades:*** Decentralized energy storage and micro-grid expansion.
- ***Advanced AI & machine learning integration:*** Enhance forecasting and energy management.
- ***V2G improvements:*** Enhanced bidirectional energy flow for the balancing of grids.
- ***Blockchain-based energy trading:*** Secure and decentralized market participation.

h) ***End***

The detailed problem-solving flowchart for the presented work is depicted in Fig. 13.

15. Conclusions

This study highlights the critical role that deregulated power systems and advanced smart grid technologies play in facilitating the integration of RES and EVs into the energy sector. Through comprehensive analysis, it demonstrates how these systems not only foster competitive market dynamics but also drive technological innovation and promote sustainable energy practices. The main contributions of the paper are as

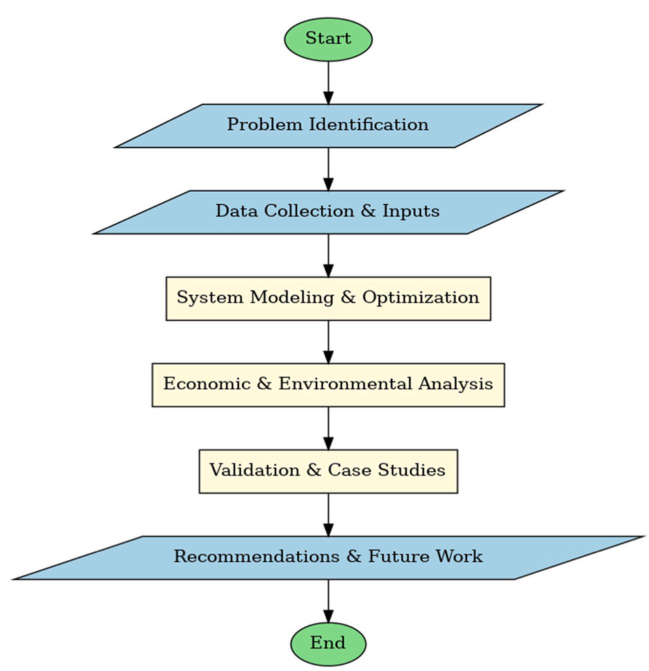

Fig. 13. Problem-solving flowchart for presented work.

follows:

- This study shows how the efficient integration of RES and EVs in smart grid systems optimizes power system performance. Advanced grid technologies provide smooth management of fluctuating outputs of RES and the charging of EVs.
- The deregulated power markets stimulate the proper competitive nature of energy providers, resulting in the creation of cost-efficient energy solutions for consumers. The competitive environment also attracts investments in clean energy technologies, making it supportive of the long-term economic viability of energy providers.
- Since deregulated smart grids reduce dependence on fossil fuels and have increased the use of RES, these promote global climate goals, where CO_2 levels are reduced and near zero by 2050. Therefore, a new shift towards such renewable sources forms a means to tackle global warming problems and work to achieve sustainability aspirations.
- In this scenario, Governments and regulatory bodies need to develop overall frameworks that will support the growth of deregulated power markets. These frameworks must encourage investment in renewable energy infrastructure, remove barriers to entry for new market participants, and promote the use of clean energy technologies.

  Following a comprehensive analysis, the recommendations are outlined as follows:
- ***Encourage flexible market mechanisms:*** The regulators need to adopt dynamic pricing structures, demand response programs, and grid flexibility mechanisms to promote RES and EV integration into the grid.
- ***Invest in smart grid technologies:*** Energy providers and grid operators should focus their investments on advanced smart grid technologies such as highly erudite advanced metering infrastructure, supervisory control and data acquisition systems, and energy storage solutions. These technologies will be very important in improving the reliability and efficiency of deregulated power systems and will benefit consumers and the environment.
- ***Focus on consumer education and engagement:*** Public awareness programs should, therefore, be carried out to educate consumers on the benefits of deregulated power systems. Such programs should stress how consumers can also play an active role in DSM, such as time-of-use pricing and distributed energy generation, allowing them to make smart energy decisions.

The active adoption of deregulated smart power systems offers a clear and promising path toward a sustainable, resilient, and economically viable energy future. Addressing the infrastructure, policy, and technological challenges related to energy transition will help stakeholders unlock the full potential of RES integration, reduce environmental impacts, and enhance long-term energy security. This is an approach that will be very beneficial not only to meet climate goals but also for the continuous development of energy systems satisfying future needs.

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CRediT authorship contribution statement

Cali Umit: Writing – review & editing, Writing – original draft, Investigation, Conceptualization. **Rao K. Dhananjay:** Writing – review & editing, Writing – original draft, Investigation, Conceptualization. **Ustun Taha Selim:** Writing – review & editing, Writing – original draft, Investigation, Conceptualization. **Vedlamudi Bindu:** Writing – review & editing, Writing – original draft, Investigation, Conceptualization. **Das Shreya Shree:** Writing – review & editing, Writing – original draft, Investigation, Conceptualization. **Dawn Subhojit:** Writing – review & editing, Writing – original draft, Investigation, Conceptualization. **Vital MLN:** Writing – review & editing, Writing – original draft, Investigation, Conceptualization.

Declaration of Competing Interest

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

Data availability

No data was used for the research described in the article.

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