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Review article

Review of challenges and key enablers in energy systems towards net zero target: Renewables, storage, buildings, & grid technologies

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A R T I C L E I N F O

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A B S T R A C T

Carbon emissions are increasing due to continued urban developments and the growth of the human population, leading to environmental issues such as global warming. Moving towards the future, projected population growth will cause an increase in energy demand. Without the transition to cleaner energy generation, a high dependency on electricity generation by fossil fuels will emit more harmful gases, worsening the impacts of global warming. Therefore, the energy industry is moving towards cleaner alternatives through renewable energy (RE) technologies. However, in the future power grid, more technological development and implementation of cutting-edge research methods will be required to upsurge the percentage of clean electricity generation to attain net zero. Renewables, energy storage systems (ESS), grid technologies, and building energy management systems (BEMS) are key technologies emerging to aid green electrification in the electricity, industry, commercial and transportation sectors. This review discusses the technical challenges and solutions that contribute towards achieving net-zero energy systems. A systematic review was conducted on research methods related to the optimal planning of renewable energy systems, ESS, power system devices, and BEMS which are research areas that are moving towards being optimally integrated in the future energy system. Based on the review, we propose new gaps to be addressed in the development of energy system modelling tools. These tools should seamlessly integrate methods for energy storage related to voltage support, microgrid dispatch strategies, optimal reactive power flow in electrical networks, and energy management in buildings. This integration will enhance the capability of these tools to incorporate detailed analyses into broader energy balance simulations for large geographical regions. This review paper aims to guide researchers in identifying and addressing specific gaps in future research directions within these research areas, thereby advancing the knowledge base and informing subsequent studies.

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List of abbreviations

AI - Artificial Intelligence
AMI - Advanced Metering Infrastructure
ANN - Artificial Neural Networks
APC - Announced Pledges Case
AR - Augmented Reality
BAS - Building Automation Systems
BESS - Battery Energy Storage Systems
BIPV - Building Integrated Photovoltaics
BEMS - Building Energy Management Systems
BIOT - Building Internet of Things
CNN - Convolutional Neural Network
CCUS - Carbon Capture, Utilisation, and Storage
CEEP - Critical Excess in Electricity Production
CO2 - Carbon Dioxide
COE - Cost of Energy
CSP - Concentrated Solar Power
DOPF - Dynamic Optimal Power Flow
DSTATCOM - Distribution Static Synchronous Compensator
DRL - Deep Reinforcement Learning
ESS - Energy Storage Systems
EV - Electric Vehicle
EU - European Union
FACTS - Flexible AC Transmission Systems
FDD - Fault Detection and Diagnosis
GA - Genetic Algorithm
GCAM - Global Change Analysis Model
GHG - Greenhouse Gas
HVAC - Heating, Ventilation, and Air Conditioning
HVDC - High Voltage Direct Current
HV - High Voltage
H2RES - Highway to Renewable Energy Systems Model
HOMER - Hybrid Optimisation of Multiple Energy Resources
IEA - International Energy Agency
ICT - Information and Communications Technologies
IoT - Internet of Things
LCOE - Levelised Cost of Energy
LEAP - Low Emissions Analysis Platform
LVD - Low Voltage Distribution
MACC - Marginal Abatement Cost Curve
ML - Machine Learning
NEMO - Next Energy Modeling system for Optimisation
NPC - Net Present Cost
NZE - Net-Zero Emissions
PIR - Proximity Infrared
PMU - Phasor Measurement Unit
PI - Proportional-Integral
RE - Renewable Energy
SCADA - Supervisory Control and Data Acquisition
SCOPF - Security-Constrained Optimal Power Flow
SDG - Sustainable Development Goals
STEPS - Stated Policies Scenario
SUC - Stochastic Unit Commitment
SOC - State of Charge
SVC - Static Var Compensator
TCSC - Thyristor Controlled Series Capacitor
THD - Total Harmonic Distortion
TWh - Terawatt-hour
UPFC - Unified Power Flow Controller

UPS - Uninterruptible Power Supply
VPP - Virtual Power Plant
VRE - Variable Renewable Energy
VR - Virtual Reality
VSC - Voltage Source Converter
oemof - Open Energy Modelling Framework

1. Introduction

The energy sector emitted a large fraction of 75 % of global greenhouse gas (GHG) emissions in recent years. Oil, coal, and natural gas provided 30 %, 26 %, and 23 % of the total energy supply respectively in 2020. This demonstrates a large dependency on fossil fuels for electricity generation due to their high-capacity factors. Based on the International Energy Agency's (IEA) Net-Zero Emissions by 2050 Scenario (NZE), approximately 90 % of all electricity will be generated from renewables, as is about 25 % of non-electric energy use in buildings and industry [1]. Hydropower has stood as a top renewable source for decades, but it is mainly the growth of solar and wind energies that will increase significantly based on the NZE scenario. The United Nations (UN) Sustainable Development Goals (SDG7) on affordable and clean energy emphasise global roadmaps to achieve net zero in the future. The roadmap demands subsidies for fossil fuel consumption to be shifted towards energy efficiency and renewable energy technologies. The UN also wants to see 30 million jobs created in the renewable energy sector by 2025, doubling to 60 million jobs by 2030 [2]. Besides achieving net zero energy, net zero also refers to the balance achieved between greenhouse gases emitted and retained from the atmosphere. It is important to mitigate the rise in the emission of these gases as they contribute to the increase in global temperatures and climate change. According to Ref. [1] in the Announced Pledges Case (APC) scenario, if the existing pledges of net zero are achieved, it would reduce global CO2 emissions to 22 Gt in 2050. It is a significant decrease compared to the present policies but it is still distant from attaining net-zero. Fig. 1 illustrates the pattern of global energy-related CO2 emissions in this scenario towards 2050.

The NZE scenario demonstrates the energy sector requirement around the globe to attain net zero emissions by 2050. According to this scenario, these emissions drop by almost 40 % between the years 2020 and 2030 and to the desired target by 2050. Fig. 2 illustrates the net and gross CO2 emissions in this scenario.

In the NZE scenario, wind and solar energy generation race ahead to raise the RE fraction in total energy generation from 29 % to approximately 90 % in 2050. This is accomplished by nuclear power, carbon capture, utilisation, and storage (CCUS), and hydrogen. The electricity generation by selected sources graph is plotted in Fig. 3 based on data obtained from IEA [1]. This graph illustrates the gradual phasing out of fossils and scaling up of renewable energy. From this target, solar and wind energy are projected to increase significantly compared to hydropower and other renewables.

Based on this scenario, electrification and renewables make the most significant contribution towards achieving net zero carbon, but a wide range of technological advancements such as building efficiency, energy supply efficiency, electric vehicles, and industry efficiency contribute towards reducing carbon emissions. With global policies and initiatives to reach net zero in the future, the main challenge that emerges is achieving a net-zero energy system that is 100 % renewable. As wind and solar energy are intermittent [3], there is a complex challenge in combining these variable renewable energy (VRE) resources to match the energy demand from users in crucial time scales for system operators. As the future energy demand is expected to increase due to population growth, the low-capacity factors of VRE generation may not match these demands at every point of time throughout the day. Therefore, the optimal planning of energy sources and energy storage integration plays an important role in demand matching with high fractions of RE generated. Power system technologies play a crucial part in sustaining grid voltage profiles within the stipulated grid code requirements, ensuring the delivery of high-quality power to the load. There will also be a decentralised energy landscape that

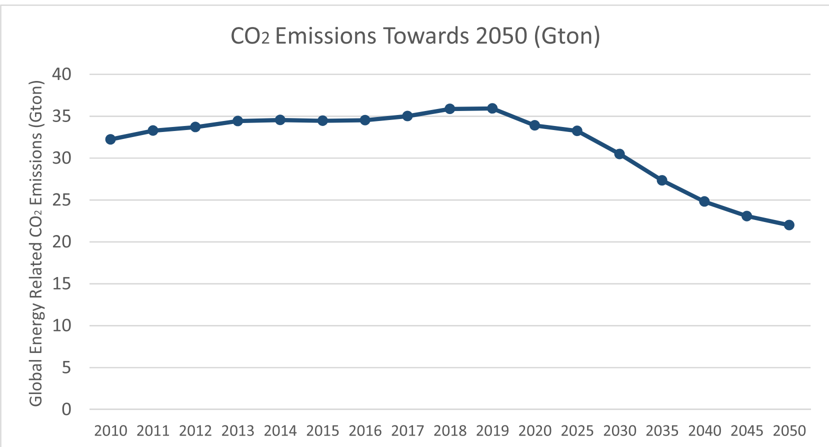

Fig. 1. APC Scenario global energy-related carbon dioxide emissions [1].

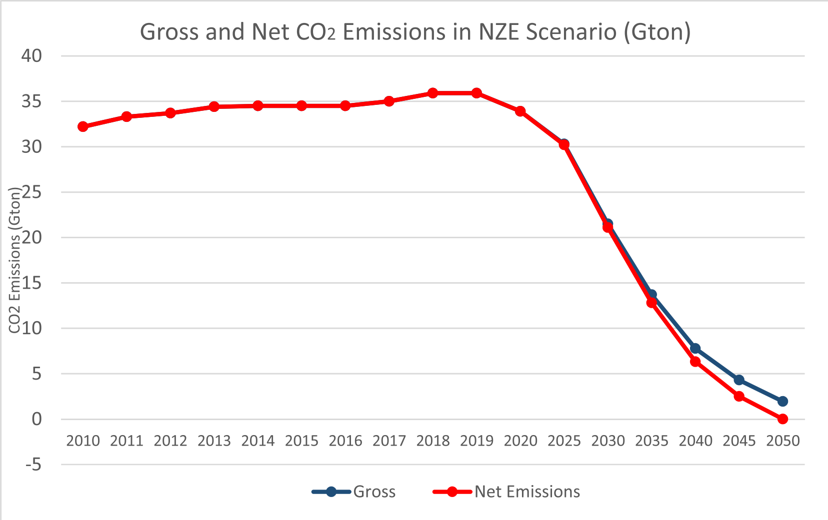

Fig. 2. Gross and net CO2 emissions in NZE 2050 scenario [1].

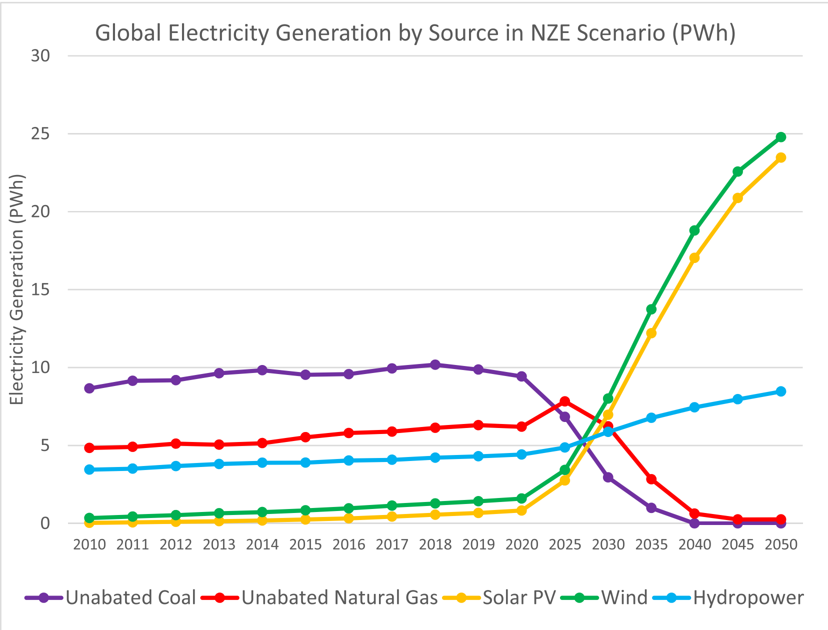

Fig. 3. Global electricity generation of selected sources in the NZE scenario [1].

synchronises thousands of microgrids with higher RE fractions. This allows each consumer to generate and manage their energy effectively. However, it is possible to expand the fraction of energy generated by renewables and to improve energy efficiency through the development and implementation of the various research methods covered in this paper:

- Optimal planning and management of renewable energy.
- Energy storage system optimisation.
- Power management in electrical networks.
- Building energy management systems.

A wide range of research methods has been reviewed from various geographical scales in the management of energy systems. These research findings will assist in energy system planning of the future with the integration of advanced communication, monitoring, and control technologies. These technologies will enhance power system reliability through the smart grid concept. Fig. 4 illustrates the

Fig. 4. Future energy infrastructure with renewables, energy storage, grid technologies and building energy management with their real-life applications.

four areas and their real-life applications to enable higher proportions of renewables and energy management across various sectors.

1.1. Research gaps

This review paper synthesises findings from recent literature to identify future advancements, and provide insights in research directions to enhance coordination and communication in the future energy system infrastructure across various sectors. This paper distinguishes itself by comprehensively investigating four key research areas: renewable energy planning, energy storage, grid technologies, and building energy management, which are key elements contributing towards the development of smart grids and are pivotal for decarbonising the future energy system. By bridging the research gaps and proposing integrated solutions across these four research areas, this study aims to propose synergies among areas for the optimum coordination and utilisation of renewable energy that can enable technological advancements of energy systems towards attaining net zero.

1.2. Contribution

The main contributions of this review paper are:

- Comprehensive and up-to-date literature review on methods that can enable the transitioning of modern power systems towards the grid of the future.

- Discussion of technical challenges in attaining net-zero energy systems that are operated by 100 % renewable energy in the future.
- Discussion of technical solutions that can be developed or implemented to aid national energy systems across all sectors to attain net zero by 2050.
- Review of recent work in the optimal modelling and integration of RE and ESS in energy system models of various geographical scales.
- Review of recent work in optimal reactive power, frequency, and voltage profiles in electrical networks with higher penetrations of VRE by using applicable grid infrastructure components such as FACTS devices.
- Review of recent work in building energy management and automation.
- Recommendations, future gaps, and forthcoming research directions for energy systems towards attaining net zero energy with high renewable fractions across different sectors.

2. Technical challenges of achieving net-zero energy

2.1. Growing electricity demand

The energy demand will grow as the human population is projected to increase by approximately two billion over the next 20 years. Fig. 5 illustrates the rise in global electricity demand from 2015 to 2050 with and without energy efficiency based on the Stated Policies Scenario (STEPS). It can be observed that energy efficiency gains can save 10 PWh of electricity demand in 2050 [4]. As there may be challenges for VRE to match the growing electricity demands, fractions of fossil fuels, investigation of biomass potential, or additional electricity imports may be required to aid the VRE generation in the energy mix. As electricity demand grows, there will be more challenges in achieving 100 % renewable energy generation.

2.2. Existing grid infrastructure

The main constraint of the electrical grid is its ageing infrastructure and inability to handle large amounts of RE penetration. Integration of variable renewable energy (VRE) into the power grid will result in stability issues in buses such as voltage fluctuations, harmonic distortion in currents, flickers, grid fault-ride through, and voltage drop or rise [5]. This will reduce the power quality of the electrical power system in terms of the power delivered to the loads. Advanced control systems, monitoring, real-time data analytics, and support tools are required for grid operations to be optimal with high reliability.

2.3. Energy storage

VRE has a random nature and there could be a mismatch in the balance (supply and demand) of energy during certain periods. Solar irradiance or wind speed could be high during a period which results in high electricity generation. However, it could be so that the electricity demand of a user is low then. In this case, there is more supply than demand and there will be a critical access of electricity produced. However, there can also be periods whereby electricity generated by VRE is low due to low levels of solar irradiance or wind speed but the electricity demand from the user is high. This would result in an insufficient supply of energy to match the demand. Mismatches in energy demand and supply are highly possible to occur without the integration of ESS in the energy system [6].

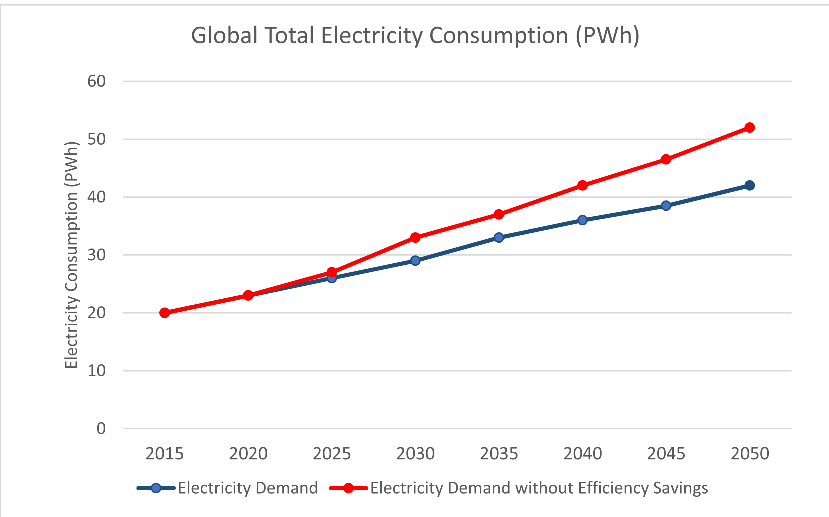

Fig. 5. Global total electricity consumption in the STEPS [4].

2.4. Energy efficiency in buildings

Energy consumption in buildings takes up 30–45 % of energy consumed globally [7]. The consumption of energy in buildings is forecasted to upsurge by more than 40 % in the next 20 years and the largest source of energy in buildings is electricity [8]. There can be an inefficient use of electricity consumption by users in buildings in terms of lighting, air-conditioning, and other electrical appliances. This could be ineffective management of utilising the components by leaving them running while they are not in use. These actions will result in more energy consumed during the day and the maximum demand of a building's energy consumption could be exceeded.

2.5. Decentralisation

In decentralised energy systems, the challenge faced is the coordination and optimisation of storage units and distributed generators. These systems will require grid management techniques and more robust control and communication systems. The optimal synchronisation and balance of demand and supply is also a key challenge in decentralised systems [9]. When a decentralised energy system is integrated with the main electrical grid, problems like voltage regulation and bidirectional power flow can occur.

2.6. Carbon capture, utilisation and storage (CCUS)

CCUS technology plays a significant role in capturing CO2 from industrial power plants, storing it underground, or using it for other operations such as enhanced oil recovery or carbon mineralisation [10]. Scalability and transportation infrastructure are some of the main challenges preventing this technology from being utilised to its full potential. Expansion of infrastructures such as storage facilities and new pipelines for capturing, compressing, and transporting CO2 at a large scale must be carried out.

2.7. Digitalisation

Complex challenges will be faced in digitalising the electrical grid as there will be many devices and software from different vendors [11]. The integration, communication, and interoperability between these products will be sophisticated to synchronise. The effective management and analysis of the large amount of data generated from these various technologies is also another challenge. Deploying these technologies effectively in the energy sector encounters numerous hurdles such as substantial initial expenses, interoperability challenges, data privacy and security, and the necessity for a competent workforce. Overcoming these obstacles necessitates stakeholders collaborating, establishing standards and regulations, and making focused investments in research and development. Advanced analytic capabilities and data management are required for data processing to make desired decisions.

3. Technical solutions in energy systems of the future

3.1. Energy storage

ESS can provide flexible options for supplying energy and many advantages for RE integration into the grid. Energy storage can store peaks in RE generation and use them during periods of peak demand when they are not in alignment. By providing a buffer, the variability in RE generation can be reduced. ESS can also aid in instant peak demand response without the need for increased generation which minimises stress on the equipment of the electrical grid. In addition, it can reduce or even remove the power fees correlated to peak loads generated in short timescales. Moreover, this technology can provide the infrastructure required for volatile EV charging. This technology is defined as the mechanism to store energy using electrical energy to other forms and deliver it back when demand is required by conversion back to electrical energy. Energy storage can be classified into electrical, mechanical, electrochemical, and thermal energy storage. Table 1 shows examples of technology used for each category of ESS.

For the integration of VRE, battery energy storage systems (BESS) are more favourable due to their fast response time, power

Table 1
Types of ESS technologies [12].

Mechanical	Thermal	Electrochemical	Electrical	Hydrogen
- Pumped Hydro Storage - Liquid Air Energy Storage - Flywheels - Compressed Air Energy Storage	- Sensible Molten Salt - Phase Change Materials - Latent Heat	- Lithium Ion - Sodium Ion - Nickel Electrode - Lead Acid - Zinc Bromide - Sodium Sulphur - Nickel Cadmium - Redox Flow - Solid-State - Sodium Sulphur - Polysufide Bromide	- Capacitors - Supercapacitors - Superconductive Magnetic Energy Storage - Hybrid Supercapacitors	- Power-to-Gas - Fuel Cells

density, energy density, efficiency, scalability, and modularity. A typical BESS system consists of batteries, an inverter, a transformer, a switchgear, a control system, a battery management system, and protection. Table 2 shows the technical specifications of various BESS technologies.

Energy storage plays a crucial role throughout the energy supply chain, encompassing generation, transmission, distribution, and consumption. It offers advantages to transmission and distribution utilities by delaying the necessity for additional energy generation and enhancing their capacity. Additionally, effective energy management is facilitated, potentially reducing reliance on fossil fuels for power generation and thereby curbing pollution. The storage of secondary energy forms like electricity and heat diminishes the reliance on primary energy sources such as fossil fuels for electricity generation [29]. This not only helps in lowering greenhouse gas emissions and addressing global warming but also safeguards against the depletion of fossil fuel reserves. In 2022, the review ESS carried out by Kebede et al. [12] found that lithium-ion batteries were the best option among the electrochemical storage technologies for the RE integration into the grid. This is due to the higher energy and power density, lower environmental impact, and higher round-trip efficiency of lithium-ion batteries, therefore being a promising option for grid-scale stationary applications, especially in the integration of renewables into the grid. Table 3 specifies the real-life applications of ESS.

ESS supports the advancement of power systems with RE integration, where they can manage load levelling, spinning reserve, frequency and voltage regulation, and peak shaving. These functions enhance power quality and ensure the stability of energy systems [31].

3.2. Microgrid control and distributed generation

A microgrid is a group of interconnected loads and distributed energy resources that operate as a single controllable unit concerning the electrical grid. Microgrids can disconnect and connect from the grid to operate either in island mode or grid-connected mode [9]. Distributed generation is the term used when electricity is generated from sources, usually RE sources, in close distance at the point of use instead of generation sources from centralised power plants.

3.3. Building energy management systems (BEMS)

The definition of BEMS can be the combination of methods and strategies needed to improve the efficiency, performance, and utilisation of energy in buildings [32]. These systems will aid in managing the combinations of energy efficiency measures in buildings, storage capacity, and the integration of heating sectors and transportation for cost reduction of energy consumption. The infrastructure of BEMS consists of building automation systems (BASs), building internet-of-things (BIoT), cloud computing, and edge computing. A BAS links different devices within a building, such as the heating, ventilation, and air conditioning (HVAC) systems, lighting, and surveillance systems. This integration boosts building performance in areas like security, energy efficiency, and indoor comfort for occupants [33]. Table 4 lists the components of BAS and its' functions.

The ICT systems in buildings work together to offer information services. Data from BIoT and BAS sensors can be stored and analysed locally by energy devices and BEMSs, or remotely in the cloud. Complex analytics can be conducted in the cloud using virtual resources. This setup allows edge computing units in buildings to work with cloud-based analytics, breaking down complex tasks into manageable parts for efficient processing. BEMS serves as the cognitive hub of a building, managing energy-related functions and effectively regulating energy assets within the structure. Its primary aim is to boost the building's energy efficiency while also aiding in the overall improvement of the smart grid's efficiency [33].

Table 2
Technical specifications of various BESS technologies [12].

Type of Energy Storage Technology	Energy Density (kWh/m3)	Power Density (kW/m3)	Power (MW)	Discharge Time (ms to hr)	Response Time (ms to hr)
Lithium Ion	170-300 [13]	1000-5000 [14]	0-100 [15]	min-hr [15]	20 ms [15]
Nickel Cadmium	60-150 [14,15]	150-300 [15]	0-40 [14,15]	sec-hr [16]	20 ms [15]
Lead Acid	25-100 [17]	10-700 [15]	0-40 [15]	sec-hr [14,15]	5–10 ms [15]
Natrium Sulphide	180-280 [17]	150-300 [15]	0.05–34 [15]	1–24 h [15,18]	sec-min [15]
Sodium nickel chloride	181 [19]	257 [19]	0-3 [20]	sec-hr [20]	less than sec [22]
Vanadium redox flow battery	16-33 [21]	0.5–2 [22]	0.3–3 [21]	sec-10 h [21]	sec [21]
Supercapacitor energy storage	2.5–15 [20]	1000-5000 [20]	0–0.3 [14,21]	ms-hr [15]	8 ms [15]
Superconductive magnetic energy storage	0.2–2.5 [20]	1000-4000 [20]	10 [23]	1 min [23]	less than 10 ms [23]
Sensible thermal energy storage	80-120 [14]	–	0.001–10 [24]	less than 10 min [23]	days-months [24]
Thermochemical storage	80- 250 [25,26]	–	0.01–1 [24]	hours-days [27]	Less than 10 min [23]
Compressed air energy storage	3-6 [20,21]	0.5–2 [21]	5-300 [21,21]	Less than 20 h [23]	Less than 15 min [23, 15]
Pumped hydro storage	0.5–1.5 [20,21]	0.5–1.5 [28]	10-5000 [15,20, 21]	6–24 h [23]	sec-min [15,23]
Flywheel energy storage	20-80 [16,20]	1000-2000 [16,20]	0–0.25 [20,21]	less than 1 h [23]	less than 10 ms [23]
Latent-phase change material	150-250 [14]	–	0.001–1 [24]	hours-days [24]	less than 10 min [23]

Table 3
Real-life applications of energy storage [30].

Application	Technical Specification
Intermittent Balancing	Different types of electrical ESS can be used to intermittently balance electricity supply, addressing variations that occur over different time scales, ranging from seasonal changes spanning months, weeks, or days, to momentary adjustments lasting seconds to minutes. The efficiency of these ESS is crucial, especially in scenarios like load following, voltage support, and frequency regulation, where rapid response times are essential.
Load Levelling	It includes storing electricity when the system experiences low demand and releasing it during times of high demand. In peak demand periods, the ESS provides power, thereby easing the strain on the distribution grid and reducing the need for costly peak-power plants. This RE time shifting application is useful for reducing the congestion in transmission and distribution systems.
Peak Shaving	Peak shaving differs from load leveling as it aims to diminish peak demand, primarily to enhance operational cost efficiency. Typically owned by electricity consumers rather than utilities, peak shaving installations aim to evade demand charges and the need for additional capacity to manage highly variable loads. With this application, consumers can lower their utility expenses by minimising charges related to peak demand, while utilities can decrease operational costs associated with meeting peak demand.
Arbitrage	This encompasses utilising electrical storage technologies to store inexpensive electricity during times of low demand and then selling it during times of higher prices. Such storage necessitates technologies capable of achieving prolonged storage durations (ranging from hours to days) while maintaining high round-trip efficiency.
Peak Reduction and Demand Shifting	This encompasses energy demand shifting for supply matching. This can be enabled by altering the time at which some happenings occur such as space heating to decrease the peak demand.
Capacity Firming/Ramp Rate Control	The intermittent and variable power generated from VRE can be sustained at a committed level for a period. The ESS controls the ramp rate and smooths the output for the elimination of power swings and rapid voltage on the grid. This enables improves grid reliability to compliance with grid code.
Frequency Regulation	The ESS responds to changes in grid frequency by charging or discharging accordingly. This method, known as fast frequency response, is highly appealing because of its fast response time and environmentally friendly operation. This increases the grid reliability and the requirement for more generators.
Power Quality	ESS equipped with reactive power capabilities can offer support for voltage and frequency, rapidly responding to voltage control signals as required. This ensures high power quality delivered to loads under electrical grid instabilities.
Black Start	This happens in situations where the power system experiences a failure, ancillary mechanisms fail, and supply resources need to be resumed without drawing power from the electrical grid. Such scenarios demand an electrical energy storage technology that can respond rapidly and operate without the need for energy-intensive auxiliary equipment.
Spinning Reserve	ESS can react in milliseconds, ensuring continuous power supply while facilitating the startup of backup generators. This capability allows generators to operate efficiently at their optimal output levels, eliminating the necessity of maintaining idle capacity for spinning reserves. This removes the requirement for standby generators to operate idly. ESS are kept charged to a level that ensures they can effectively serve as spinning reserves and respond promptly in case of power outages. This lessens the requirement for generation sources to be ready to operate as it functions as a back-up source of power.
Renewable Energy Penetration	With the growing integration of VRE, energy storage is important for adjusting and optimising the RE output to counteract the seasonal and rapid fluctuations in energy supply resulting from their intermittency. Key characteristics required for such electrical ESS include the efficiency and duration of storage.
Mobile Application	This pertains to standalone ESS where the technology can be conveniently relocated from one site to another site, often observed in off-grid applications. Electric vehicles (EVs) utilising stored energy in hydrogen fuel cells and batteries are examples of mobile applications.

Table 4
Components of BAS and functions [33].

Component	Function
Building Management Systems (BMS)	They perform control decisions regarding building operations using data from sensors and predefined operational preferences.
Actuators	A component to perform operations (Moving sunshades under specific sunlight conditions, activating light when user occupancy level is high).
Sensors	Devices that monitor real-time conditions of a building (noise, temperature, lux level, humidity, CO2 levels, occupancy, pressure, power consumption, weather conditions, air quality, etc) and transfer this data to BMS.
Communication Protocols	Framework for BMS can interact and communicate with other devices.
User Interfaces	Digital portals that allow the building occupants to interact with the BAS. Users can monitor the condition of the building, change settings, and send control commands.

3.4. Grid infrastructure

The power grid's reliability in terms of its power quality delivered to the load is an important factor in the energy transition. Flexible AC transmission systems (FACTS) and High-voltage direct current (HVDC) are significant technologies to maintain grid stability with high penetrations of VRE. As RE sources are often located in remote areas that have high energy demand, HVDC enables large amounts of energy to be transmitted over long distances. Reactive power compensation devices are designed to improve the control and stability of AC power grids. These devices aid in curbing stability issues by improving electrical networks' reactive power flow and voltage. This reduces the risk of power disruptions and blackouts, thus improving grid reliability [34]. FACTS devices can curb power quality problems like overvoltage, undervoltage, harmonics, voltage flickers, voltage sags, voltage swells, transients, voltage unbalance, and frequency deviation [35]. Table 5 shows the types of FACTS devices and their functions to improve power

Table 5
Reactive Power Control Devices [35].

Type of FACTS Device	Applications
Static Var Compensator (SVC)	- Improving under-voltage problems. - Dynamic control of reactive power. - Oscillation attenuation in power.
Static Synchronous Compensator (STATCOM)	- Quickly deliver reactive and real power to the system, which improves the damping and voltage. - Voltage and flicker control. - Transient stability in power grids. - Mitigates reactive power imbalances. - Important for grids with VRE.
Thyristor Controlled Series Reactor (TCSR)	- Maintains voltage control. - Smooth inductive reactance varies.
Thyristor Switched Series Capacitor (TSSC)	- Effective in improving power system dynamic behaviour and control of power flow. - Lessen the line reactance during balanced and steady operation. - Minimising collapse in voltage. - Dampening dynamic oscillations.
Thyristor Controlled Series Compensator (TCSC)	- Providing controlled series capacitive reactance. - Improving power transfer capacity and angle/voltage stability of power systems dynamically. - Improving steady-state voltage profile. - Reducing harmonic distortion. - Eliminating power oscillations. - Moderating sub-synchronous resonance. - Enables greater VRE penetration by smoothing power transfers from VRE sources.
Static Synchronous Series Compensator (SSSC)	- Controlling power flow. - Expanding capacity for loading and power transmission. - Inserts compensating voltage in series with the power system transmission line. - Uses controllers for reactive power adjustment. - Reducing voltage fluctuations and oscillations. - Mitigates voltage swells or sags caused by intermittency of VRE.
Unified Power Flow Controller (UPFC)	- Controlling phase angle, voltage, and impedance in transmission lines simultaneously. - Increasing reactive and real control power flow. - Improving transient stability. - Improving sub-synchronous resonance damping. - Regulating the steady state or dynamic performance. - Maintaining voltage stability. - Enables large-scale RE integration by managing the multi-directional flow of power.

quality issues when VRE is integrated into the electrical grid.

3.5. Smart grids

The smart grid will have more capabilities than the traditional grid such that it will be automated to provide control over electricity distribution, transmission, and generation. There will be an incorporation of sensing technologies, data processing, two-way communications, and distributed computing in the smart grid. This intelligent infrastructure will accommodate EVs and have communication capabilities to notify the utility when power outages occur [36]. The smart meters will allow bidirectional communication between consumers and utilities, real-time monitoring of energy consumption, and improved billing accuracy based on the actual electricity consumption. The data from these intelligent digital technologies can be utilised for more efficient grid planning, load forecasting models, predictive maintenance, fault detection, demand response programs, and grid optimisation. Automated fault location, isolation, and service restoration (FLISR) systems can efficiently identify faults and isolate the affected sections thereby

Table 6
Comparison between the traditional grid and the smart grid [37].

Aspect	Traditional Grid	Smart Grid
Technological	Operate by electromechanical power which results in limited communication and internal regulation.	Operate with digital technological devices to enable communication and autonomy
Maintenance and Power Restoration	Requires physical travel to breakdown locations for repair and maintenance to minimise power outage period.	Operates with sensors to detect and repair irregularities.
Energy Control Method	Less control over the supplied energy	Better control over the distribution of electricity.
Desire of Consumers	Does not allow consumers to select how they obtain electricity.	Provides consumers with admission to a variety of sources.
Distribution System	Unidirectional	Bi-directional
Monitoring of Power Plants	Manual monitoring is used for the distribution of energy.	Cutting-edge technological devices self-monitor to reduce outages in power.
Integration of Sensors	There is a restricted number of sensors deployed, which makes the detection of a fault more difficult.	The installation of multiple sensors along the line can be carried out, which aids in the detection of faults.

improving grid reliability. Demand response programs also enable consumers to moderate the consumption of electricity in their homes during peak periods in response to financial incentives. Table 6 compares the capabilities of the smart grid with the conventional grid.

The smart grid network holds immense potential due to the increasing complexity and overloading of the power grid infrastructure [38]. Ageing infrastructure struggles to meet current energy demands, particularly during peak load hours when demand often exceeds supply, resulting in concerning power cuts [39]. Smart grid technology improves the automation of distribution networks, crucial for maintaining the supply-demand balance [40]. This capability of smart grids facilitates load shedding during peak time intervals, promoting efficiency in the electrical network. Therefore, smart grid technology represents an advancement tailored to meet global energy demands efficiently and economically [41]. The smart grid utilises Information and Communications Technologies (ICT) for its operation, monitoring, and control. ICT empowers energy companies to manage power demand effectively, ensuring dependable and efficient delivery of electricity at lower operational expenses [42]. This grid demonstrates intelligence through the implementation of protective systems at central/grid control, grid computing, comprehensive diagnostics for transmission equipment, and self-healing capabilities in electrical networks using distributed computer agents. These technologies are facilitated by Supervisory Control and Data Acquisition (SCADA) systems, specialised for remote monitoring, control, and management of equipment and critical processes [43]. SCADA systems gather data from instruments and field sensors, process it, and enable operators to make informed choices, initiate controls, and respond to faults in real time.

Smart meters are a distinctive feature of the smart grid, facilitating advanced metering infrastructure (AMI) that enhances data collection efficiency. Unlike traditional meters that record data hourly or monthly, smart meters gather data every minute. For more precise monitoring of grid parameters such as current and voltage phasors at shorter intervals, phasor measurement units (PMUs) are employed. Research into PMU integration within smart grids has significantly advanced security, estimation, and control [44]. AMI integration brings numerous benefits to smart grid technology as it enhances the implementation of demand response programs by enabling real-time monitoring of energy consumption. Demand response involves incentivising consumers to reduce their energy usage during peak periods, helping to manage grid resources effectively and prevent power outages. AMI also promotes energy efficiency by supporting distributed generation. Data gathered from RE sources can be analysed to optimise resource management, considering the variability in their generation. AMI integration enhances consumer engagement through remote management and improved customer service. By collecting extensive data, AMI allows customers to monitor and manage their energy consumption efficiently, while enabling utilities to offer guidance on enhancing efficiency. In 2024, a comprehensive review of the challenges, real-life industrial applications and future research trends on smart grids was reviewed by Powell et al. [45].

4. Literature review method

The methodology used in reviewing the literature on technical solutions of energy systems in achieving net zero was conducted via a systematic search for published works using various relevant keywords, such as but not limited to “net zero energy” “100 % renewable energy planning”, “renewable energy scenario analysis”, “energy transition modelling towards 2050” “energy storage integration”, “optimal energy storage dispatch strategies”, “energy efficiency”, “building automation”, “FACTS devices for VRE integration”, “reactive power compensation in electrical grids with renewable penetration”, “optimal reactive power flow” “building energy management”, “smart grid”, and “sector coupling”. The literature search was conducted on various digital libraries such as ScienceDirect, Elsevier, IEEE Xplore, Springer, Google Scholar, Scopus, Web of Science, and more. This search was distinguished by using filters such as but not limited to publication date (within the last 5 years), and document type (peer-reviewed articles, technical reports, and conference proceedings).

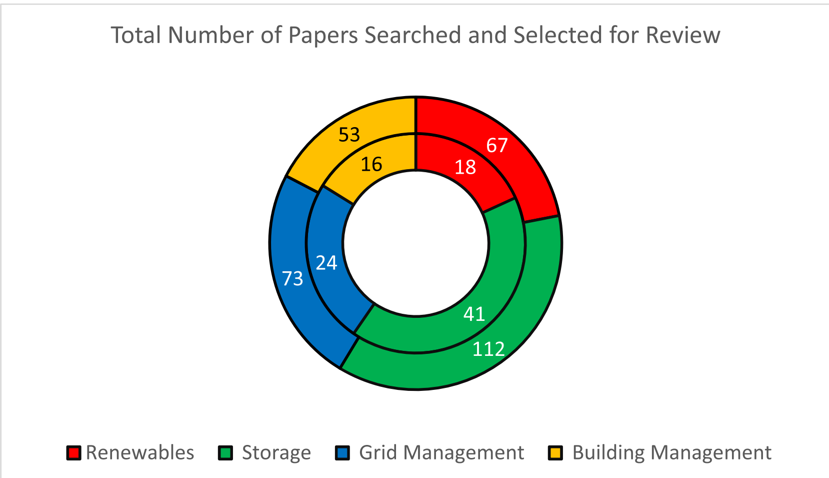

Fig. 6. Total number of papers searched, screened, and selected for review.

Many journal articles and conference proceedings were identified by evaluating their topics, methods, research areas, and novel contributions. The literature search in sections 4.1 to 4.4 was divided into four sections. The first section covered optimal planning and integration of renewable energy sources for large geographical regions. The second section consisted of ESS which was further divided into three subsections: 1) Optimal planning and integration of ESS in the power sector with sector coupling. 2) Power system support with VRE integration. 3) Dispatch strategies, decentralisation, and microgrid applications of ESS. The third section covered the grid technologies for reactive power management in power systems with high VRE integration. The fourth section covered the research methods and applications in BEMS. This review is followed by significant proposals, identification of further gaps for investigation, and future research recommendations in these four key research areas and smart grid technology in sections 5.0 and 6.0.

For section 4.1 on renewable energy planning, 67 papers were searched and screened for evaluation and 18 papers were chosen for review. In section 4.2 on energy storage, a total of 112 papers were covered in the search and 41 papers were selected to be reviewed. In section 4.3 on reactive power management, 24 papers were chosen for review from a total of 73 screened papers. In section 4.4 on building energy management, 16 papers were selected for review from 53 searched papers. In total, 305 searched papers were screened for a selection of 99 papers in these four subsections for review after evaluating the impact factor, citations, theoretical content, literature presented, methodology, technical applications, novelty, and comprehensive findings. Fig. 6 illustrates the literature searching, screening, and selecting of the papers for review under the four research areas.

4.1. Recent work on optimal planning and integration of renewable energy systems

In 2023, Icaza-Alvarez et al. [46] presented a 100 % RE system constructed in accordance with its actual potential and usage of renewables for the Ecuadorian Amazon using EnergyPLAN. A smart RE approach was presented and a convergent method was developed for higher contributions from solar and wind energy. It was concluded that the 2050 energy mix includes 36.47 % hydroelectric power, 33.04 % solar, 29.73 % wind and 0.74 % other technologies. Surpluses in energy can be transferred into cross-border interconnection sites which are Peru and Colombia, thus attaining income levels in the economy to preserve and develop the electricity infrastructure. In 2024, Alabbasi et al. [47] conducted a study of Bahrain's power system. This paper proposed an intelligent decision-making method based on a combination of Artificial Neural Networks (ANN) and the Analytical Hierarchy Process in evaluating future investments in RE for power generation. The outcomes from the proposed model discovered that wind turbines were the most suitable technology with 32.5 % priority, followed by solar PV with 32.3 % and concentrated solar power (CSP) with 16.3 %. Further investigation can address gaps in the advancement of intelligent decision support systems to identify optimum sites for RE technology deployment. This development would necessitate integrating a Geographic Information System (GIS), allowing the precise determination of locations for RE technologies aligned to the sustainability objectives of a country.

Oshiro and Fujimori [48] investigated diverse options for attaining the net-zero target for Japan by the year 2050. This work discovered that demand-side electrification and around 100 Mt per year of CO2 removal implementation, equal to around 10 % of the present nationwide CO2 emissions, were vital across all scenarios of net-zero emissions. Energy demand reduction and upscaling of hydrogen-based alternative fuels can avoid more reliance on CO2 removal. This work emphasised on global trade in the development of net-zero emission scenarios for nations. Rauf et al. [49] proposed a linear programming optimisation technique for the integration of floating solar PV and hydroelectric generators using MATLAB. The energy generated by the integration of 200 MW floating solar PV corresponded to an additional 3.5 % power on a 1450 MW hydropower plant. The generation of floating solar PV met with the day-to-day peak load.

Liao et al. [50] proposed probabilistic modelling of RE in smart grids by stochastic optimisation. The research focused on applying machine learning (ML) algorithms to enhance the reliability and efficiency of RE integration into smart grids. An ML algorithm was proposed for optimal resource allocation and energy generation forecasting followed by an ML-based grid stability enhancement for anomaly detection. Moreover, an autonomous control optimisation for dynamic grid environments was also proposed. With the application of the proposed methods, substantial advancements have been attained in optimising RE forecasting models, improving energy efficiency, and enhancing grid stability.

Priyadharshini et al. [51] proposed a new algorithm to estimate the wind turbine numbers to be worked to meet the hourly peak demands using HOMER and MATLAB. The energy demands were met by the detailed sharing of the solar, wind, and grid energy sources for all 24 h in a day. With the proposed method, the total cost was reduced and it also provided an uninterrupted power supply to consumers. Dominković et al. [52] investigated a technology of biomass hydrogenation, which upsurges the efficiency in the transportation sector and lessens biomass consumption compared to biofuel usage proposed in the integrated RE system using EnergyPLAN. A 100 % RE system in South East Europe has been reached. The developed RE system of South East Europe consumed 702.86 TWh of primary energy which is 50.7 % less than in 2012. The developed system achieved zero carbon emissions with the critical excess in electricity production (CEEP) remaining below 5 %.

Gomes et al. [53] developed an energy system that is economically feasible for Mainland Portugal in 2040 with a higher percentage of renewable energy shares by using the EnergyPLAN technical optimisation algorithm. Based on the findings, RE sources can fully meet the electricity demand in Mainland Portugal for long successive periods in terms of energy balance and thermal power plants could be downscaled from 6.3 GW to 3 GW by 2040. This research demonstrated that an energy mix prominent in wind energy will be most effective in decarbonising the electricity sector in Mainland Portugal. Wang et al. [54] developed energy system models of the power sector from the years 2030–2050 with carbon peaking, power generation, and carbon neutralisation in five different scenarios. Based on the five scenarios of installed capacity to meet the optimised scenario in terms of sustainability, total cost, carbon emission, RE proportion, and total installed capacity, scenario 3 was chosen. Scenario 3 is composed of 15 % of hydro, 14 % of wind, 16 % of solar, 50 % of non-renewable power 50 %, 3 % of nuclear, and 2 % of others.

Quevedo and Moya [55] analysed alternate scenarios for RE expansion in the Dominican Republic using the Open Source Energy Modelling System (OSeMOSYS). The findings suggested a significant role for RE technologies, with projections indicating penetration levels surpassing 40 % in the foreseeable future. Karatayev et al. [56] examined the impacts of adjusting the proportions of wind, biomass, and solar PV within the energy scenarios for the Slovak Republic leading up to 2050. The study revealed that in 2020, the Slovak Republic's primary energy consumption was 177.1 TWh/year, with electricity consumption at 28.6 TWh/year. However, future projections indicate a continual increase in electricity demand, projected to reach 40.84 TWh by 2050. Consequently, it is anticipated that supplementary RE capacities from biomass, wind, and solar will need to be integrated, totalling 3.0, 3.6, and 1.8 GW respectively by 2050.

In 2024, Akpahou et al. [57] analysed energy generation mix strategies with increasing RE shares for a case study in Benin towards 2050. An energy mix of hydropower, solar, wind, concentrated solar power (CSP), and natural gas was used to build three scenarios. The results showed that a combination of 600 MW hydropower, 200 MW wind, 125 MW solar PV, 60 MW concentrated solar power (CSP), and 563 MW natural gas would attain 50 % of RE by 2050. This 50 % RE scenario resulted in no excess electricity generated and was projected to decrease CO2 emissions by 50 %. Icaza et al. [58] evaluated and proposed a feasible 100 % RE scenario by 2050 in Heritage cities. The results found for 2050 in the Galapagos energy mix consisted of 41.66 % of solar, 33.33 % of wind, 8.33 % of biomass, 5.55 % of small hydro, 5.55 % of geothermal, and 5.55 % of other sources. In the case of Cuenca, hydropower would be sustained at 35.34 %, wind power would grow to 25.3 %, geothermal at 6.42 %, biomass at 2 %, solar at 28.91 %, and other sources at 2 %. The optimum 100 % RE Mix was determined and suitable locations for solar and wind generation plants were identified through geographical analysis of energy potentials and land use. 38 sites in Galapagos and 14 sites in Cuenca were proposed as the most viable locations for these plants. The findings indicated the feasibility of utilising 100 % RE systems in Heritage locations. It also demonstrated that transitioning the proposed locations to sustainable energy is both feasible and achievable.

OTSUKI et al. [59] developed a global energy system model using NE_Global-R dynamic linear programming model with hourly temporal resolution for hydrogen and electricity balances, aiming to evaluate the role of VRE on a carbon-neutral globe. The share of VRE was analysed in a net zero energy system and it was discovered that a 100 % RE system will pose economic challenges. The outcomes of optimisation indicate that integrating different technical solutions tailored to local energy situations is crucial for efficiently reducing CO2 emissions globally. Li et al. [60] proposed a long-term planning model with concentrated solar power (CSP) and enhanced flexibility limits of energy systems with high RE integration to meet the heat and electricity demands. With the proposed planning model applied to a typical "Clean Heating" region in China, it demonstrated that optimal distribution by CSP integration can decrease the maximum-minimum depth of coal units, thereby minimising carbon emissions and RE curtailment by 19.05 % and 37.64 % respectively.

Danieli et al. [61] built a multi-regional model to discover the most suitable energy transition pathway towards a 100 % RE system in an Italian case study. The innovation of this study is the optimal planning for decarbonising energy demand sectors, aiming to minimise costs, both globally and regionally. The outcomes of the optimisation simulations demonstrated that prioritising cost minimisation, the transition of energy should prioritise the decarbonisation of four specific energy demand sectors in the sequence of: low-temperature heat, electricity, high-temperature heat, followed by transportation. In 2023, Bamisile et al. [62] proposed a novel study in the techno-economic analysis of 100 % RE electrification in Chad, a country with limited access to electricity around the globe. The developed energy system models were simulated for 2030, 2040, and 2050 concerning dissimilar global decarbonisation targets. Based on the results obtained, it was found that biomass power plant utilisation was the one scenario that did not result in CEEP in the power system. Additionally, these scenarios demand the lowest power capacities compared to other scenarios in this study: 270 MW by 2030, 650 MW by 2040, and 1600 MW by 2050. Wind and solar energy were promising options due to their mature technology and widespread use in various countries, but they will need integration with pumped hydro storage. Further gaps can be investigated in the policies and economics that will improve the realisation of the solutions presented.

In 2024, Flores et al. [63] assessed the impacts of integrating variable RE in long-term decarbonisation strategies. The research denotes the first attempt at the evaluation of how hourly resolution affects the assessment model results, specifically the Global Change Analysis Model (GCAM). A novel soft-linking method was proposed between GCAM and the H2RES to achieve this and the approach was conducted using Chile's Nationally Determined Contributions in the power sector. The findings demonstrated that it was likely to use the capacity attained from GCAM and implement it in hourly timeframes. Feasible RE integration was attained with high CEEP levels approaching 20 % by 2050. The different modelling methods of RE in GCAM and H2RES resulted in higher electricity generation levels in H2RES as compared to GCAM. The findings indicated that there was room for more effective power sector integration with buildings, industry, and transport sectors by improving their levels of electrification, which ultimately results in a more efficient energy system that will lower CEEP levels. From this research, the gap in addressing the specific capacity factors of technologies in various regions of a country as compared to using the assumed average capacity factors of technologies for one region could be further investigated.

4.2. Recent work on energy storage systems (ESS)

4.2.1. Optimum planning and integration of ESS in the power sector with sector coupling

In 2022, Adun et al. [64] developed a 100 % RE generation model using EnergyPLAN. Different combinations of VRE sources were analysed to meet the anticipated electricity demand of Cyprus in 2050. The most viable option for a 100 % RE generation model was the solar PV, wind, and storage. Based on the findings, this system had installed capacities of 7500 MW of wind, 4000 MW of solar, and 30 GWh of storage capacity. Okonkwo et al. [65] analysed the limitations and potential of integrating diverse RE resources and energy storage systems in Qatar's power sector. The results demonstrated that increasing the RE share in electricity generation is attainable by as much as 80 %. The optimal cases for the deployment of solar, wind, and concentrated solar power (CSP) with storage technologies presented a 23.4 %, 28.3 %, and 38.2 % share of electricity produced, respectively. Pump hydro and electro-fuel storage were the optimum alternatives to improve the storage capacities of the RE sources.

Jannesar et al. [66] proposed a Genetic Algorithm (GA) to optimise the performance and cost by the optimal sizing, siting, and scheduling of BESS using MATLAB and DIgSILENT. 93 % of solar PV penetration was achieved after the optimal siting and placement, and daily charge/discharge time of BESS were implemented. The optimised solution demonstrated that energy and overvoltage losses were reduced, reverse power flow was prevented, environmental emission was decreased and economic profit was maximised. Chen and Song [67] conducted the techno-economic performance of the different batteries in active distribution networks. Batteries were simulated in detailed configurations with wind generation and grid-connected solar. In accordance with the economic and technical characteristics of the energy characteristics, optimal combinations were explored. Based on the results, lithium-ion batteries performed the best in terms of CEEP absorption, emission reduction, and energy savings while the sodium sulphur batteries were the most cost-competitive.

Herc et al. [68] developed an optimised smart energy system to achieve CEEP reduction, CO2 reduction, total annual cost minimisation, electricity import minimisation, and maximisation of renewable share using EnergyPLAN and EPLANopt for a Croatian energy system. The most effective technologies were the smart charge, vehicle-to-grid (V2G), pumped hydro storage, and energy efficiency as they demonstrated a positive correlation with the total annual cost reduction. The implementation of smart charge and V2G reached a share of above 70 % for the share of RE above 90 %. Gaps can be further investigated on technologies such as hydrogen and synthetic fuels in households. Wang et al. [69] developed a hybrid RE decarbonisation model by determining the installed capacity and energy supply mix based on future energy demand in Sichuan Province, China. The clean electricity importing model from neighbouring provinces had the best flexibility and cost-effectiveness. The energy storage model effectively improved the absorption of wind and power on-site as well as the economic and technical transmission efficiency. All 2030 optimisation models achieved zero carbon emissions and clean energy substitution compared to the policy models. Asghar et al. [70] modelled an optimised configuration of a standalone hybrid power generating system for rural sites in an area of Northern India using HOMER Pro. The optimal combination of the hybrid system was found to consist of a 13 kW diesel generator, a 16 kW solar PV, a 50 kWh lead-acid battery, a 9 kW inverter, and a 4 kW wind turbine which resulted in a 98.4 % renewable fraction.

Prina et al. [71] introduced an innovative modelling approach for optimising energy system planning, demonstrated through a case study in Italy. Scenario outcomes for 2050 were projected using EnergyPLAN. Results showcased significant reductions in CO2 emissions, and improvements in energy source diversity, alongside cost minimisation within the system. This research demonstrated the effectiveness of discovering near-optimal scenario outcomes and the optimum planning of RE systems at a national level using additional indicators. The gap in applying these methods for energy system planning in other regions or countries to support energy transition towards more green energy and low carbon systems can be investigated further. In 2023, Prina et al. [72] conducted an optimal energy mix analysis of 7 European Union (EU) countries: Italy, Spain, Germany, Sweden, France, Poland, and Netherlands for years 2030 and 2050. EPLANopt which couples the deterministic simulation model EnergyPLAN with a Multi-Objective Evolutionary Algorithm (MOEA) was applied to conduct this analysis. From the findings, decarbonisation enhanced security and the energy system resilience was improved by RE and electrification. The increase in electrification in transport and heating boosts security.

Handayani et al. [73] analysed the integration of 100 % RE generation for Laos, Cambodia, and Myanmar by using the Low Emissions Analysis Platform (LEAP) with the Next Energy Modeling system for Optimisation (NEMO). The results indicated that these nations can fully integrate RE into their electrical grids by implementing non-hydro renewable sources and harnessing hydropower potential. It is anticipated that ESS will be important for VRE balancing, with 16.1 GW total storage capacity by 2050. Cosgrove et al. [74] explored the physics of RE systems and their impact on the design and operation of large-scale storage technologies for grids, considering both weather patterns and energy system dynamics for a UK energy system model. This study aimed to comprehend the storage requirements necessary to consistently meet demand across a broad spectrum of weather conditions and system setups in the energy system of the UK in 2050. The results indicated that for a 70 % RE share, 30 % overcapacity, and 80%-to-20 % wind-solar PV mix, the minimum physical volume of energy storage for the UK is approximately 70 TWh, which can deliver 27 days of mean demand. This study concluded that zero-carbon energy systems that depend on a high supply of wind and solar will have big requirements in ESS capacities. These requirements can be reduced by the choice of wind-solar PV mix, the use of some baseload supply, and the amount of overcapacity.

Yu et al. [75] built a 100 % RE generation base with a solar PV, CSP, wind, and energy storage combination for a Qinghai Province, China case study. This study proposed a flexible operation model in accordance to the interval theory. A coordinated operation strategy of a 100 % RE base was then formulated by the specified energy technologies. For this coordinated operation strategy in Qinghai, the LCOE with an optimum solar, CSP, wind, and energy storage grouping was 20.3 % less than the case with no CSP station. Misconel [76] computed a step-wise marginal CO2 abatement cost curves (MACC) for determining the most economically efficient sequence of investments in decarbonisation measures for the sector-coupled energy system in Germany spanning from years 2030–2045. Findings indicated that the optimal decarbonisation strategy involved upscaling solar and wind energy capacities and enhancing demand-side flexibility through the integration of battery EVs, power-to-gas, and power-to-heat technologies. The results underscored the significant interaction among decarbonisation measures and highlighted that incorporating surplus electricity via sector coupling could markedly alleviate the curtailment issues. Zhao et al. [77] introduced a method for optimal configuration of ESS to relieve transmission congestion in areas with abundant RE. This research used a Monte Carlo approach to assess transmission congestion and determine suitable locations for ESS installation. The optimal configuration technique used stochastic programming to mitigate congestion in transmission. Numerical experiments were conducted on a practical 129-bus system and a modified IEEE-RTS 24-bus system. Numerical findings indicated that ESS enhanced power system flexibility and increased RE utilisation. Laugs et al. [78] utilised a simulation to mimic the operation of a local residential power grid in the Netherlands powered solely by decentralised wind energy and solar PV sources. The simulation incorporated various setups of hydrogen and batteries as storage solutions to explore how they operated together. The findings suggested that integrating battery and hydrogen storage into the grid enhanced its resilience and adaptability compared to relying solely on one of these technologies.

Cruz et al. [79] conducted a thorough analysis of the dynamics between the local markets and distribution grid on Brava Island (Cape Verde) to enable optimum power generation from a hybrid plant consisting of wind turbines, floating solar modules, a diesel generator, and a hydro-storage subsystem. Two algorithms, Artificial Bee Colony, and Particle Swarm Optimisation (PSO), were utilised to ascertain the optimal plant component size. The outcomes of the proposed method indicated that RE penetration on the island could reach up to 48.3 %. Moreover, the study demonstrated the economic viability, with a small LCOE of approximately $0.23/kWh over 20 years. Díaz-González et al. [80] proposed a two-level controller for managing a hybrid ESS solution (supercapacitor and lead-acid battery) for solar PV integration into distribution grids. The controller's higher level relies on mathematical optimisation to resolve the optimal energy storage scheduling for peak shaving. The results indicated that storage was effective in meeting the grid overvoltage alleviation and solar PV grid code. The hybridisation of ESS was effective for the integration of solar into the electrical grid.

Copp et al. [81] proposed a method that outlined an optimisation challenge aiming to assess the necessary RE generation and storage to meet 100 % of a utility's electricity needs on an hourly basis across several years, while keeping costs low. This approach was explored in a case study of New Mexico, United States. With the analysis of historical weather and demand data over multiple years, findings indicated that RE generation was significantly greater than average demand, resulting in surplus energy, thus prompting consideration for a regional energy trading strategy. In 2023, Patel et al. [82] conducted a stochastic optimisation and monetary analysis of combined hydrogen ESS and high-temperature superconducting magnets for smart grid applications. A novel energy management algorithm was proposed to maximise the operational time of a group of energy storage devices in meeting unpredictable power demands. It was found that the algorithm enhanced the reliability and fleet lifespan by up to 9 % with dependency on the connected capacity. Groppi et al. [83] applied the EPLANopt model in a Favignana Island case study to analyse the optimal configuration of Smart Energy Systems on the island towards 2050 through multi-objective analysis. The results indicated that sector coupling solutions would result in significant impacts in economic savings and carbon reduction. This is attained by managing non-dispatchable RE generation and keeping CEEP within feasible limits. The findings suggested that Favignana should have indeed focused on solar energy, and widespread adoption of vehicle-to-grid (V2G) strategies would have greatly reduced the necessity for electricity storage.

4.2.2. Power system support

Fan et al. [84] developed a dynamic optimal power flow (DOPF)-based scheduling framework in MATLAB and MATPOWER for optimisation of the day(s)-ahead operation of a grid-scale BESS. The proposed framework mitigated the predicted curtailment of non-firm wind generation and smoothed out the system demand provided by the conventional generating units on a 33 kV network. Ismail and Mishra [85] proposed a control algorithm that combines the operation of Uninterrupted Power Supply (UPS) and DSTATCOM with a single Voltage Source Converter (VSC) and a battery-supercapacitor ESS. The proposed system mitigated source voltage swell, sag, reactive power, interruption, unbalance, and load current harmonics. The supercapacitor control scheme increases the battery life cycle and eliminates load angle ripples. Bangash et al. [86] proposed an enhanced ESS charging and discharging coordination control using MATLAB/Simulink (Simscape Power Systems Library). Proper charging and discharging mechanisms of the BESS improved the transient stability of the network. Fast switching of BESS was helpful during transient fault disturbance to retain system stability when any of the renewable DG is tripped. Wang et al. [87] proposed a double-layer nested model of distributed energy storage (DES) planning to resolve voltage profile problems resulted from the mismatch between distributed solar PV output and residential load. The evaluation of voltage included three-phase voltage deviation, fluctuation, and unbalance. The outer optimisation model was established for DES sizing and siting considering the cost-performance ratio of voltage profile enhancement. The outcomes from simulations conducted on the modified IEEE 33-bus distribution network illustrated an improvement in voltage safety margins and a consequent reduction in the costs associated with voltage management. Ma et al. [88] developed a state-of-charge (SOC) balancing control strategy for storage units with a function of voltage balance for a bipolar DC microgrid. An evaluation of SOC trends was conducted in response to the micro-sources and power changing of loads. Based on the results obtained, the proposed strategy could quickly realise SOC balancing when the SOC deviation was substantial. The strategy was also feasible in the reduction of bus voltage unbalance. In 2023, Bonilla and Le [89] proposed a multi-functional ESS to support power distribution systems and solar power plants. Six control modes were developed for BESS, specifically, power limiting, current limiting, power factor correction, voltage regulation, load levelling, and simultaneous reactive and active power supply. These control modes were confirmed using three solar power plants and a real utility 2.8 MW (5.6 MWh) BESS that were integrated into an electrical distribution grid. The control systems were implemented by using MATLAB Simulink Stateflow. The results demonstrated that BESS can address critical operational challenges in power distribution grids, including power factor correction, voltage regulation, load balancing, peak load reduction, and congestion alleviation. Through optimal charging schedules, BESS can store surplus RE from intermittent sources, thereby minimising the need to curtail RE. In 2024, Jarosz [90] proposed a novel method of active power voltage regulation by using model reference adaptive control in energy storage. This work offered a practical implementation of active power control using the proposed algorithm, with the consideration of grid parameters for enhanced performance. The algorithm resulted in effectiveness in grid control with active power and successfully determined independent power values for the thirteen nodes in the grid. The proposed method resulted in a substantial impact on stability and voltage regulation, thus enhancing the reliability and overall performance of the whole grid. Further gaps in future studies can be carried out for model adaptive control in the development of more resilient and robust energy systems by leveraging optimisation techniques, AI-based approaches, and advanced control algorithms.

4.2.3. Dispatch strategy, decentralisation, and microgrid applications

In 2023, a robust optimisation approach in accordance to budget uncertainty set was proposed by Zhang et al. [91] to accommodate variations in wind power during dispatch. This enhanced the resilience and efficiency of electrical grid operations against realistic uncertainties. The effectiveness of the proposed strategy (day-ahead dispatch) was verified through comparisons and extensive simulations, providing better support for modern power systems with high wind power penetration. Chaurasia et al. [92] investigated the operational impacts of cycle-charging, load following, combined, and HOMER predictive power dispatch strategies on single resource hybrid systems (solar-distributed generator-battery) and complex multiple resource hybrid systems (Solar PV-wind turbine-distributed generator-battery). The solar-distributed generator-battery under the HOMER predictive strategy significantly reduced the LCOE by 59 % and GHG emissions by 90 % compared to the distributed generator-battery. Uwineza et al. [93] proposed a custom dispatch to optimise the technical and economic parameters of a solar-fuel cell-BESS system using HOMER and MATLAB. From the results, the proposed dispatch achieved cost savings of 4 % compared to the cycle-charging and load-following strategies. Fuel cells contributed around 23.7 % of the total produced electricity in the hybrid ESS, which is more than that of load-following (18.6 %) and cycle charging (18.2 %).

Arevalo et al. [94] developed energy control models for dispatch strategy optimisation of Solar PV-Wind Turbines-Hydro-electric Storage-BESS. An increase in pumped hydraulic storage and solar PV capacity reduced the LCOE. Based on the findings, these islands can attain 100 % RE penetration with the configuration of wind turbines, solar PV, pumping hydroelectric storage system, batteries, and diesel generators (only as backup). The electricity cost of the hybrid system of Baltra-Santa Cruz was reduced from 0.32 to 0.23 $/kWh and the CO2 emissions decreased by 16,000 tons. Citalingam and Go [95] modelled an optimised hybrid ESS dispatch strategy by using supercapacitors. It was found that the load following strategy was more suitable than the cycle-charging strategy from the results of the annual throughput. The proposed system demonstrated an improvement of 30 % in annual throughput under the load following dispatch strategy and the RE fraction increased by 10 % after adding a supercapacitor.

Rashid et al. [96] proposed a genetic algorithm (GA) based custom dispatch strategy to optimise the PV-diesel-BESS system. The custom dispatch had higher technical and economic benefits than the LF and CC strategies. Fodhil et al. [97] proposed a particle swarm optimisation (PSO) algorithm custom dispatch to optimise the solar PV-diesel-BESS system. The LF and CC strategies were more economically costly than the PSO custom dispatch strategy. This custom dispatch strategy demonstrated higher solar PV penetration than the LF and CC strategies. Dalala et al. [98] examined how the increased RE sources in Jordan's national electricity grid affects its operations using PLEXOS software. Various scenarios were tested by incorporating ESS into the grid after accurately determining their technical specifications to address dispatch challenges. Mixed integer programming was utilised to discover the best solution for each scenario. Findings revealed that the high RE penetration altered the optimal functioning of the grid, necessitating different dispatch strategies for effective management.

Ju et al. [99] designed a novel structure of a micro-energy grid with the integration of a CCUS system and hydrogen ESS for full utilisation of RE resources in Henan Province, China. A two-stage optimal dispatch model was developed for resolving uncertainty variables and an entropy-Shapley-based allocation method was proposed for advantages in CO2 emission reduction, energy conservation, and RE consumption among various devices. The proposed method and model demonstrated the utilisation of RE resources in county-level areas, which was better for promoting low-carbon transition of the whole energy infrastructure. Ding et al. [100] proposed a two-stage scheduling model of hybrid ESS that precisely assesses the rescheduling capability. The column-and-constraint generation algorithm and analytical target cascading method were applied. In a case study presented, the proposed model demonstrated improvements in the system's economy by 2.8 % and discovered that the running time impacts the operating cost.

Zamanpour et al. [101] conducted the planning, design, and optimisation of a hybrid energy system for a case study in Iran. The system was comprised of wind turbines, solar PV, a diesel generator, a natural gas generator, and a storage bank. HOMER Pro was used for hybrid system optimisation and to supply an average demand of approximately 820 kWh/day through five dispatch strategies. Based on the findings, the predictive dispatch outperformed the generator order, cycle-charging, load-following, and combined dispatch strategies. The optimal case demonstrated an 84 % RE fraction which improved the local grid reliability and the potential for RE utilisation by the industrial unit. Gaps can be investigated in predictive dispatch development for hybrid RE units using machine learning techniques and advanced long-term forecasting algorithms that utilise primary stochastic data for load, solar irradiance, and wind speed. Álvarez-Arroyo et al. [102] introduced a novel method to handle microgrid uncertainty by utilising ESS as the primary flexible asset. To tackle this issue, a mathematical formulation was developed as a two-stage stochastic programming model, accounting for uncertainties in solar and wind power generation to reduce the operational cost of a microgrid while optimising the maximum capacity of the ESS. The results demonstrated that higher volatility in RE generation resulted in higher operational costs and necessitated a larger storage capacity. Further gaps in can be investigates in the development of more efficient and robust microgrids such as mitigation of RE uncertainty with the inclusion of an ESS in each uncertain technology, EV integration as mobile ESS, and demand-side management.

In 2023, Tang et al. [103] proposed an optimum energy management control strategy in households based on the scheduling of ESSs and EVs. The findings indicated that the operating conditions of the systems can be enhanced to attain the target of reducing household electricity costs and improving solar PV consumption under the proposed control strategy. The efficiency of the developed model was confirmed by the simulation and analysis of a household customer under real-time electricity prices. In 2024, Yadav et al. [104] proposed a hybrid RE source (solar PV, wind, fuel cell) with multiple ESS (hydrogen and BESS). The optimal design and techno-economic analysis for the microgrid system were performed using HOMER and the design objectives were to minimise the net present cost (NPC) and the cost of energy (COE) in the proposed system. The outcomes demonstrated that the (fuel cell, wind turbine, solar PV, electrolyser, hydrogen, BESS, converter) was the optimal microgrid with the lowest COE and NPC. The unmet loads and excess energy were also the lowest for the system. The gaps in this research that could be further investigated may involve minimising or utilising surplus energy for additional types of loads, like thermal loads, and applying multi-objective optimisation to incorporate a broader range of objective functions.

4.3. Recent work on electrical power management systems

Mohamed et al. [105] addressed the OPF problem with the integration of RE sources and FACTS devices by applying the Chaos Game Optimisation (CGO) algorithm. The proposed method was tested on the IEEE-30 bus system. The objective functions considered included minimising emissions, generation costs, voltage deviation, active power loss, and improving voltage profiles. The results demonstrated that the proposed algorithm was more effective than other approaches in resolving optimal power flow issues. Gaps in the incorporation of ESS into the optimal power flow framework to improve the reliability and flexibility of the network can be further investigated. Exploring advanced AI and ML algorithms for the optimal power flow in electrical networks could offer more precise solutions. Loji et al. [106] assessed the effect of upscaling solar power penetration on power system stability with the integration of FACTS devices using DigSILENT™ PowerFactory™. The simulation results demonstrated that the stability of the system depended on the network load status, the penetration level of distributed generation, and the conditions of network faults. With static var systems being used near the load with the combination of a solar PV unit distribution at load buses, resulted in the most effective solution for dynamic stability and voltage of the system. Gaps can be further investigated in the integration of BESS into the system to evaluate the overall loss reduction and stability of the system. Sulaiman and Mustafa [107] proposed an improvised Salp Swarm Algorithm to manage problems in optimal power flow in an adapted IEEE-30 bus system integrated with stochastic solar power. The proposed algorithm is used to optimise control variables like real and reactive power, transformer tap settings, and voltage at generation buses. This optimisation procedure aims to attain minimum power loss, emissions, and costs from generation of power. The results from the simulation demonstrated that the proposed algorithm in this work performed better than all the compared algorithms across all objective functions considered. One of the gaps that can be further studied includes addressing more operational challenges in power systems, like economic dispatch, load forecasting, and unit commitment. In addition, the scalability of the algorithm to be applied to more complex power systems with larger variables can be further investigated.

Tran et al. [108] optimised the placement locations of renewable distributed generators, shunt capacitor banks, and soft open point devices in the IEEE 69-node system. The results indicated that the total one-year energy loss was reduced significantly, thereby obtaining a large profit. Smaller losses in power were also attained for a single 1-h period compared to the previous studies specified in this research. Mirzapour et al. [109] investigated how implementing FACTS affects RE integration and CO2 emission reductions. The study examined different factors like the level of RE penetration, loading patterns of the system, the location of FACTS devices, and the location of RE generation. Simulations were performed on an adapted RTS-96 system using a two-stage stochastic unit commitment model. Findings indicated that while impedance control was successful in reducing costs, it had limits in fully integrating RE into systems dominated by low-priced fossil fuel power plants. Wang et al. [110] proposed a model for distributing voltage and reactive power in RE power plants. Additionally, it formulated a coordinated control strategy that considers the synchronisation of different time scales and multiple sources of reactive power. This approach demonstrated improved stability in controlling voltage and reactive power across regional power networks. Bakir and Kulaksiz [111] proposed Bacteria Foraging Algorithm and Genetic Algorithms for gain parameter optimisation of four proportional-integral (PI) controllers in STATCOM control circuit to obtain voltage stability and better responses concerning the nonlinear nature of wind and solar hybrid microgrid using MATLAB/Simulink. The fluctuation in voltage at the busbar end was decreased by 8 % using a conventional PI controller, by 10 % for Genetic Algorithm-based PI controller, and 15 % for Bacteria Foraging Algorithm-based PI controller under a variable load. Peprah et al. [112] developed an optimisation algorithm in Python to provide active voltage management and power loss minimisation in prosumer PV grids. From the findings, operating the system with solar power and reactive power support injections with specific transformer capacities resulted in no high-power loss and over-voltage problems. The operation of the system as a consumer grid resulted in a higher loss in power compared to the system with solar power and reactive power support. Shi and Le [113] designed a single-tuned filter, band-pass filter, and low-pass filter to mitigate harmonics from residential solar PV systems following the IEEE 519–1992 standard requirements. From the results, the low-pass filter reduced the total harmonic distortion (THD) from 27.7 % to 0.71 %. The band-pass filter and single-tuned filter managed to reduce the THD to 0.15 % and 6.13 % respectively.

Souri et al. [114] specified the compensation equilibrium point by using a solar PV smart inverter by minimal operational, investment, and maintenance costs in the low voltage (LV) grid. The inverter capacity was determined by penetration levels in the actual networks. The results indicated that there was a decrease in energy losses in the LV distribution grid. Li et al. [115] proposed a deep reinforcement learning (DRL) based algorithm in Python for the coordination of multiple PV smart inverters. The proposed algorithm achieved the near-optimal performance of power flow by the mitigation of every voltage violation while minimising solar production curtailment by 88 % in comparison to the autonomous volt-var scheme. Pereira et al. [116] proposed an algorithm in MATLAB for the optimum placement of distributed generators and capacitor banks based on wind and solar energy in distribution feeders. The algorithm validated a minimisation of up to 73.4 % in active power annual losses in the Recife feeder and 71.7 % in the Bandeira feeder, with acceptable voltage profiles. Smrithi and Jayanand [117] proposed an inverter-based STATCOM with high DC link utilisation and fewer components. This approach enhanced injected current quality for the compensation of reactive power and the load voltage achieved a THD of 2 %. Gandotra and Pal [118] proposed an analytical optimal power flow approach to determine the best locations of FACTS devices and distributed generators in the IEEE-30 bus under maximum loading conditions. The analysis includes evaluating the performance of transmission lines, voltage levels at load buses, and active and reactive losses in transmission lines under various load conditions, both with and without distributed generators. The optimum location of FACTS devices was discovered to be at lines 18, 16, 14, 13, and 1 of the bus system. Fernandez and Go [119] utilised the optimal placement of capacitors algorithm developed by Siemens (PSS SINCAL) and a volt-var regulation method in the IEEE-9 bus system to improve the voltage levels and deviations after the injection of solar energy. With the optimal capacitor allocation method, the voltages for all buses in the IEEE-9 bus improved to be within the range of 0.94 p.u. to 1.01 p.u. The volt-var method enhanced the average voltage deviations of the buses from 2.71 % to 0.81 %. A hybrid algorithm was proposed by Amrane and Kouba [120] to tackle optimal reactive power planning, using the SVC and TCSC. The approach was conducted on the equivalent Algerian 114-bus power system. The findings revealed that integrating SVCs minimises the active power losses of the system more effectively than TCSCs. Conversely, for achieving satisfactory minimum voltage stability, TCSCs performed better than SVCs. Simulation outcomes demonstrated the efficacy of the proposed method in minimising power losses and the number of FACTS devices. Zand et al. [121] carried out a sensitivity analysis to integrate UPFC in the electrical grid, with an examination of the IEEE-14 bus. From the outcomes, an optimum UPFC location was discovered, reducing reactive and active losses by 11 % and 55 % respectively, thereby optimising current flow in the network. Roy et al. [122] proposed a hybrid shunt compensator for extra-high voltage systems to curb voltage stability issues. The results demonstrated that the HSC provided reactive current, maintained bus voltage, and prevented voltage drop at the point of common coupling (PCC). Paredes et al. [123] investigated the dynamic voltage stability of microgrids with FACTS device integration. The results indicated that DSTATCOM performed better than SVC in improving the voltage stability and operational resilience of the microgrid. Zadehbagheri et al. [124] conducted economic and technical analysis for the optimal capacity and placement of TCSC in transmission networks. The results demonstrated that the TCSC allocation increased the load capacity by 23.02 % and reduced power loss by 4.17 %, as validated using MATLAB. Premkumar et al. [125] examined the strategic allocation and sizing of FACTS devices, in minimising the total power production cost. This study investigated the optimal flow of power in an adapted IEEE-30 bus with stochastic wind and solar energy integration. A constraint handling mechanism and multi-objective flow direction algorithm were formulated to address the optimal power flow issue. The results, compared to various advanced metaheuristic algorithms, demonstrated the superior effectiveness of the proposed algorithm. Kamel et al. [126] proposed a new weighted techno-economic index for the assessment of various FACTS devices used for wind farms. This proposed index combined the improved voltage index and the cost-related index. The findings indicated that the UPFC was the preferred solution based on the technical performance of the system operator. However, the STATCOM was preferrable when the focus was based on economic performance. A hybrid power system with an integrated storage system encounters difficulties in effectively using batteries due to uncertainties arising from intermittent power generation and varying demand.

In 2024, a study by Goyal and Vadhera [127] proposed a hidden Markov model based on real-time pricing and an improved demand response approach to resolve these issues in such systems. The proposed model was validated using the IEEE 30-bus system, both with and without RE sources, and incorporated the grasshopper optimisation algorithm for optimal generating unit scheduling. The proposed method demonstrated its effectiveness by providing energy savings, cost benefits, reduced peak hour demand, and reduced emission dispatch as compared to what energy efficiency programs can achieve by themselves. Rui and Sahraei-Ardakani [128] proposed an innovative successive flow direction enforcing algorithm to solve power system operation models using FACTS devices. In the deployment of FACTS devices, its' additional modelling computational complexity in power systems is one of the main issues. The proposed algorithm in this paper tackles the problem of not being fully optimal while also achieving enhancements in computational efficiency. Simulation studies validate that the method effectively converges to the globally optimal solution within a few iterations in nearly all practical scenarios. Further gaps can be investigated in implementing the suggested algorithm in more intricate models for power system operation and planning, such as stochastic unit commitment (SUC) and security-constrained optimal power flow (SCOPF).

4.4. Recent work on building energy management systems (BEMS)

Khichadi et al. [129] built an energy management system by interfacing power meters and cloud in Siemens building. An energy management system was implemented by using Modbus Communication Protocol and the Raspberry Pi. The energy monitoring dashboard was interfaced and implemented successfully for real-time monitoring of total energy consumption in the building. Mudaliar & Sivakumar [130] developed and implemented an IoT-based energy monitoring system for the switchgear industry to analyse daily energy consumption. The proposed system with a graphical output of data collected in Grafana was successfully implemented in the industry. The Raspberry Pi was discovered to be the optimum option to complete the procedure following the technical conditions. Further exploration can be conducted to investigate gaps in implementing energy conservation measures, which could benefit industries by lowering costs and improving power consumption efficiency.

Oltmanns et al. [131] proposed a model using the Open Energy Modelling Framework (oemof) for the optimisation of BESS, RE, and EV in buildings. From the findings, uncontrolled charging can upsurge the combined load peaks to the point of grid overload. However, the controlled charging does not upsurge the total load at all. More annual savings could be made by the controlled charging compared to the uncontrolled charging. Megahed et al. [132] built a neural network predictive control model using MATLAB/Simulink to manage energy in net-zero buildings. From the results obtained, the control system could supply the household loads without the necessity for the grid and the system can sell energy to the grid. Majdi et al. [133] modelled a smart energy management system using DesignBuilder and EnergyPlus to decrease the total energy consumption of a 7-story building in Jakarta. The highest reduction in energy consumption occurred in the lighting, and the proposed system reduced the residential energy consumption by up to 37 %. A reduction in energy consumption of between 20 and 27 % could be attained. Masoomi et al. [134] developed a demand side management model using LEAP, where the power demand is optimised due to the consumption of different sectors with the simulation of transmission and distribution losses. From the results, the pollutant emission rates of the optimised and demand side management scenarios were 144 and 429 Mt of CO_2 for 2035 respectively.

Wu et al. [135] proposed a novel occupancy detection approach based on a CNN model using smart meter and proximity infrared (PIR) sensors for data collection. This model was applied to a university office case study. The model was utilised to enhance outdoor air system control, contributing to energy savings and a more comfortable built environment. Surpassing conventional artificial neural network (ANN) models, this proposed model exhibited a notable accuracy enhancement of 26.8 %. Yelisetti et al. [136] proposed an enhanced model for BEMS considering outdoor illuminance, outdoor temperature, and internal heat generation. 46 swarm intelligence algorithms were used to assess the proposed model's performance. These algorithms were compared using statistical analysis, convergence curve analysis, and box plot analysis. Based on the comparison, the Bald Eagle Search algorithm was discovered to be the optimal case among the 46 algorithms. Liang et al. [137] proposed an IoT-based smart energy management system for a net-zero emissions building for optimal scheduling of HVAC components to trade-off between remaining battery energy and user comfort level. Data-driven models were formulated to predict future baseload, room thermal dynamics, and solar PV generation. A novel demand compliance method was developed to manage building user loads effectively. The test outcomes showed that the newly designed EMS could attain a comparable level of user comfort to the rule-based approach, while maintaining significantly higher battery energy reserves. Thoy and Go [138] modelled building integrated PV (BIPV) designs towards attaining net zero energy building by adopting realistic meteorological data and design considerations. 3D building geometry modelling of an optimal solar PV layout and estimation of energy yield were carried out. From the results obtained, the proposed system design was projected to supply 49.27 % of the building's energy consumption while minimising CO_2 emissions by 20155.32 tonnes throughout the system deployment lifetime. A performance ratio of 83.9 % was achieved at RM 0.118/kWh with a 7.6-year payback period.

Zhang et al. [139] formulated a novel multi-objective Particle Swarm Optimisation-support vector machine method to reduce energy consumption in green buildings with novel materials. There was a substantial saving in the green building energy consumption by 42.44 % for biogas and 28 % for electricity compared to the common building. Gaps of new ML approaches such as instance-based learning and hybrid Gaussian Process Regression are useful for further investigations. Tsao and Vu [140] researched an optimum sensor system for smart buildings with uncertain demand and supply of energy by using a continuous approximation approach. This research aimed to determine the type, location, and number of sensors required by a building to reduce the building's energy system cost. The results indicated that this approach could aid in finding the optimal value of decision variables and objective functions rapidly by elementary calculus. However, the satisfaction levels and occupant behaviour were not included in this work and this gap can be further investigated.

In 2023, Li et al. [141] proposed a method of optimal communication topology in smart buildings. This approach integrates methods from distributed computation fields and wireless communication and guarantees the fully distributed optimum control performance for HVAC systems. The results demonstrated an enhancement of network stability and a lowering of network energy consumption. The optimal topology outperformed the typical topologies of conventional design methods. A study by Ref. [142] proposed a novel approach for managing the energy demand and supply sides in buildings with grid-connected BIPVs, with the consideration of electricity price. This approach demonstrated a much better performance in comparison to other approaches in managing energy demand, supply, and real-time electricity prices. Simulation results validated its effectiveness in a specific environment, particularly for lighting loads, underscoring its suitability. This approach promoted the development of smart buildings and smart cities alongside the expansion of smart grids and deregulated energy markets. Sun et al. [143] formulated a novel method for real-time energy management in large-scale smart buildings in 2024. This method prioritises voltage safety within online multi-agent reinforcement learning systems. Enhancements in task performance were achieved by redesigning the estimation Q-network's loss function target. From the results, leveraging expert demonstrations enhanced stability and expedited learning processes in reinforcement learning applications for smart building systems.

In 2024, Zhou et al. [144] developed a data-integrated convolutional neural network (CNN) model for occupancy state classification. From the occupant schedules obtained, space occupancy patterns of users were retrieved by means of hierarchical clustering, followed by space optimisation for enhancing energy efficiency. The proposed approach was implemented in a building on a campus in Wuhan, China. The findings indicated that the optimisation methods can help attain a 23.5 % energy consumption reduction of the building. Future gaps can be investigated by combining various sensor data like sound, light, and gait can enhance recognition accuracy. Additionally, understanding occupant behaviour entails intricate interactions between humans and buildings. This study only examined occupancy space optimisation for energy-efficient buildings through occupant distribution. However, future research should also consider occupants' subjective perceptions and passive feedback on the building environment.

Nojedehi et al. [145] proposed an approach that combines input from occupants with personal data to improve the effectiveness of fault detection and diagnostic (FDD) systems in buildings. The method employs a smartwatch application named Cozie to gather occupants' personal feedback regarding thermal comfort and air quality. This information is then transmitted to a cloud database via a data stream. The findings from the experiment demonstrate that occupant feedback effectively confirmed or refuted alarms, leading to a quicker and more precise FDD. From this paper, it was concluded that combining occupant feedback with personal data can greatly improve the performance of FDD, resulting in more comfortable environments for building users. Gaps can be further explored in the future regarding how occupant feedback or personal metrics, like heart rate, can enhance FDD methods related to indoor air quality.

Zhong et al. [146] assessed the performance variations in FDD between the proposed convolutional and recurrent neural networks, examining both limited seasonal fault data scenarios and an optimal scenario that encompasses diverse climatic conditions across multiple seasons. Fault and normal data were collected through simulations conducted with a validated prototype EnergyPlus model, along with two actual fault datasets. The diversity of fault data across various seasons plays a more significant role in improving FDD performance than the volume of fault data available for each individual season. These insights will guide researchers in addressing this important factor when assessing new or existing data-driven techniques for FDD.

Gao et al. [147] developed a method for automatically formulating a Bayesian network based on the topology of HVAC systems, such as the Haystack approach. The network effectively models and assesses the condition of all system components, aiding users in pinpointing the most likely root cause of faults. The method had been evaluated using data from both real and simulated office environments. It demonstrated flexibility in handling various HVAC system topologies and differing data availability, requires minimal computational resources, and achieves a high level of diagnostic accuracy. Gaps can be further investigated on how users can utilise data-driven techniques, particularly equipment-level fault detection models, to generate virtual evidence, thereby streamlining the diagnostic process.

5. Assessment and discussions of literature reviewed

Table 7 specifies the literature categorised into its specific research areas. Figs. 7–10 illustrate the various methods applied in the specific research areas of renewable energy, ESS, grid technologies, and BEMS.

The research methods on renewable energy systems demonstrated a relatively high technological maturity with various modelling approaches in the optimum integration and coordination of RE technologies to improve RE generation fraction in the energy mix. The cost of the technologies used to implement these methods can vary accordingly as they depend on the project size and the type of technologies used. The large-scale implementation of these methods on national or regional geographical scales will project a relatively high reduction in global CO2 emissions and a high contribution towards global net-zero energy systems due to the phasing out of fossil fuel power plants.

For the research methods in energy storage, there was a demonstration of relatively mature technology with many applications in large-scale energy mix integration. The contribution towards attaining net zero for large-scale implementation of energy storage technology methods is relatively high as it will complement the generation of more RE into the grid while maintaining grid stability by optimum electricity demand and supply management. As the fraction of solar and wind energy is targeted to grow significantly with the gradual phasing out of fossil fuels to attain net zero by 2050, large-scale modelling and integration of ESS will play a substantial part in the integration of high penetrations of VRE sources.

The research methods of grid technologies for reactive power management in electrical networks with high VRE demonstrated relatively high technological maturity and advancements. There was also great feasibility and potential with AI-based methods to enhance the control algorithms for improved power quality of electrical networks with further gaps that can be investigated in optimal power flow problems in real-world networks.

The contribution of methods involving BEMS towards achieving a global net zero energy and carbon system demonstrates a relatively low to medium contribution as compared to technologies such as large-scale RE and ESS mainly due to the scale and relatively lower contribution of RE generation and demand matching in buildings as compared to that of in the power sector. However, BEMS helps to complement these other systems towards achieving net zero. For BEMS, there is a medium to high level of technological maturity with gaps for further enhancement with more advanced AI and cloud computing methods.

Attaining net zero emissions is not only constrained by these factors but also influenced by others, such as government initiatives [187], green economy transition [188], reforestation [189], energy consumption behaviours [190,191], alternative fuels (biofuels

Table 7
Overview of research areas and related literature.

Research Areas	Specific Areas	Reference
Renewable Energy	Resource Optimisation and Integration	[46,47,48,50,51,52,53,54,55,56,57,58,59,60,61,62,63,158,161,162,169,180]
	Energy Management Systems	[49,50,59,63,170,171,172]
	Optimal Projection, Forecasting or Scheduling	[47,50,51,54,55,56,57,58,59,60,61,62,63,171,172]
	Grid Ancillary Services	[50,148,149,150,151,152,153,154,155]
Energy Storage Systems	Optimal Planning and Integration	[64,65,66,67,68,69,70,71,72,73,74,75,76,77,78,79,80,81,82,83,98,104,155,158,168,170,172,215]
	Demand Shifting or Peak Reduction	[67,68,71,72,76,79,82,83,84,87,89,91,92,93,94,95,96,97,98,99,101,102,103,157]
	Black Start, Load Balancing, or Frequency Balancing	[77,85,86,87,88,89,90,91,92,93,94,95,96,97,98,99,101,156]
	Time Shifting or Firming Capacity	[64,65,66,69,70,73,74,75,78,85,86,88,90,91,92,93,94,95,96,97,98,99,100,101,102,103,104,157]
	Arbitrage or Peak Shaving	[80,81,100,104,159,160,163,164,165,166,167]
Grid Technologies	Dynamic Reactive Power Control	[105,106,107,108,109,110,111,112,114,115,117,118,119,120,121,122,123,124,125,126,127,128,173,216]
	Phase Angle, Impedance, Voltage, and Flicker Control	[106,109,110,111,112,115,116,118,119,120,121,122,123,124,126,128]
	Harmonic Distortion Reduction	[113,117,174,175,176,177,179]
	Load Balancing for Power Quality Improvement	[105,107,108,114,116,125,127,178,179]
Building Energy Management Systems	Demand Side Management	[129,130,131,132,133,134,135,136,137,138,139,140,141,142,144,181,182]
	Model Predictive Control	[131,132,133,134,136,137,138,139,141,142,143]
	Real Time Condition Monitoring	[129,130,135,140,143,144,183,184]
	Fault Detection and Diagnosis	[145,146,147,185,186]

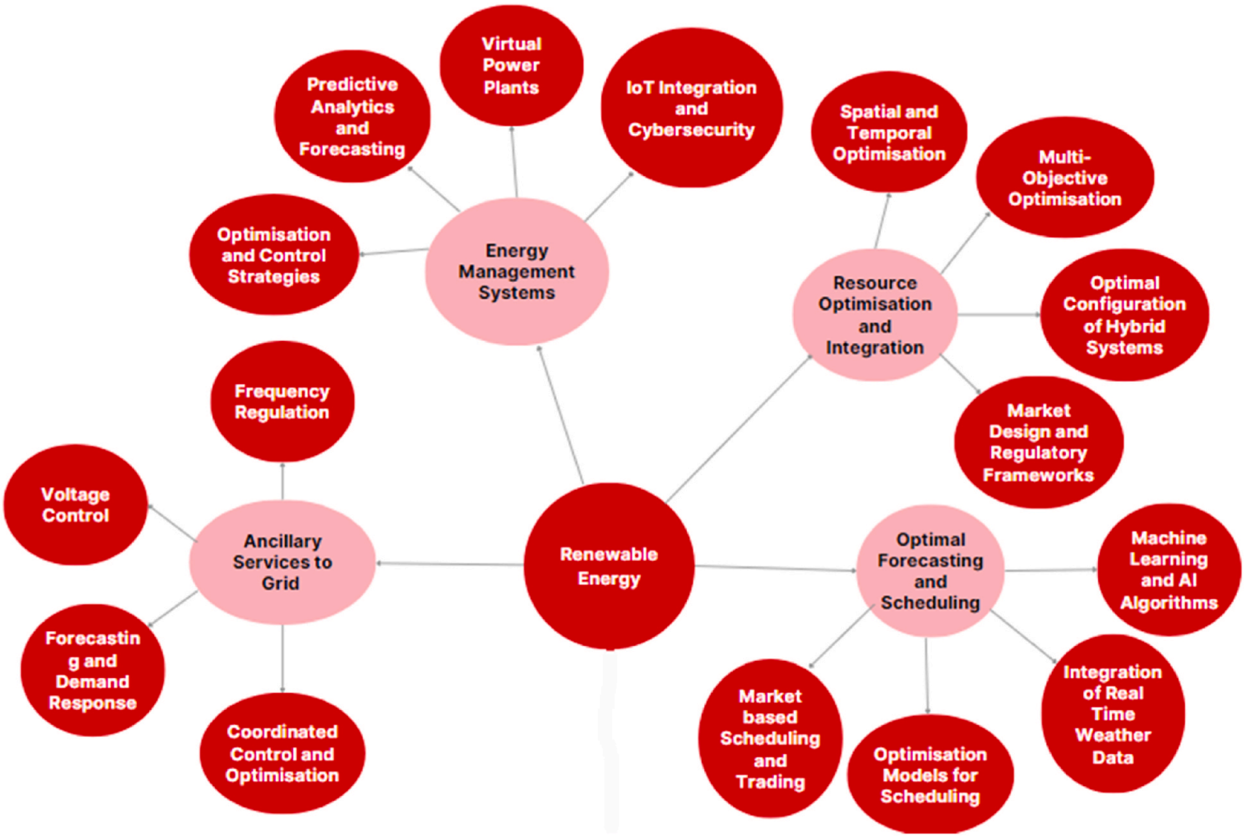

Fig. 7. Real-life applications of renewable energy modelling and integration with recent work in research.

[192], hydrogen [193]), electric vehicles (EVs) [194], carbon capture, utilisation, and storage (CCUS) [195], industrial decarbonisation [196], sustainable agriculture [197], and waste management [198] among others. Future research can include a detailed review of these factors to identify gaps in the literature.

6. Gaps and technological advancements for energy transition

6.1. Renewable energy modelling and integration

As VRE is targeted to increase significantly towards 2050 to attain net zero, the next generation of solar PV technology (perovskite cells, tandem cells, bifacial panels) and wind turbines (smart blades, carbon fibre composites, offshore wind, direct-drive generators, superconducting generators) can be researched further to be modelled and integrated into energy system models tools for nationwide or regional energy planning and analysis. In future research on solar PV systems, hybrid optimisation methods to tackle complexities such as optimal orientation, sizing, and tracking to attain highly efficient and adaptable systems hold high potential for improved solar energy capture. This area of research focuses on advanced algorithms to determine the optimum tilt angle, tracking strategies, and sizing of PV systems. The parameters considered are energy demand, location-specific weather conditions, type of solar PV module, and electricity prices. Large datasets of these parameters can be analysed by machine learning (ML) and artificial intelligence (AI) methods for improved design of solar PV systems. In addition, advancements in global solar radiation and estimation models can be further investigated. These estimation models involve research in ML algorithms to handle complex data relationships to develop more robust and accurate estimation models of global solar radiation. Developing research methods to assimilate data from different weather and climate models and its integration to obtain more accurate solar radiation models is also a key research area moving towards the future.

Research in satellite-based remote sensing explores methods of utilising remote sensing data and satellite imagery to improve spatial coverage and model accuracy. IoT technologies can also be further researched for defect detection, automation of cooling and tracking mechanisms, cloud storage of data, preprocessing, and analysis to improve solar PV performance. One of the scopes of this research area focuses on smart PV monitoring systems which can collect real-time data from solar PV panels and inverters. Cloud-based remote monitoring and control of solar PV systems to effectively manage many installations in different areas. Approaches in the advancements of these emerging technologies with their integration into national energy system modelling are a gap that can be further investigated to understand how these technologies can improve the RE fraction generated in the energy mix. Furthermore,

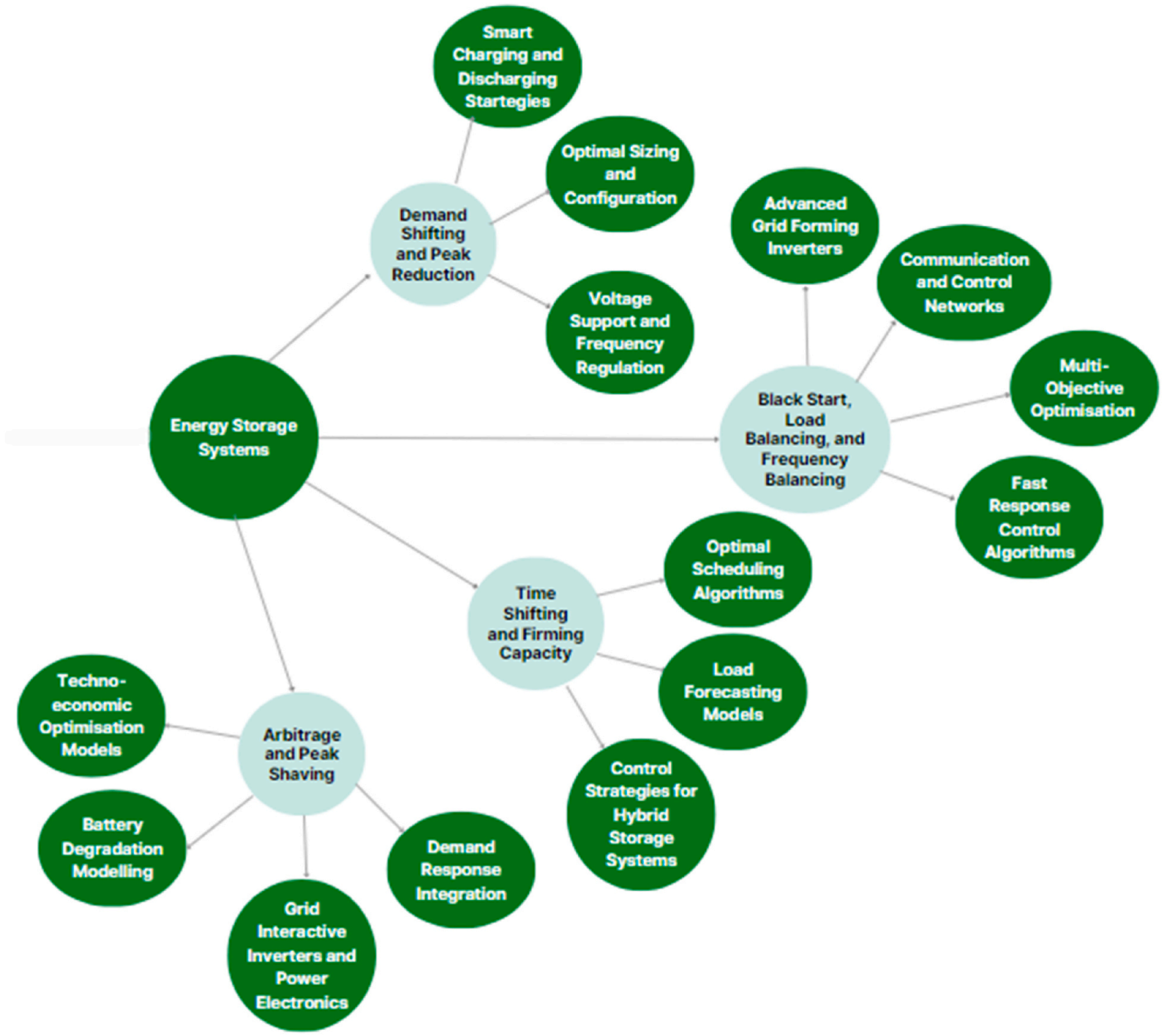

Fig. 8. Real-life applications of energy storage with recent work in research.

adaptation of current energy system modelling tools or development of new tools that consider the unique characteristics of developing countries, like limited electricity access, informal economies, political environments, power shortage, and distinct weather conditions, to develop robust energy strategies is a gap that can be investigated.

The coupling of existing energy system modelling tools can be researched and developed to benefit from the unique capabilities of these tools (EnergyPLAN, LEAP, OSeMOSYS, etc). Addressing uncertainty in energy system modelling involves recognising the uncertainties in RE systems and energy costs, which can affect model outcomes and lead to inaccuracies in long-term energy balance analysis. Future research directions might focus on scenario creation and sensitivity analysis within energy system modelling. Utilising ML and AI techniques can enhance the accuracy and efficiency of energy models, potentially mitigating these challenges [199]. Moreover, energy modelling analysis could be developed to encompass the continental regions, considering electricity trade between nations, and evaluating the balance between electricity imports, production, and storage. This method would offer policymakers a broader perspective on the energy security and economic consequences of energy transition approaches.

6.2. Energy storage systems

Novel or customised multi-objective optimisation methods for the optimal dispatch strategy of ESS can be further investigated and developed. This can consider more aspects such as grid support, economic viability, and environmental impacts to obtain the best trade-offs and optimal results of performance parameters such as capacity, power loss, CO2 emission reduction, battery lifetime, and charge/discharge time. The operation strategy of novel dispatch algorithms can be designed to operate in load following or cycle

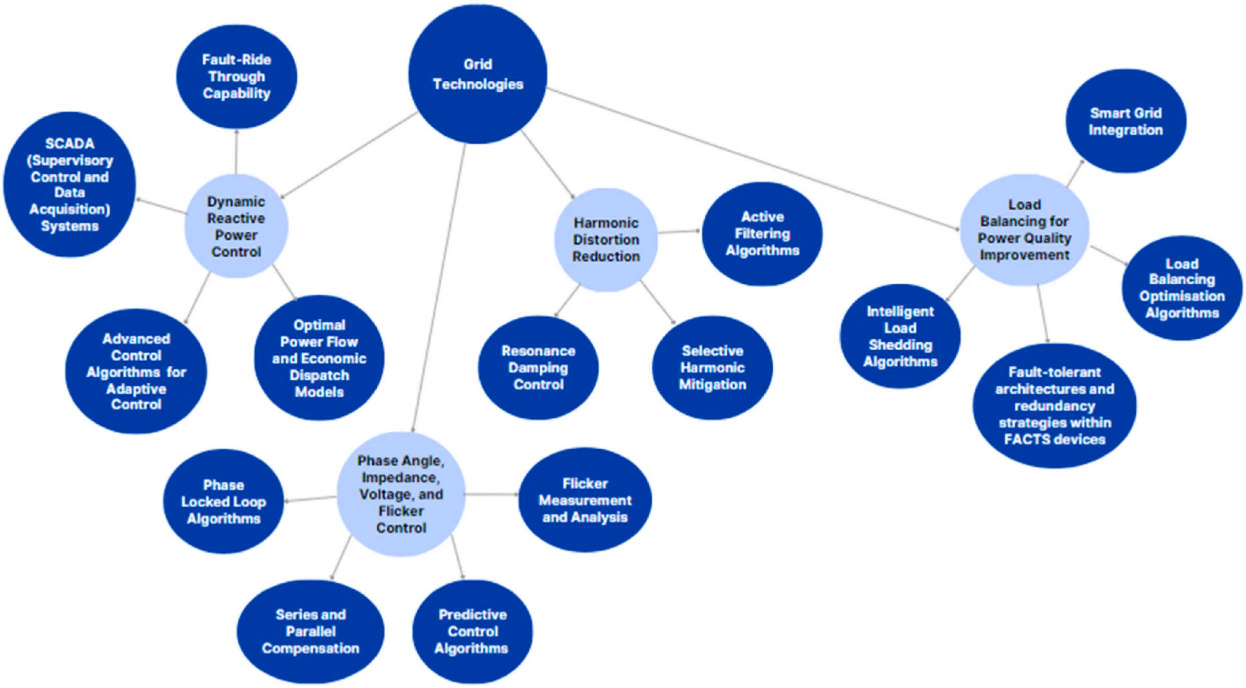

Fig. 9. Real-life applications of grid technologies with recent work in research.

charging depending on the circumstances to improve adaptability with RE integration thus enhancing the operation of the entire energy system. New materials of BESS for the enhancement of energy density, battery lifetime, efficiency, and safety can be further researched. This scope covers new electrolytes and electrode materials for higher energy density, fast charging and discharging materials, solid-state batteries, redox flow batteries, multivalent ion batteries, supercapacitors, hydrogen storage, metal-air batteries, and nanotechnology. Regarding lithium-ion batteries, issues arise concerning energy density, power capabilities, longevity, and thermal management when employing new materials and chemistries [200].

Future developments in advanced lithium-ion BESS are anticipated to improve safety, temperature tolerance, reduce costs, and improve fast charging capabilities [201]. Hybrid supercapacitors represent a new class of storage technology that combines the storage capability of lithium-ion batteries and the power capabilities of electrochemical double-layer capacitors. This lithium-ion capacitor can provide a higher power and longer lifetime compared to lithium-ion batteries, higher energy density and nominal voltage compared to electrochemical double-layer capacitors, but lower than lithium-ion batteries [202]. Future research can focus on the development of robust control strategies for voltage and management in multi-feeder microgrid systems, emphasising voltage control and precise power-sharing at individual load feeders. These investigations can explore advanced control methodologies aimed at improving microgrid stability, guaranteeing dependable regulation of voltage amidst the integration of distributed generators. More investigations can delve into integrating load frequency control and automatic voltage regulators within management systems for distributed energy storage. This research can examine the combined advantages of these approaches to attain efficient load equilibrium and voltage regulation in intelligent electric power distribution networks.

Furthermore, upcoming studies could explore the creation of hierarchical scheduling strategies to bolster the robustness of decentralised microgrids with RE sources. This research can encompass proactive strategies and mobile units for the optimal scheduling of RE resources, ESS, and demand response initiatives, thereby promoting effective and resilient microgrid operations. ESS integration into smart grids with security and IoT applications is a research direction moving towards the future. Demand response programs enabled by IoT technology can synergise with ESS to manage peak loads and shift energy consumption more efficiently. This will lead to more efficient use of the stored energy and a reduction of strain on the electrical grid. IoT-based monitoring systems can provide real-time data on ESS which enhances system reliability and enable predictive maintenance. ML algorithms can also benefit ESS in forecasting more accurate flows of energy from demand to solar PV generation. AI approaches can support the optimal dimensioning and investment in BESS technology with less oversizing. AI can also aid in the advancements of ESS in the aspect of increased lifespan from optimal cycling of batteries to reduce cycling ageing, while enhanced preventive maintenance boosts system reliability. The emergence of these advancements in ESS technology and dispatch algorithms can be further enhanced to fill the gap of being integrated into energy system models for optimum planning and management of energy in large geographical regions. The preliminary analysis carried out from these results will be useful for moving forward towards the stage of implementing these technologies in the real world.

Fig. 10. Real-life applications of BEMS with recent work in research methods.

6.3. Grid power management

Optimal positioning of FACTS devices encounters obstacles like defining objectives, refining criteria for efficiency, overseeing system variables, and devising feasible computational methods. Future investigations should address the integration of RE into power grids and advancements in FACTS device functionality. Emphasising advanced optimisation techniques or combining metaheuristic approaches could further elevate studies on device placement [203]. The planning of power factor correction devices in electrical networks with an abundant number of RE generators can be carried out by more advanced heuristic algorithms to obtain optimal results of voltage profiles, frequency, flickers, reactive power, and real power supplied to loads with increased complexity in computation. The efficacy of real-time control algorithms used in the aspect of computation time, number of iterations, and convergence rate can be further developed. More investigation on optimal power flow problems with high penetration of VRE using novel metaheuristic approaches, analytical approaches, conventional methods, and hybrid-based approaches have gaps that can be further investigated [204]. Moreover, gaps in smart inverter coordinated control for grid stability improvement can be further investigated. The incorporation of adaptive algorithms into smart inverters can give them the ability to adapt their reactive power control according to the evolving conditions of the electrical network. In 2023, Hailu et al. [205] explored approaches to enhance static security in electrical networks, comparing ML with conventional approaches. This study recommended the use of deep learning algorithms and FACTS devices for reliable security assessment in complex networks with RE and EVs. The extension of research with the consideration of real-world power grids in various areas allows a more detailed analysis of the efficacy and suitability of proposed optimisation strategies.

6.4. Building energy management systems

Further research into more advanced detection systems for human occupancy (e.g., thermal sensors, microwave radar sensors, infrared sensors, acoustic sensors, and cameras with image processing) could explore their computational complexity in determining the number of occupants in an area. Novel methods of neural networks to process more complex input data of sensors and make decisions on the control of energy consumption levels in the thermal and electrical appliances in buildings to optimise the parameters of energy consumption, cost, and CO2 emissions from buildings is a gap to be further investigated. The development of novel sensors which can detect multiple parameters can also aid in the reduction of sensors used. In addition, occupant behaviour models based on ML methods for the analysis of energy consumption patterns are a gap to be researched for improvements in integration with the BEMS infrastructure. The optimal design of BIPV towards attaining net zero buildings also possessed several research gaps. The seamless integration of BIPV into various structural elements like roofs, shading structures, windows, and facades has great potential to be further analysed and improved for buildings of unique structures. BEMS research can also be focused on the collaboration and co-ordination of energy among vehicles and buildings [206], the expansion of the energy storage demand in buildings and flexibility options [207], prediction models of energy consumption for different subsystems, and demand management with the consideration of electric vehicles being new loads. Future research should prioritise key areas to advance smart building technology. These areas include conducting comprehensive cost-benefit analyses and model development for the evaluation of economic feasibility in smart buildings, thereby increasing their adoption in the market. Additionally, there is a need to explore new materials and enhance current materials to for optimal performance, focusing on improving aspects like light modulation, self-cleaning capabilities, and thermal insulation. Research should also address the effective integration of smart building envelopes with other building systems, such as HVAC, lighting, and security, to maximise energy efficiency and enhance user comfort. Evaluating the environmental impact of smart building envelopes across their lifecycle is crucial for promoting sustainable development. Moreover, investigating the user behavioural responses to these systems will facilitate the design of systems that better meet user demands [208]. Future works in the advancement of optimal neural network methods for energy management in zero-energy buildings with intermittent BIPV can be further investigated. Advancements in this area can provide an overview for decision-makers in the development of smart electrical management systems for net zero buildings that operate on high renewable energy fractions [209].

6.5. Smart grids

Knowledge gaps can be further investigated in advanced metering infrastructure (AMI), as there is insufficient foresight regarding implementing it strategically with smart meter data management. There exists a demand for better energy transmission, enhanced distribution control, real-time analytics, and standardised communication, all beneficial to energy customers and utilities alike. Investigations in forthcoming energy management systems should focus on the integration of EVs and the readiness of smart grids. Specific aspects needing further investigation include the integration of BESS with control measures, and the effects of integrating BESS on the grid, such as harmonics and voltage fluctuations. When completely formulated, an optimum energy management system will enhance the sustainability of transport energy on smart grids. Further research is needed to determine the optimal utilisation of RE sources for producing sufficient energy in the most effective method possible. It is advised to investigate uncertainties affecting the integration of various RE sources into Virtual Power Plants (VPPs), particularly concerning economic electricity dispatch. Given the critical need for effective communication and management models for VPPs and EVs, additional research should explore how communication disruptions impact their integration into grid networks. Furthermore, to achieve reliable and eco-friendly energy sources, significant emphasis ought to be given to the application of AI in smart buildings and smart homes to gather useful data and optimise operations.

Technologies of Virtual Reality (VR) and Augmented Reality (AR) are beginning to influence big data analytics by offering interactive and immersive methods for visualising and interacting with complex datasets. These technologies have the potential to revolutionise data exploration, enhancing its intuitiveness and engagement. Analysts can gain understanding through a more interactive and intuitive encounter facilitated by AR and VR [210]. Quantum computing offers significant advancements in processing power for big data analytics. Its main benefit is its capability to perform complex computations exponentially quicker than conventional computers. This capability is especially critical for big data applications, where the quantity, speed, and variety of data frequently exceed the processing capabilities of traditional systems. Quantum algorithms, including those applied in quantum machine learning, show potential for more efficient analysis of large datasets, enabling faster pattern recognition, predictive analytics, and optimisation. Nevertheless, the technology remains nascent, necessitating extensive research to develop practical quantum computing systems that can effectively tackle real-world challenges posed by big data [211]. Federated learning, an approach to machine learning that operates in a decentralised manner, holds substantial promise for big data analytics. This method enables model training across distributed devices while ensuring data remains localised. This localisation not only bolsters privacy but also accelerates processing speeds by reducing the need for data transfer. Federated learning harnesses contextual information efficiently through local data processing, resulting in more accurate insights tailored to specific applications. For example, this method can improve specialised services in smart cities. Federated learning gathers insights from dispersed origins without aggregating sensitive data, offering a scalable and privacy-protecting framework for analytics [212,213]. Transitioning to a future with net-zero energy needs the adoption of cutting-edge digital technologies, such as IoT, quantum computing, AI, blockchain, cloud computing, big data, digital twins, and robotics. In 2024, Ferdaus et al. [214] reviewed how these technologies can enable energy system optimisation towards attaining net zero by RE integration, carbon emission reduction, and new energy sector business models.

7. Conclusion

Modelling and optimal planning of energy supply and demand in future years have become fundamental in achieving energy security, environmental sustainability, and economic prosperity. The use of energy system modelling tools for various geographical regions plays a vital role in discovering optimum renewable energy solutions across various sectors to solve problems related to energy balances, climate change, and economic competitiveness. However, to attain net zero for large geographical regions, the synchronous operation of various technical solutions such as renewables, energy storage, grid power management, and building energy management will play a significant role in their effective interoperability and communication among the power, buildings, transport, and industry sectors. These elements constitute the infrastructure of the smart grid and smart cities in which the advancements of future energy systems are being developed rapidly. The challenges and technical solutions of attaining net zero energy with a high share of renewables were discussed.

This review paper aims to synthesise findings from recent work to provide insights and identify future gaps in research directions to enhance coordination and communication in the future energy system infrastructure across various sectors. A systematic search was conducted on various digital libraries such as ScienceDirect, Elsevier, IEEE Xplore, Springer, Google Scholar, and more. This search was distinguished by using filters such as but not limited to publication date (within the last 5 years), and document type (peer-reviewed articles, technical reports, and conference proceedings). This work distinguishes itself by comprehensively investigating four key research areas: 1) optimal modelling and integration of renewable energy, 2) energy storage systems, 3) grid technologies to incorporate more renewables, and 4) building energy management systems, which are key elements contributing towards the development of smart grid infrastructure and are pivotal for decarbonising the future energy system. The review in renewables and energy storage demonstrated that energy system modelling tools are significant in regional planning of energy transition pathways towards net zero in the future by scenario analysis. These approaches can assist decision-makers in establishing policies, after further study in defining more accurate optimal capacity combinations, and conducting energy balance analyses for years ahead.

Based on the various energy system modelling tools reviewed, gaps can be further investigated in developing novel models that can completely include the political, environmental, social, and economic conditions of various regions. These tools can be further enhanced in complexity, integrations, cost, accuracy, and standardisation. The coupling of existing energy system modelling tools can be researched and developed to benefit from the unique capabilities of these tools (EnergyPLAN, LEAP, PLEXOS, MARKAL/TIMES, OSeMOSYS, etc). Addressing uncertainty in energy system modelling involves recognising the uncertainties in RE systems and energy costs, which lead to imprecisions in long-term energy balance analysis results. New energy system modelling tools can be developed with the seamless integration with new methods or tools based on the review of energy storage for voltage support, microgrid dispatch strategies, optimal reactive power flow in electrical networks, and energy management in buildings. This will provide the capability of these tools to incorporate these detailed analyses into the larger sector of energy balance simulation for a large geographical region. This will aid the formulation of more robust and effective solutions for the challenges faced in modern energy systems. The findings from this study can assist policymakers, researchers, and practitioners in identifying gaps and developing future research in the development of more accurate, environmentally friendly, and economically feasible energy models followed by their real-life implementation towards attaining net zero energy systems. This review paper recommended gaps and future research directions in the areas reviewed which can enable more advancements in the smart grid infrastructure. In summary, the smart grid holds a fundamental role in achieving net zero energy by integrating RE, ESS, advanced grid infrastructure, and smart buildings synergistically. RE generation can be efficiently harnessed and distributed across the grid using smart technologies that optimise production and consumption patterns. ESS, like batteries and pumped hydro, help balance supply and demand fluctuations, ensuring a stable grid even when renewables are intermittent. Advanced grid infrastructure, including smart meters and sensors, enables real-time monitoring and optimal control of energy flow, enhancing grid reliability and efficiency. Smart buildings equipped with BEMS can dynamically regulate energy consumption with adaptation to the power grid conditions and demand response signals, thereby intelligently optimising energy consumption and reducing overall demand peaks. These components of a smart grid together with its' future advancements in AI, IoT, quantum computing, cloud computing, blockchain, big data, and digital twins can create a resilient and sustainable energy infrastructure across all sectors capable of supporting the net zero energy goals.

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Malcolm Isaac Fernandez: Writing – original draft, Methodology, Formal analysis. **Yun Ii Go:** Writing – review & editing, Supervision, Project administration, Funding acquisition. **Dennis M.L. Wong:** Supervision. **Wolf-Gerrit Früh:** Supervision.

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.

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