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Green energy management: Combining sustainable technologies for efficient power generation

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ABSTRACT

Green technologies are innovative methods for reducing environmental impact and enhancing resource efficiency, thereby significantly promoting sustainable power production. This comprehensive review has been discussed the significant impact of energy management and green technology on advancing sustainable power production. To implement green technology for sustainable energy systems, the study has emphasized the significance of energy management to reduce carbon emissions by integrating renewable energy sources such as solar, wind, hydro, and geothermal power which minimizes waste and ensures that supply matches demand. By managing variations in the output of renewable energy and balancing load, these systems enhance grid stability. In addition, storing excess energy at times of low demand and releasing it during peak hours, energy management has improved the charging and discharging cycles in energy storage devices, such as batteries and pumped hydro storage. Energy waste and greenhouse gas emissions have dramatically decreased because of the adoption of energy efficiency measures and through an analysis of the obstacles and challenges that come with putting these technologies into practice, like high costs and regulations, the study has made recommendations for how to improve the efficacy of green energy management. It has been found that effective energy management is critical to maximize the benefits of green technologies and achieve a more sustainable and efficient energy future.

1. Introduction

As the global population grows, so does demand for natural resources and energy [1]. Manufacturing businesses are expanding with new technologies and processes to meet their needs. Rapid development in resource use and energy consumption puts a pressure on the environment, increasing pollution, greenhouse gas emissions, and waste creation [2]. Energy and resources are two of the most crucial elements of economic progress. Economic progress is impossible without adequate resources and energy; so, resources and energy must be used wisely and efficiently [3]. Climate change and environmental degradation provide serious challenges to the world economy. This problem endangers not just people's health but also their finances and productivity [4]. Energy consumption rises along with economic activity, which increases greenhouse gas emissions that have an impact on the environment. By joining the Agreement of Paris, almost all nations have committed to reducing their greenhouse gas emissions in order to combat climate change. The accomplishment of targets and the attainment of sustainable development goals are contingent upon a nation's commitment to these goals. The world economy will lose more than 18 % of its GDP due to climate change, with Asian economies predicted to be the most severely affected, based to the Swiss Re Institute in 2021. However, if the Paris Agreement's objectives are quickly accomplished, the influence might be diminished [5].

With environmental issues on the rise, it is critical to take steps to mitigate them. Energy is one of the most important areas contributing to the current environmental condition. This sector is critical to a country's well-being and economic growth [6]. Unfortunately, the current production schedule surpasses the cap set by the Paris Agreement, as per the UN Production Gap Report [6]. To reduce carbon emissions and accomplish sustainable development objectives, all governments must act. The world still needs more energy, even if many nations have started to transition to green and renewable energy sources as substitutes. Green development has attracted a lot of interest recently because the global quest of economic development typically results in environmental devastation. Reducing the effects on climate change on humankind

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through investments in green technology is essential to separating environmental degradation from economic prosperity [7]. Reducing the impact of the environment on the economy at large, from production to consumption, is the aim of green growth [8], which is accomplished by developing green technologies and implementing clean energy sources. Because it lowers emissions from the processes of production and consumption, technical innovation is therefore viewed as the primary force behind the evolution of the industrial sector [9]. According to the Organization for Economic Cooperation and Development, countries with diverse histories and socioeconomic circumstances may select different strategies for striking a balance between economic growth and environmental protection because There isn't a “one-size-fits-all” guideline for encouraging environmentally friendly growth. To guarantee that economic development wastes less natural resources, generates fewer hazardous byproducts, and is more adaptable to shocks, countries and international organizations usually agree on the significance of enacting green growth policies [10].

The amount of research on green energy technology that has been published to date clearly demonstrates a lack of fragmentation, with studies often focusing on specifics such as solar or wind power without providing a comprehensive overview of the entire spectrum of developments that are available. This split narrows the field of study and hides the interconnectedness of multiple technologies that are critical to the functioning of sustainable energy systems. Furthermore, in the context of energy management, there is a lack of integration between energy storage options and renewable energy technology. Numerous studies examine these subjects separately. To close this gap, this review introduces green technologies and their place in sustainable energy management need to be examined in a more thorough and integrated manner.

This paper highlights a number of important contributions that have advanced our understanding of energy storage technology and the integration of renewable energy sources into energy management frameworks. In order to promote sustainable power generation and use, the study offers a thorough analysis of new renewable energy sources, such as solar, wind, hydro, and geothermal energy, and investigates how these resources might be effectively handled. In order to handle the intermittent nature of renewable energy sources and maintain grid stability, special emphasis is paid to energy storage technologies such batteries, pumped hydro storage, and thermal energy storage. The paper also lists the difficulties and impediments to putting these technologies into practice, such as financial limitations, legal issues, and technological restrictions, and offers workable ways to get around them. This work intends to support current efforts to improve energy management systems and promote a more sustainable and efficient energy future by providing a thorough analysis and suggesting future research options.

1.1. Review methodology and reporting protocol

This review was conducted using a transparent and structured approach designed to ensure replicability while remaining appropriate for heterogeneous engineering and energy-systems evidence. The protocol consisted of (i) database searching, (ii) de-duplication and screening, (iii) eligibility assessment, (iv) data extraction, (v) quality appraisal, and (vi) narrative–thematic synthesis with cross-comparative mapping. Details are shown in Table 1.

1.1.1. Search strategy and information sources

A comprehensive literature search was performed in Scopus, Web of Science Core Collection, IEEE Xplore, and ScienceDirect. The search covered publications from January 2015 to November 2025. The search strings combined three keyword families: (A) “green” and sustainability terms (green technology, sustainable energy, low-carbon, decarbonization, net zero); (B) management and optimization terms (energy management, demand-side management, scheduling, optimization, control, policy, market, techno-economic); and (C) technology pillars (renewable energy, photovoltaic, wind, biomass, hydrogen, energy storage, batteries, supercapacitor, thermal storage, smart grid, microgrid, power-to-X, digitalization, artificial intelligence). Boolean operators were used to combine families (A AND B AND C), with title–abstract–keyword fields searched where supported. Reference list screening (“snowballing”) was subsequently applied to identify additional relevant studies not captured in the initial database query.

Table 1
Summary of review protocol elements.

Element	Details
Databases	Scopus; Web of Science Core Collection; IEEE Xplore; ScienceDirect
Coverage window	January 2015–November 2025
Search fields	Title–Abstract–Keywords (where supported)
Keyword families	Sustainability/green terms; management/optimization terms; technology pillar terms
Screening stages	Duplicate removal → title/abstract screening → full-text eligibility screening
Inclusion criteria	Green/sustainable energy + system-level management/integration/optimization; peer-reviewed; English; full text available
Exclusion criteria	Out-of-scope; editorials/opinion; insufficient methodological detail; duplicates; non-scholarly sources
Synthesis method	Narrative–thematic synthesis + cross-comparative mapping matrices
Quality appraisal	Tailored checklist (boundary clarity; assumption transparency; method fit; validation rigor; reporting completeness)

1.1.2. Eligibility criteria

Studies were included if they: (i) addressed green/sustainable energy technologies and/or energy storage and their role in decarbonization; (ii) discussed energy management, integration, optimization, or system-level implementation (technical, techno-economic, regulatory, or operational); (iii) were peer-reviewed journal articles, peer-reviewed conference papers (where relevant in IEEE Xplore), or scholarly book chapters; and (iv) were available in English with accessible full text. Studies were excluded if they: (i) focused on unrelated environmental themes without energy-management relevance; (ii) were purely editorial/opinion pieces without technical content; (iii) reported insufficient methodological detail to support interpretation; or (iv) were duplicates or non-scholarly sources.

1.1.3. Study selection workflow

All retrieved records were exported to a reference manager and duplicates were removed. Title/abstract screening was conducted first to remove clearly irrelevant papers, followed by full-text screening against the eligibility criteria. Any borderline cases were resolved by discussion among the authors with a conservative inclusion approach when a study contained substantive system-level energy-management insight.

1.1.4. Data extraction and synthesis

For each included study, we extracted: technology scope (renewables, storage, hydrogen, etc.), application domain (buildings, industrial, grid/microgrid), objective(s), methods (modeling, control, optimization, AI/ML), validation approach (simulation, experiment, field deployment), key quantitative indicators where available (efficiency, cost, emissions, reliability), and implementation constraints (policy, standards, interoperability, safety). Evidence was synthesized using narrative–thematic synthesis (grouping by technology pillar and application context), complemented by cross-comparative mapping that highlights convergent findings, implementation trade-offs, and maturity gaps across technology categories.

1.1.5. Quality appraisal (risk-of-bias analogue)

Because the included studies comprise heterogeneous engineering evidence (models, simulations, pilot deployments, and techno-economic studies), a conventional clinical risk-of-bias tool is not applicable. Instead, we applied a structured quality checklist covering: (i) clarity of problem definition and system boundary; (ii) transparency of assumptions and data sources; (iii) appropriateness of methodology (model/control/optimization) for the stated objective; (iv) presence and rigor of validation (benchmarks, sensitivity analysis, experiments, field data); and (v) completeness of reporting (metrics, limitations). The appraisal was used to weigh confidence in claims and to explicitly flag where evidence is predominantly conceptual or simulation based.

As shown in Fig. 1, the PRISMA-style flow diagram summarizes the study identification, screening, eligibility assessment, and final inclusion of **165** articles in the qualitative synthesis.

1.1.6. Novelty and contribution relative to recent reviews

Several recent review efforts have focused on individual pillars of the green transition (e.g., hydrogen-centric integration studies, storage technology surveys, or grid modernization overviews). In contrast, the contribution of this review is an integrated "green energy management" perspective that unifies: (i) renewable generation technologies (solar, wind, biomass, and hybrid systems), (ii) energy storage options and their operational roles, (iii) hydrogen and power-to-X pathways as flexibility and decarbonization vectors, and (iv) cross-cutting enabling layers including digitalization, artificial intelligence, market mechanisms, and policy/standards. This integrated framing is intentionally management-oriented: it emphasizes how technology choices interact at the system level (planning, operation, reliability, cost, and emissions), rather than treating each pillar in isolation. Accordingly, the review provides a comparative synthesis of implementation trade-offs and maturity, and it consolidates actionable gaps and future research directions to support researchers and practitioners in designing deployable decarbonization pathways.

2. Green technology

Green technology is defined as a collection of procedures for making, adjusting, applying, and comprehending tools, techniques, crafts, machines, systems, and ways to arrange them in order to accomplish a task, solve an issue, enhance a problem that has already been solved, reach a goal, manage and applied input/output relationship, or carry out a particular function [11]. It is the branch of science that studies the creation, usage, and application of technological tools as well as how they interact with society, the environment, and human existence. Numerous modern activities result in unwanted byproducts that damage the ecology on Earth by contaminating and depleting natural resources. When new technology is used, it often raises ethical questions and changes the culture and values of the society. To improve existing systems, it is common practice to compare them to a hypothetical "Ideal system" [12]. Green technology, as the name implies, has a "green" purpose. Green inventions are those that benefit the environment and often involve recycling, energy efficiency, renewable resources, safety and health concerns, and other areas. Natural resources are limited in the earth and some have already been exhausted or destroyed. Toxins

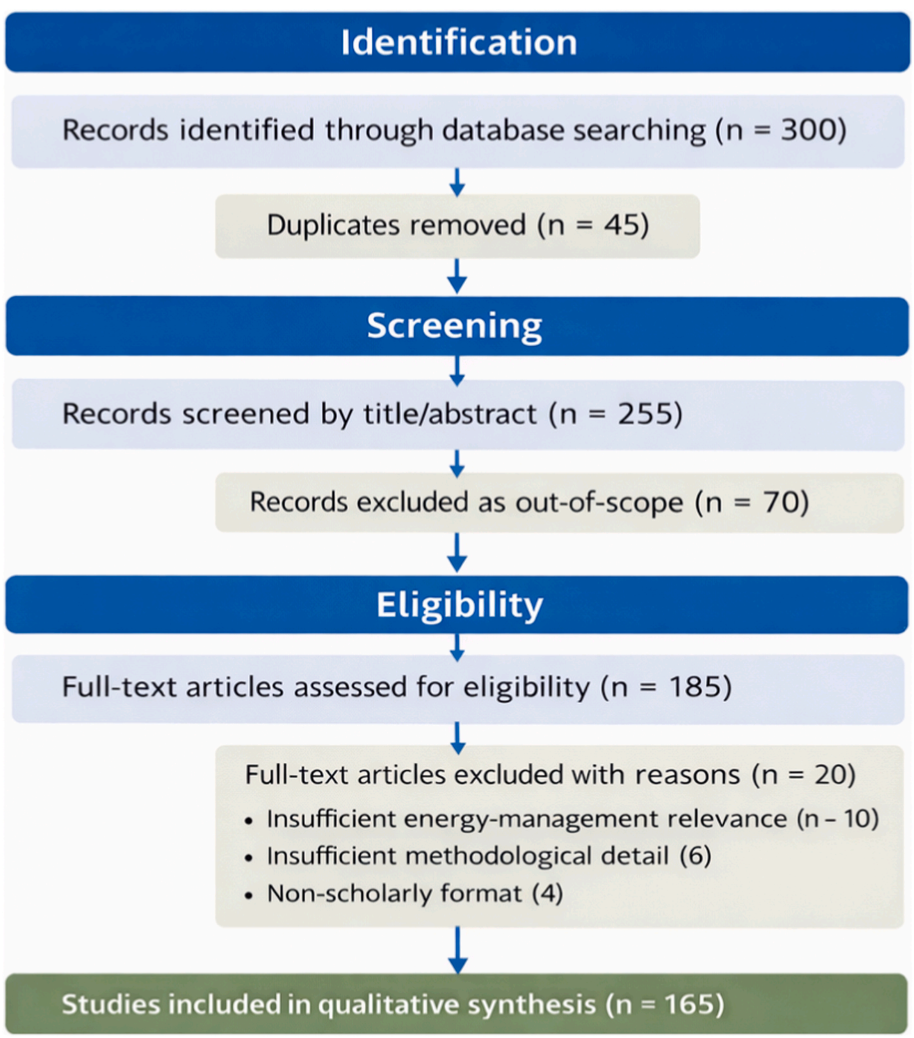

Fig. 1. (PRISMA-style flow summary). Records identified through database.

that cannot be eliminated from drinking water or food crops grown on contaminated land, for instance, are commonly found in household batteries and devices, which can contaminate groundwater after disposal [13].

3. Significance of green technologies in energy management

Sustainability depends heavily on energy, and managing it will always be crucial. The Kyoto Protocol deadline, the best indicator of the current decarbonization of many economic sectors, and the tightening regulations surrounding direct electricity generation by end users also known as self-generation are linked to the energy management process [14]. Green technologies are essential for energy management since they solve major issues and have many advantages. The lessening of environmental effect is one important benefit. Green technologies lessen dependency on fossil fuels and GHG emissions by utilizing renewable energy sources like solar, wind, and hydro power. The vast majority of recent expansions to the world's power capacity have been made possible by renewable energy technologies, demonstrating the clear move towards renewables [15]. Additionally, by lowering use and reliance on pricey fossil fuels, green technologies help to lower energy costs. With the use of solar panels, people and companies can produce their own electricity, reducing their dependency on the grid and their energy costs. Additionally essential to lowering energy consumption and associated operating costs are energy-efficient systems, such as high-efficiency buildings and appliances [16].

Energy efficiency strategies, including maximizing energy utilization and reducing waste, are another emphasis of green technologies. Smart grids, energy-efficient appliances, and building automation are examples of energy-efficient systems that help save energy and save resources. Energy efficiency initiatives have the potential to contribute roughly 40 % of the greenhouse gas emissions reductions required to reach global climate targets, according to projections from the International Energy Agency [6]. A further important factor is increased energy security. According to Ref. [17], green technologies increase energy mix diversification, minimize reliance on imported fossil fuels, and lessen sensitivity to price swings and geopolitical unrest. Decentralized renewable energy sources, such as off-grid solar arrays, also enhance energy security by opening up access to otherwise neglected distant areas [18]. Creating jobs and boosting the economy are two more important advantages. With millions of jobs globally, the renewable energy sector has seen a notable increase in employment and is expected to continue growing [17]. Innovation, investment, and new business prospects are generated by green technologies in industries like energy efficiency, solar power, and wind power.

Green technologies, at the forefront of the drive for sustainable energy management, encompass a wide range of breakthroughs. Referring to Fig. 2 below, there are many types of green technologies used for sustainable power generation. Energy conservation methods, such as the use of smart power bars, open the way for greater resource efficiency. Solar power and wind turbines use renewable energy, making significant contributions to sustainable energy generation [19,20]. Hydropower and geothermal energy broaden the repertoire by exploiting the movement of water and the Earth's inner heat, respectively [21]. Biomass energy diversifies the portfolio by producing energy from organic elements such as plant matter. Solar power captures energy from the sun, wind power converts wind energy into electricity, hydropower generates electricity from the movement of water, geothermal energy harnesses power from the Earth's interior, and biomass energy derives energy from organic materials [22]. For the purpose of storing and managing extra energy, energy storage technologies such as thermal energy storage, pumped hydro storage, and battery storage are essential [23].

In light of this, this paper aims to achieve several goals. First, to perform a thorough examination of different green technologies, defining their uses, capabilities, and contributions to the production and use of sustainable power. This paper seeks to clarify the revolutionary potential of green technology in propelling the shift to a low-carbon economy by a methodical investigation of renewable energy technologies and energy storage options.

3.1. Renewable Green Energy Technologies and management

The electrification of numerous industries, including transportation and housing, has resulted in a notable rise in the need for electricity, making the electrical power field crucial. A rising number of energy resources are needed to generate electricity due to the sharp rise in demand for it. CO_2 emissions are reduced by 76 % when electricity is

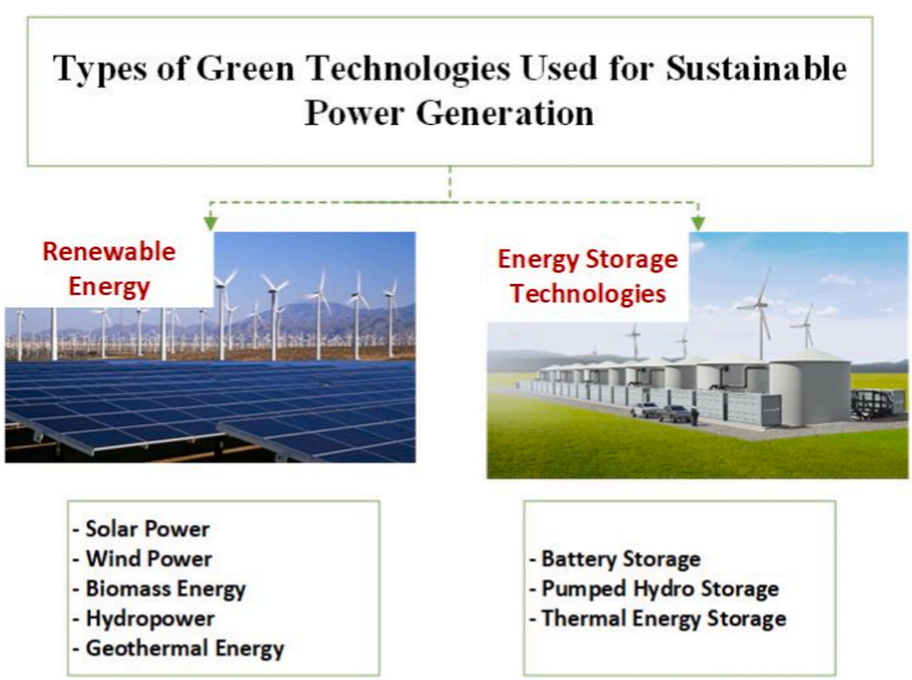

Fig. 2. Types of green technologies used for sustainable power generation.

generated utilizing renewable energy sources (RES) [24]. Although transitioning to renewable energy is expensive, it would minimize the expense by enhancing both the environment and human health. Additionally, the costs of fossil fuels are fast rising [25]. The notion that renewable energy sources are expensive has been disproved by the standardized cost of energy measure. The truth is that solar and wind power technologies are becoming more affordable at a faster rate than most people had anticipated. Nuclear energy and fossil fuels would be substantially more expensive by 2030 compared to renewable energy and storage technologies [26]. A 100 % financial system of renewable energy could be accomplished during 2050, particularly on a regional scale, due to technical advancements, interconnection, storage systems, and rules [27].

Energy is a fundamental component of sustainable development (SD) that is limited by climate change concerns in order to reduce GHG emissions. Sustainable development has developed to consist four topics that serve as sub-goals for sustainable energy development (SED). First, obtain a contemporary energy service at cheap pricing. This refers to the availability of affordable energy sources. Second, sustainable energy supply entails a shift toward ecologically favorable energy resources. Third, consuming sustainable energy, which entails altering present generation and consumption habits. Fourth, ensuring energy supplies, which entails delivering enough amounts of energy in various forms at reasonable costs [28]. RES impacts the electrical power system in numerous ways, including lowering GHG emissions, raising environmental awareness, creating investment opportunities, and generating economic advantages. In addition, it helps with reduced operating expenses, safe energy, a stable power grid, high-quality energy, more jobs, regional and national development, and a smaller carbon impact. Because RES is unpredictable and sporadic, it requires sophisticated control strategies and an efficient energy storage system. Power generation from RES necessitates cutting-edge technology, a novel idea, and a substantial financial investment. RES affects economies differently in developed and developing nations. Generally speaking, the green economy is the foundation of the electrical power sector in order to handle climate change and meet load increase [29].

To optimize efficiency and reduce waste, energy production, distribution, and consumption must be optimized. This is known as effective energy management. It includes a range of tactics and technological advancements to guarantee the dependable and sustainable use of energy resources [30]. Energy management strategies can be implemented at various scales, ranging from private residences to corporations, sectors, and even entire nations [31]. Data analysis, monitoring, and decision-making technologies are also necessary for effective energy management. Systems for managing energy use monitor usage, pinpoint inefficiencies, and offer optimization-related insights. Proactive and well-informed energy management decisions are made possible by predictive maintenance, load estimation, and energy demand

Fig. 3. Renewable green energy technologies.

optimization made possible by advanced analytics and machine learning algorithms [32].

A key component of sustainable energy management is renewable energy, which includes solar, wind, biomass, and geothermal energy. Effective energy management techniques can facilitate the seamless integration of these sources, which provide a range of advantages, into energy systems. As shown in Fig. 3.

3.1.1. Wind energy (WE) management

The Wind Energy technology preceded other forms of renewable energy systems. Furthermore, it ranks second only to hydropower energy. Technologies for wind energy have been developed over many years. Having evolved throughout the years, wind turbines are the primary parts of the wind energy system. Size and capacity increases make this apparent. The growth in generated power as an economic indicator is another. Moreover, the installation of wind turbines in challenging locations. Due to enhance system stability, the growing number of installed Wind Energy systems has resulted in more sophisticated connectivity requirements [33]. The highest power output of most wind turbines was 2 MW between 2005 and 2013, although it is been boosted to 3/3.5 MW. In addition, the tower's height has grown by more than twice as much since 1990, reaching a height of 100 m or more [34]. The nacelle and tower have a significant impact on small-scale wind turbines [35]. The manufacturing of wind turbines is currently advancing technologically, which has resulted to higher limitations. The size of the unit has grown to 3.00 MW and beyond. Consequently, Wind energy has a crucial function in the electrical grid [36]. Government support is driving tremendous growth in the large wind business, whereas the small-scale market is still rather small. Government subsidies and cheaper installation costs are key factors in the proliferation of small-scale turbines [37].

Depending on the layout and orientation of the rotor shaft, wind turbines can be categorized. Vertical axis wind turbines (VAWT) and horizontal axis wind turbines (HAWT) are the two main categories of wind turbines. The generator, gearbox, blades, rotor shaft, and tower are the major components. Every variety has distinct structures and features. In Vertical axis wind turbines, the wind and the rotor shaft are parallel. Every part is installed on the uppermost tier of the tower. In contrast, the rotor shaft of the VAWT is connected to the turbine and is oriented perpendicular to the direction of the wind. At the foot of the tower are the gearbox and generator. Drag-based and lift-based turbines are the two categories into which VAWTs are divided. The simplest type of turbine is the drag-based one. It revolves in the same direction as the wind and the other way around. Because the lift-based turbine needs a powered engine to start, it cannot start on its own. HAWT comes in two forms: downwind and upwind [38]. VAWT offers many benefits, including the ability to extract energy from the air in any orientation, the ability to work at low wind speeds, the ability to make substantially less noise than HAWT, the ability to perform better than HAWT in turbulent wind flow, the ease of installation, and the ease of maintenance. It is perfect for urban settings because of all of these characteristics. For VAWT to produce energy efficiently, an efficient control strategy is required. Fixed pitch or variable pitch control methods are the two most common methods used by VAWT controllers. At low speeds, the variable pitch management method is more efficient and self-starting [38]. The VAWT outperforms the HAWT in tropical and windy areas.

Because VAWT can function in turbulent and low-speed wind conditions, it has been studied for urban applications. It has proven to operate well, be safer, and make less noise [39]. Aerodynamic design characteristics have been utilized in the evaluation of the lift-type VAWT. Every attribute has been assessed to ascertain its benefits and drawbacks [40]. It has also been assessed for uses in both onshore and offshore environments. Modern designs and capacities more than 10 Megawatt are much better suited for offshore WT; onshore WT capability can be increased by adding towers and blades [41]. Lift-type VAWT performance enhancement options have been examined in regard to design, flow monitoring strategies, pitch controller strategies, blade design, and auxiliary power devices [42]. Several criteria have been used in the investigation of VAWT for offshore applications to evaluate its acceptability [43]. Three components make up the duct that supports the VAWT power output: the diffuser, nozzle, and flange. Consequently, there was a maximum 2.9-fold increase in the power coefficient [44]. Involute rotors and wind flow modulators have been suggested as ways to raise the highest possible power coefficient in urban applications [45].

Efficient energy management techniques can facilitate the seamless integration of wind energy, a renewable resource, into energy networks. The goal of energy management in wind power is to balance the stability and balance of the overall energy system while optimizing the economic, reliable, and efficient performance of wind farms. To maximize the energy output of wind farms, it is imperative to identify locations with significant wind resources. Sophisticated methods of wind resource evaluation, like data analysis and wind mapping, aid in the identification of appropriate locations [46]. To reduce wake effects, which occur when downstream turbines receive less wind as a result of turbulence from upstream turbines, wind farms must optimize their turbine configuration. The overall production of energy can be enhanced by strategically placing and spacing turbines [47]. Furthermore, it is crucial to select the appropriate turbine technology taking into account site-specific variables and wind conditions. Technological innovations enhance energy capture and efficiency. Examples of these include larger rotor diameters and taller towers [48].

For wind energy systems to be optimized, resource management and wind forecasting are essential. Robust wind forecasting, attained by sophisticated meteorological models and data analysis, facilitates well-informed choices regarding power generation, grid integration, and energy exchange. Ongoing evaluation and monitoring of wind resources, including the application of LiDAR technology, aid in the identification of performance variances, the optimization of maintenance plans, and the guarantee of optimal turbine operation [49].

Energy storage and demand response are essential tactics for maximizing the utilization of wind energy [50]. Demand response methods modify electricity use in accordance with available electricity, hence facilitating the incorporation of wind generation. With the aid of this demand-side management strategy, supply and demand can be better balanced, improving wind energy usage. When demand is low or wind availability is great, energy storage devices like batteries or compressed air energy storage are essential for storing excess wind energy. In order to provide a steady and dependable supply of electricity from wind sources, this stored energy can be released during times of high demand or low wind availability [51].

In wind energy systems, efficient energy management techniques improve overall system reliability, grid integration, and energy efficiency. We can optimize wind farm operations, reduce intermittency issues, and create a more robust and sustainable energy system by merging wind energy with cutting-edge monitoring, control, and automated technology.

3.1.2. Solar energy management

Earth receives a tremendous amount of solar energy. Through the absorption of photon energy from solar radiation, a photovoltaic cell produces electricity. Creating affordable and effective energy sources is the main objective of technological advancement. Three generations of PV systems can be distinguished. Single- and multi-crystalline silicon makes up the majority of the first generation. Cadmium sulfide (CDS), cadmium telluride (CDTe), and amorphous silicon are the main materials used to make thin-film photovoltaic cells (PV cells) of the second generation. Perovskite solar cells, quantum dot solar cells, and dye-sensitized solar cell applications are examples of the third generation of silicon-free technology [52]. This new technology faces several challenges, including sociotechnical barriers due to lack of data, management issues, poor after-marketing services, and high installation costs. As a result, people are turning to traditional sources of energy, despite governmental impediments caused by missing or inefficient legislation [53]. For photovoltaic cells to be widely used, affordable, highly efficient, have an extended life cycle, and be made of easily obtainable materials, they need to fulfill specific requirements. PV cells based on crystals satisfy each of these specifications [54].

PV solar cells are seeing a new trend with the use of bifacial technology. It arrived on the scene with a tremendous presence. By 2028, it is expected to hold a market share of more than 35 % in photovoltaics. Bifacial photovoltaic cells have many benefits. It increases the amount of power generated by absorbing solar radiation from both directions. Eliminating the metal foundation would result in no power loss. Additionally, because silicon and aluminum have different rates of thermal expansion, it keeps the cell from bending [55]. Bifacial crystalline Photovoltaic solar cells outperform traditional PV cell technology, as demonstrated by the authors in Ref. [56]. Bifacial photovoltaic field research begins in 2009. However, available research is relatively restricted. It has some challenges, such as complex processes and uneven rear-side irradiation. One of the main differences between photovoltaic systems that are mono-facial and bifacial is the back surface of the PV cell. In bifacials, there are electrical connections and an antireflection coating, while in mono-facials, there is only a back surface field. Consequently, photons from both sides could be harvested by bifacial PV cells [57]. Bifacial PV technologies can be classified into six types: passivated emitter rear contact [58], passivated emitter rear locally-diffused (PERL) [59], passivated emitter rear totally diffused [60], heterojunction with intrinsic thin-layer (HIT), interdigitated back contact [61], and double-sided buried contact solar cell [62].

Using hollow semiconductor photocatalysts is another exciting method for photovoltaic cells. The cell can use light more effectively thanks to this mechanism. Currently, efforts to develop high-performance photocatalytic materials are concentrated on the combination of oxides, sulfides, nitrides, and organic semiconductors [63]. The future is bright for hollow nanostructures used in photocatalysis-based photovoltaic cells. It has less of an impact on the environment while producing more energy. Three processes make up the photocatalysis process: surface reaction, charge splitting and transfer, and light absorption. Many benefits stem from the hollow nanostructure: enhanced light utilization through slow photon effects and light diffusion; deactivation of charge integration through decreased carrier separation and charge transition distance; and acceleration of surface reactions through increased surface area and redox reaction discrimination. Numerous issues plague hollow nanostructure-based photocatalysis, such as its narrow scope of use, difficult production procedures, novel, undefined technology, and challenges in producing significant amounts of pure crystalline surface area in an industrial setting [64].

Several energy management techniques can be used to effectively capture and manage solar energy. Maximizing the effectiveness, dependability, and financial sustainability of solar power installations while guaranteeing optimal usage and integration with the broader energy system is the main goal of energy management in solar power [65]. Finding areas where solar radiation is at its highest is crucial to optimizing the energy yield of solar power plants. During site assessment, variables like land appropriateness, shading analysis, and the availability of solar resources are taken into account. For maximum energy production, the solar system's size and configuration must be determined. To optimize solar energy capture, variables like panel orientation, tilt angle, and shade mitigation strategies are taken into account [66]. In Addition, by putting monitoring systems in place, data on the operation of solar panels, inverters, and other parts may be continuously collected [67]. This information aids in locating any problems with system performance, enhancing maintenance plans, and guaranteeing peak system performance. To maximize the effectiveness and durability of solar panels and related equipment, regular inspection, cleaning, and maintenance are important. Timely repairs and early defect identification can maximize energy production and reduce downtime [68].

Batteries and other energy storage devices can deliver excess solar energy during high solar generation periods and store it for use during low or high solar demand seasons. This improves solar power's adaptability and dependability, enabling more efficient use and stable grid conditions [69]. Demand response programs that integrate solar power allow power usage to be adjusted according to solar availability. This optimizes solar energy consumption and lessens grid stress by balancing supply and demand [70]. Optimizing solar energy system performance and integration requires the use of effective energy management techniques. The efficiency, dependability, and general sustainability of solar power in the energy sector can be improved by fusing it with cutting-edge monitoring, control, and storage technology. In order to examine configurations and running regimes beneath sustainability standards, this examine examines sun-pushed hybrid multigrid designs that co-optimize the generation of freshwater and the supply of power. Reliability and resource performance can be progressed by using linking photovoltaic (PV) and concentrated solar energy systems with desalination demands in multi-node grids. It additionally describes techno-financial change-offs that are pertinent to making plans. In strong, low-carbon systems, those findings lend credence to included management frameworks that coordinate water and energy offerings [71].

3.1.3. Biomass energy management

Biomass energy (BME) is regarded by most as one of the most confusing energy sources. They are either linked to combustion, like in conventional energy sources, or they don't fully comprehend how the mechanism works. It is the main source of energy and nutrition for all living things, including humans. BME required that profitable and carbon-free renewable energy be used for proper employment. The word "biomass" is made up of two words: mass, which describes plants, and bio, which describes animals. Because the amount of carbon dioxide released while burning and the amount consumed during photosynthesis are equal, biomass is a carbon-neutral energy source. Furthermore, it doesn't release any additional greenhouse gases like nitrogen dioxide or methane [72]. Biomass fuels account for 10 %–14 % of energy produced globally, 40 % of energy produced in urban areas, and 90 % of energy produced in rural areas. Several forms of energy, such as heat, power, and fuel for vehicles, are produced from biomass. Numerous biofuels, such as bioethanol, biodiesel, biogas, biobutanol, biooil, and bio-hydrogen, are produced from biomass [73]. Three basic types of biomasses exist: solid, liquid, and gaseous. These types are further separated into byproducts and source materials [74]. Growing the use of clean BME, such as biofuels and biogas, benefits both the environment and human growth. On the other hand, widespread use of BME has a negative impact. Technology advancement is linked to the appropriate utilization of biomass. Governments should therefore encourage investment, oversee institutional research, and control legislation that impact BME. This is to hasten the technological advancement of biomass to lower installation and operating expenses. The choice of site is crucial for investors as it lowers transportation expenses and guarantees a sufficient supply of biomass sources. This would reduce greenhouse gas emissions and strengthen the BME sector [75]. Biomass is classed based on the type of vegetation and application, and there are numerous classifications. For example, biomass can be classified according to plant type as woody, herbaceous, animal and human waste, aquatic, or combinations [76]. Woody biomass consists of tree barks and leaves, both above and below ground, as well as tree and root waste [77]. Herbaceous biomass refers to non-woody stem plants including agricultural waste and energy crops [78]. Animal and human waste biomass, like animal manure, flesh, human dung, and bones, is turned into agricultural fertilizer or biogas [79]. Aquatic biomass includes microalgae, macroalgae, and plants that grow partially submerged in wetlands [80]. Biomass mixes are made up of two or more ingredients from the previous classes [81].

Biomass is hard to use in its original state, thus it is transformed into another energy source. Thermochemical, biochemical, and physico-chemical biomass conversion processes are all widely employed [76]. Four phases make up thermochemical conversion: combustion, pyrolysis, gasification, and liquefaction. It involves both chemical and heat reactions. Carbon and biomass are fused together in a hot environment during burning. Water vapor, CO2, and heat are produced during this process. This process generates around 90 % of the overall energy that biomass provides. The main goal of the pyrolysis process is to partially burn biomass at different temperatures in order to convert it into liquid bio-oil, gaseous combustible gas, and solid charcoal. This procedure includes evaporation, drying, distillation, and exothermic processes. The process of gasification is the conversion of solid biomass into synthetic gas. Synthesis gas is used to produce energy and is an essential part of the petrochemical and refining industries. Liquefaction is the process of turning biomass to a liquid biogranule [82]. The biochemical conversion procedure involves the breakdown of biomass to simpler carbohydrates by biological species like bacteria in order to produce liquid fuels and biogas. The two most common types of biochemical conversion are anaerobic digestion and fermentation. Anaerobic digestion is an organic process that produces renewable energy and is used to manage garbage. The process of fermentation is a set of biological reactions that use microorganisms like yeasts to transform simple carbohydrates to ethanol and CO2 [83].

The term "biomass energy" describes the process of producing heat, electricity, or biofuels from organic materials, such as forest debris, agricultural wastes, or special energy crops. Optimizing system performance, minimizing environmental effects, ensuring a sustainable feedstock supply, and maximizing energy production efficiency are the goals of effective energy management techniques in biomass energy systems [84]. It is essential to determine appropriate biomass feedstocks based on sustainability, energy content, and availability standards. To prevent conflict with food crops, sustainable biomass sources are favored, such as agricultural wastes or special energy crops cultivated on marginal lands. Reliability and consistency in feedstock supply are guaranteed through the use of effective supply chain management and logistics strategies. This covers the procurement, warehousing, preliminary processing, and conveyance of biomass feedstocks to the energy production plant [85]. Stoker boilers and fluidized bed boilers are two examples of biomass combustion systems that are optimized for producing heat effectively. In order to achieve high energy conversion efficiency and reduce environmental pollutants, proper combustion management, air-fuel ratio adjustment, and emissions monitoring are necessary [86]. To co-produce firm electricity and green hydrogen, Golaki et al. describe a hybrid energy system that combines biomass heat with compressed-air energy storage (CAES) and a proton-exchange-membrane (PEM) electrolyzer. The paper illustrates how biomass-supplied heat management enhances compression/expansion efficiency and how excess electricity may be directed to PEM electrolysis without causing power block instability by comparing operating modes [87].

3.1.4. Geothermal energy management

An energy source that is dependable and plentiful is geothermal energy (GTE). It contributes significantly to the generation of power in El Salvador (26 %) and Iceland (27 %). It is an emergent RER that originates from the heat inside the earth, mostly from radioactive element decay and molten magma. It is separated into three categories: hot dry rock resources, subsurface thermal water, and shallow GTE. A low temperature concentration in soil, gravel, and water that is less than 200 m below the surface is known as shallow surface GTE. Thermal water below 4000 m in depth that is over 25 °C. Resources of hot, dry rock that are over 150 °C are buried 3–10 km below the surface [88]. Heat production and electricity generation are the two main uses of GTE. By 2050, GTE is expected to produce two to three percent of all electricity produced [89]. The basic idea behind a geothermal power plant is to use water or another hydrothermal fluid to absorb the earth's natural thermal energy. The turbine, which is attached to generators, turns because of the pressured steam produced by the hot water. There are three different kinds of power plants used: binary cycle, flash steam, and dry steam. Thermal energy is produced in a dry steam power plant by pumping a hydrothermal fluid deep beneath. The steam was then transformed and used to power a turbine, which generated electricity. The steam would then be condensed and reinjected into the well. The former procedure is repeated in a flash steam power plant; However, the raised steam is directed toward a steam divider that is filled with a very hot hydrothermal fluid that is converted to steam before being divided. The turbine was powered by this split steam. For this plant to function, the temperature must be higher than 182 °C. When using binary cycle power, the heat is transferred to a different hydrothermal fluid that boils less quickly. There, it is transformed into steam and used to drive the turbine, which produces electricity [90].

Bio-thermal energy has been converted into electricity using five different processes. Dry steam, binary cycle, single and double steam, and other intricate conversion systems incorporating the hybridization of numerous technologies are all included in these power plants [91]. GTE can be used right away in many different contexts. It might be used, for instance, in space heating, heat pumps, and thermal industrial processes. Additionally, it can be used to dry vegetables and in greenhouses. Applications for the home include bathing and swimming, melting snow, and space heating and cooling [92]. There has been an increased focus on heating and cooling systems in residential buildings. To extract more thermal energy and reach deeper levels, better techniques have been developed. It has also been suggested to use lower temperatures at lower depths to reduce heat loss and the amount of contaminated substances that enter the system [93]. Using GTE to generate hydrogen is a potential area of research. The production of hydrogen from geothermal power plants has been researched in terms of thermodynamics, techno-economics, and environmental implications [94]. Various geothermal power plants were examined to determine the most efficient technology for producing hydrogen. The flash-steam mixed cycle and binary cycle exhibit higher efficiency [95]. To get adequate temperatures for big projects, additional depth is required. Deep GTE necessitated the use of advanced techniques including hot dry rock, U-tube single-well, closed loop single-well, and open loop single-well [96]. To optimize GTE efficiency, enhanced geothermal power plants use hot, deep-dry rock that is between 120 and 220 °C. The idea of operation is to infuse water with heat from hot, dry rock, which is subsequently converted to steam to generate energy. A circular loop is created by injecting the drained fluid once again [97]. In order to place the system within the water–energy–food (WEF) nexus, this has a look at assesses anaerobic digestion–based totally pathways to ammonia by means of undertaking strength and exergy accounting across biogas production, upgrading, and ammonia synthesis. The thermodynamic hotspots (along with compression and reforming) are identified, and it is demonstrated how warmth integration and renewable strength coupling can increase typical electricity performance while reducing NH_3 emissions intensity [98].

Different extraction methods, including single well, doublet, or multilayer layouts, can be used to manage geothermal reservoirs. In order to enhance energy extraction and reservoir performance, energy management procedures comprise improving well design, flow rates, and reinjection strategies [99]. Reintroducing the extracted fluids into the reservoir is a necessary step in the sustainable functioning of geothermal systems in order to sustain reservoir pressure. Energy management techniques reduce the possibility of induced seismicity and guarantee appropriate reinjection rates [100].

Effective energy management systems are critical for guaranteeing the stability, reliability, and cost-effective operation of stand-alone microgrids powered by renewable energy sources [101]. Overall, renewable energy technologies play an important role in optimizing energy management in a variety of settings. Table 2 shows numerous

Table 2
Studies on Renewable Energy and its Relationship to Energy Management.

No	Reference	Insights	Methodology	Contributions
1	[102]	The paper examines project management in the wind energy area, specifically the appraisal of wind energy projects employing the net present value method.	- The Net Present Value (NPV) Method -Examining wind energy projects before installation	-This study offers a strategy for appraising wind energy projects. -The approach aids in deciding whether a wind energy project is worth pursuing.
2	[103]	The paper discusses a wind-hydrogen system with a speed-adjusting mechanism for steady grid connection, highlighting the need for optimal energy allocation and continuous operation.	-For wind power generation, a speed-regulating differential mechanism (SRDM). -Mathematical modeling using the energetic macroscopic representation (EMR) approach	-Outlining the best allocation scheme for consistent performance and maximum income
3	[104]	The study emphasizes the importance of energy management systems in wind storage systems for enhanced reliability, efficiency, grid security, wind power usage, and reduced lifetime costs.	-The development trend of energy management systems -Key technology in the wind storage energy management system	-Improving system efficiency, grid security, and wind energy use. -Reducing total life-cycle costs.
4	[105]	The paper presents an energy management strategy for a solar photovoltaic system with hybrid storage, focusing on optimizing battery storage and collaborating with supercapacitors and panels.	-The article provides an energy management strategy (EMS) for battery energy storage systems (BESS), photovoltaics (PV), and supercapacitors. -The Meta-heuristic Jaya method is used to optimize BESS flow rate, discharge, and charge cycles.	-The proposed energy management technique optimizes the energy system's flow rate, discharge, and charging cycles. -The method decreases battery stress and increases battery life.
5	[106]	The paper describes how to integrate solar energy and energy management in a microgrid system by utilizing hybrid energy storage alternatives and a power management method.	-Integration of various hybrid energy storage options. -Use of maximum power point tracking (MPPT) circuits and converters.	-Active management technique that incorporates several hybrid energy storage alternatives. -Photovoltaics, fuel cells, supercapacitors, and batteries are all integrated into the system.
6	[107]	The paper explores the potential of bamboo biomass for energy production, its advantages and disadvantages, and proposes solutions to issues related to biomass burning in power plants.	-The study used desk research as a secondary method. -The information was gathered from international literature as well as yearly reports from energy firms.	-Companies should reduce the carbon level of their products by 20 % by 2030, 45 % by 2035, and 100 % by 2050. -Bamboo biomass can serve as a renewable energy source for thermal power plants.
7	[108]	The study examines energy management in a hybrid power system that combines biomass and solar photovoltaics. It mentions the biomass gas generating facility as one of the system's energy sources.	-Power management solutions include dispatch, load-following, and cycle-charging. -Algorithm and storage units for efficient energy system operation.	-Pilot projects using integrated hybrid microgrid energy systems in various geographic regions. -Research on hybrid configurations of renewable energy systems using various optimization algorithms.
8	[109]	The research explores the use of ground source heat pumps with high temperature terminals to enhance energy efficiency in museums, emphasizing the importance of energy management policies.	-Ground-source heat pump with high temperature terminals -Energy management policies	-Ground-source heat pumps can help museums increase their energy efficiency. -Energy management policies are critical to lowering energy use and expenses.
9	[110]	The study underscores the importance of comprehensive energy management strategies at local, regional, and national levels for the efficient development and utilization of geothermal resources.	-Using geothermal systems to reduce energy consumption in district heating and cooling. -Modeling shallow geothermal energy systems.	-Geothermal stress phenomena must be carefully monitored in geothermal energy systems. -Rules and Regulations, education, and energy management are all key parts of geothermal resource development.

studies of renewable energy and its effect on the energy management.

3.2. Green energy storage technologies management

Renewable energy sources are rapidly rising in the electrical grid due to a growing demand for power and a decreasing reliance on conventional energy sources. Energy storage systems (ESS) and renewable energy resources can be integrated more effectively thanks to the microgrid. The need for electrical energy has significantly increased in the industrial, transportation, and communication sectors [111]. Renewable energy sources are essential to supplying the increasing need for energy. RES has inadequate load following and cannot be dispatched. If ESS is successfully implemented, these limitations can be removed. Batteries, flow batteries, and supercapacitors are just a few of the methods that RES energy can be stored. Compared to ordinary capacitors and secondary ion batteries, supercapacitors are more powerful [112]. Therefore, ESS significantly contributes to power generation by enabling a variety of energy sources to meet load requirements. ESS can help lower power intermittency because most RES rely on meteorological conditions to generate power. Thus, ESS like batteries, flywheels, ultracapacitors, and thermochemical storage mechanisms can be widely used to supply the user with continuous power, see Fig. 4. Conventionally, fossil fuels are easily stored and can produce electricity whenever the customer requests them. Resources for renewable energy as opposed to fossil fuels, can only provide energy when there is wind or sunlight. When there is excess energy generated or when it is not in use, ESS can store it. In addition to providing more services, ESS can control frequency and voltage, manage power fluctuations, and improve power quality [113].

Batteries, flywheels, supercapacitors, compressed-air energy storage, pumped hydro, hydrogen storage, and superconducting magnetic energy storage (SMES) devices have all been created as a result of this desire. Chemical, mechanical, electrical, and electrochemical are the four basic categories of these technologies. Batteries are regarded as a key ESS for ensuring stability of the power system [114]. ESS is essential in off-grid systems because it regulates power fluctuations, frequency, and stability. Moreover, combining different energy storage devices could work well for managing and storing electricity for use when needed [115]. Fig. 5 below illustrates how different methods of energy storage are categorized.

3.2.1. Green electrical and electrochemical energy storage and management system

Electrical energy can be electrochemically stored in batteries and capacitors. Three types of capacitors are distinguished: electrochemical, electrostatic, and electrolytic. Electrochemical capacitors are one of the capacitor kinds that were previously described. They have a large capacity per unit volume because of their complex electrode structure. These capacitors are sometimes referred to as supercapacitors or ultracapacitors (UC). Batteries have outstanding energy density and cutting-edge technology. For a wide range of applications, there are several battery alternatives. Flow, nickel-cadmium, sodium-sulfur, zebra, lead-carbon, lithium-particle, and stream are among the several types of batteries. The cost, power, density of energy, safety, and longevity of batteries have all been evaluated and improved with a variety of electrolytes and terminal materials [114]. In Ref. [116], the authors provided a summary and comparative analysis of several electrochemical energy storage technologies, such as premier corrosive battery and nickel hybrid-related battery. In Ref. [117], the authors emphasize recent improvements in battery technologies to increase their performance. In Ref. [118], The authors emphasized cutting-edge techniques such electrolyte moderating, coatings over active materials, doping, functionality, and reducing the size of active materials. The presentation highlighted the characteristics, difficulties, and present level of technology for the anode and cathode components of lithium batteries. Due to its incredibly specific energy and energy density, lithium-based (Li-based) batteries are among the several battery kinds that are essential to ESS. An electric car powered by a charged Li-air battery could eventually replace petroleum in terms of useful energy density. A few technological challenges, such as cathode structure restoration, lowering electrolyte compositions, and clarifying chemical interactions while facilitating easier battery charging and discharging, need to be overcome before Li-air batteries are widely used [118,119]. Prior to using Li-air batteries, the researchers made an effort to offer a thorough evaluation in Ref. [120] to guarantee that the benefits, restrictions, and challenges are all clearly understood [121] compared the characteristics of Li-air and Li-sulfur batteries to those of Li-ion batteries and looked at possible advancements in Li-ion battery technology.

Energy storage devices, both electrical and electrochemical, are essential for managing and storing electricity in a variety of applications. These devices give the grid flexibility and stability by storing and releasing energy through electrochemical reactions [122]. Optimizing energy storage efficiency, maintaining system reliability, and making the most use of stored energy are the three main goals of energy management techniques in electrical and electrochemical energy storage systems [123].

Electric vehicles (EVs), portable devices, and grid-scale energy

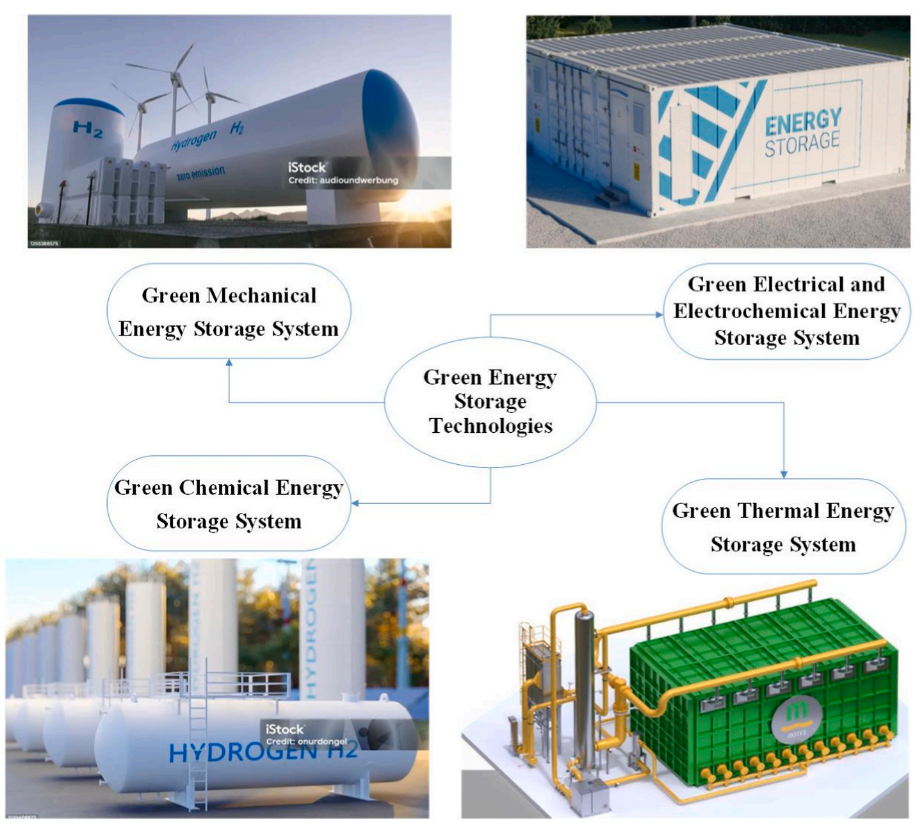

Fig. 4. Energy storage in green technologies.

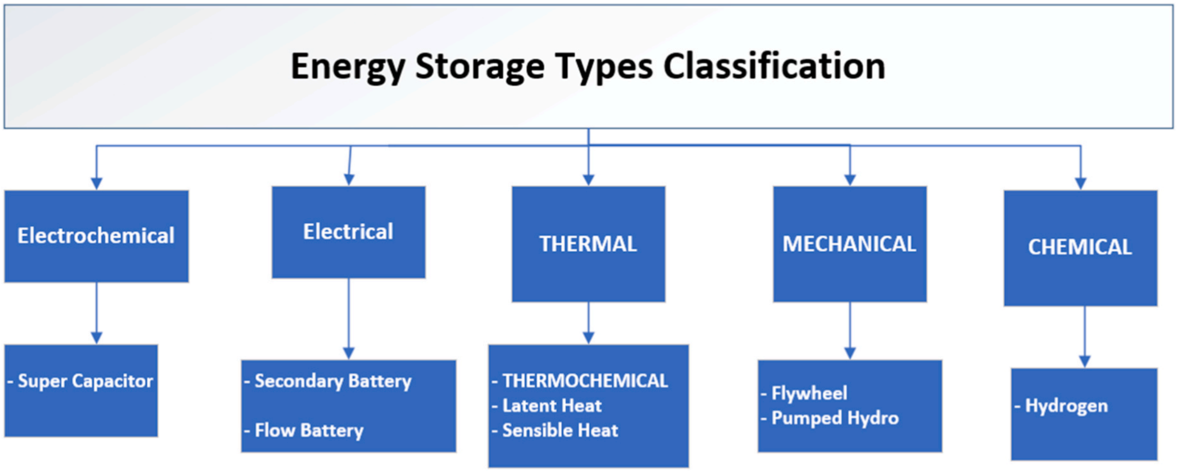

Fig. 5. Types and classification of energy storage system.

storage all frequently employ lithium-ion batteries. Battery management systems (BMS) are used, sophisticated algorithms are used for charging and discharging control, and batteries' states of charge (SoC) and health (SoH) are monitored as part of energy management procedures [124]. Energy management for grid-scale applications is centered on maximizing battery charging and discharging rates to maintain grid stability, balance supply and demand, and offer frequency regulation. Optimizing scheduling and dispatch techniques can be achieved by utilizing intelligent algorithms and predictive analytics [125]. Liquid electrolytes are used by flow batteries, including vanadium redox flow batteries (VRFB), to store energy. Energy management techniques include monitoring the electrolyte and charge conditions, optimizing the charge and discharge cycles, and regulating the electrolyte flow rate. The lifespan and efficiency of a system can be increased by utilizing advanced control systems [126]. Supercapacitors, sometimes referred to as ultracapacitors, use the electrostatic charge at the electrode-electrolyte interface to store energy. Energy management techniques include monitoring voltage and current levels, regulating charging and discharging rates, and putting in place effective power electronics for energy conversion [127]. The goal of energy management is to optimize power delivery and energy flow to meet the particular needs of each application.

Lithium-ion batteries and supercapacitors have complimentary functions in energy storage systems. Supercapacitors are perfect for applications needing quick energy delivery, including high-frequency devices or regenerative braking systems, because of their exceptional power density and robustness. However, lithium-ion batteries have a far higher energy density, which makes them essential for long-term energy storage in renewable energy systems and electric cars, see Table 3. Their short lifespan and slower recharge rates, however, make them less useful in high-frequency situations. The potential of hybrid storage solutions, which combine the advantages of both technologies to maximize energy system performance, is highlighted by this trade-off.

3.2.2. Green thermal energy storage management system

Thermal energy storage is the process of keeping heat or cold in a medium-sized storehouse. It consists primarily of a heat-extraction or heat-injection device for the storage medium and storage componentry. A structure composed of soil or a container that either retains heat or absorbs it from the environment can serve as the storage medium. The three primary categories of thermal energy storage mechanisms are sensible modes, latent modes, and thermochemical modes. Heat is often stored at a moderate temperature, which contributes to the containers' increasing heat. Examples of thermal energy storage techniques include hot water storage, subsurface thermal energy storage, as well as rock-filled storage [130]. Latent heat storage is the technique of varying the length of a storage material, typically between strong and fluid phases, though accessible stage transitions of liquid-gas and solid-solid are additionally recorded. The isothermal stage shift cycle, low weight/capacity constraint, and conservative design of the latent heat storage system have made it more and more popular. Compared to other heat storage materials, its thermal characteristics have improved, especially its constant phase transition temperature and high latent heat. Water, eutectic salts, fatty acids, paraffin waxes, esters, and other typical phase change materials are used as storage mediums [131].

Seasonal variations or shorter time intervals may be observed in the heat distribution of thermal energy storage systems. The maximum amount of energy can be used to sustain the heat required for long-term storage system functioning. A great example of this is ground heat storage, which is attached to the building to collect heat. In the summer, this gadget may release heat, and in the winter, it may use heat. Storing summertime solar thermal energy for use in the winter is a similar tactic. The devices have a lower energy storage capacity and can only hold heat for just a few hours to a short period of time. These devices can be used to store solar thermal energy during the day for use in the cooler months later on. By collecting thermal energy throughout the day, homes equipped with thermal energy storage systems can lower their electricity bills [132]. There have been several advancements in thermal energy storage systems that are detailed in Ref. [133]. The mechanisms of thermal energy storage, properties of heat materials, design strategies, and thermal enhancement methods for latent and heat energy storage systems were discussed by the researchers. To improve the features of thermodynamic media and find new storage mediums, research on latent heat-storing systems is essential.

Systems for storing and releasing thermal energy can be used to provide heating or cooling as needed. These technologies aid in peak demand reduction, energy optimization, and increased heating and cooling process efficiency. In thermal energy storage systems, energy management techniques include maximizing the use of thermal energy that has been stored, regulating energy flows, and optimizing storage efficiency. In order to store and release thermal energy, sensible heat storage systems heat or cool a storage medium, including water, rocks, or phase-change materials [134]. To reduce energy losses and increase

Table 3
Comparative Analysis of Supercapacitors vs. Batteries (Lithium-Ion).

Parameter	Supercapacitors	Batteries (Lithium-Ion)	References
Energy Density (Wh/kg)	5–10	150–250	[128]
Power Density (W/kg)	10,000	200–2000	[128]
Charge Cycles	1,000,000	500–3000	[129]
Charge Time	Seconds	Minutes to Hours	[128,129]

storage efficiency, energy management techniques include temperature differential control, thermal insulation, and process optimization for heat transfer. The main goal of energy management is to balance the thermal energy supplied from the storage system with the amount of heat or cold that is required. When there is a surge in energy demand or when there is extra thermal energy available, the control system can activate the storage system by monitoring the temperature inside the system or the temperature of the process [135]. In Addition, Phase Change Materials are materials that undergo phase transitions from solid to liquid or liquid to gas, which store thermal energy. For optimal storage capacity and performance, energy management techniques include choosing PCMs with the right phase change temperatures, refining the charging and discharging submissions, and guaranteeing effective heat transmission during phase transitions [136].

Reversible chemical reactions are used in thermochemical energy storage devices to store and release energy. For energy storage and release processes, energy management techniques include maximizing reaction conditions, managing reactant flow rates, and guaranteeing effective heat transfer [137]. System performance and storage efficiency are optimized through the use of sophisticated control mechanisms. In order to control heat exchange processes, optimize the insulation and thermal qualities of the storage medium, and implement predictive control algorithms to manage the movement of energy and guarantee effective energy storage and retrieval, seasonal storage systems must employ energy management strategies [138]. Advanced adiabatic compressed-fuel (air) power storage (AA-CAES) configurations are compared between single - and multi-level layouts, strain ratios, and thermal storage media. This evaluation demonstrates how efficient heat capture/reuse will increase round-trip performance in contrast to diabatic designs. With regard to grid-scale flexibility services, the object affords design tips through highlighting length and vicinity elements (caverns vs. Vessels) as well as the effect of thermal stock on price and performance [139].

3.2.3. Green mechanical energy storage management system

A flywheel energy system is another name for kinetic energy (KE) storage. Energy efficiency and performance are improved via mechanical energy storage. KE is moved in and out of the flywheel using this manner using an electric device that functions similarly to a motor or generator, depending on the charging or discharging mode. Flywheels are frequently made of permanent magnet machines due to their high power density, low rotor losses, and excellent efficiency [140]. The spinning mass of a flywheel stores charging power through the utilization of kinetic energy. When it's time, you can use this stored energy. By handling the spinning mass in a vacuum, magnetic bearings reduce frictional losses [141]. The rotational bearing system might be magnetic, mechanical, or a combination of the two. Magnetic bearings are frictionless since they don't need to be lubricated. But in order for its intricate control system to function, more electricity is needed. Superconductive magnetic bearings are frequently used in high-speed applications, but a cryogenic cooling system needs to be powered by electricity. High speeds and power are best achieved with density flywheels during energy storage is directly proportional to mass and speed squared [117]. Flywheel rotors and casings can spin at 10,000 RPM and are constructed of composite materials such stainless steel alloys [140].

Systems for mechanical energy storage store and release energy as kinetic or mechanical potential energy. These systems offer versatility in regulating energy supply and demand, mitigating variations in the grid, and bolstering grid stability. In mechanical energy storage systems, energy management techniques include maximizing the use of mechanical energy that has been stored, regulating energy flows, and optimizing storage efficiency [142]. Flywheel energy storage devices use a high-speed rotor's rotating motion to store energy. To increase storage efficiency, energy management techniques include rotor speed optimization, energy input and output control, and frictional loss minimization [143]. To control rotor speed, keep an eye on system

Table 4
Studies on Green Energy Storage and its Relationship to Energy Management.

No	Reference	Insights	Methodology	Contributions
1	[160]	This research explores a hybrid energy storage system for electric vehicles, utilizing batteries and supercapacitors, and focuses on designing an energy management system to maintain DC link voltage and prolong battery life.	- Developed a power management strategy for a hybrid energy storage system using batteries and supercapacitors. - Developed battery-based bidirectional converters for charging electric vehicles.	- Proposed control approach to increase battery life. - A dual-purpose DC-DC converter that charges and discharges batteries.
2	[161]	The research examines energy storage technologies and energy management in the context of hybridizing energy storage systems (HESS) in electric vehicles.	-Comparison and benefits of energy storage methods -Presentation of hybrid energy storage system (HESS) architectures.	-A comparison of energy storage technologies and HESS topologies. -Presentation of cutting-edge energy management solutions for HESSs.
3	[162]	The paper discusses using a small-scale PV-Wind-Battery hybrid system to manage energy storage in a building, as well as using electric vehicles as mobile storage batteries.	-Combination of renewable energy and transportation electrification. -Energy storage management system based on vehicle-to-home and home-to-vehicle strategies.	-Combination of renewable energy with transportation electrification for a sustainable future. -Proposal for an energy storage management system based on vehicle-to-home and home-to-vehicle strategies.
4	[163]	The study offers an energy management system for a pure electric vehicle using a Li-ion battery and a supercapacitor (SC). The study concentrates on the use of regenerative control and lowering battery degradation factors.	-Energy management system (EMS) for power split in a dual-source. HESS is a technique that uses -Energetic Macroscopic Representation (EMR) to design and organize systems.	-Developed an energy management system for a dual-source Hybrid Energy Storage System. -The suggested architecture and EMS were evaluated via simulation using Matlab/Simulink modeling.
5	[164]	The study enhances the performance of a hybrid energy storage system (HESS) in a plug-in hybrid electric vehicle (PHEV) by integrating gradient boosting decision tree technique.	-Jellyfish searching optimizer (JS) -Gradient boosting decision tree algorithm (GBDT)	-Created the best control plan possible for hybrid energy storage systems' energy management. -using gradient boosting decision tree methods and jellyfish search optimizer.
6	[165]	The study examines energy management solutions for battery-	-Classification and explanation of energy management strategies	-Investigates the difficulties, advantages, costs, and applications of

(continued on next page)

Table 4 (*continued*)

No	Reference	Insights	Methodology	Contributions
		ultracapacitor hybrid storage systems for electric vehicles.	-Comparison of techniques using various indexes	hybrid energy storage systems in electric cars. -Investigates cutting-edge energy management strategies for hybrid battery-ultracapacitor storage systems.
7	[166]	The study explores the role of grid-connected Li-ion battery energy storage systems (BESS) in power markets, focusing on battery modeling, BMSs, and challenges in their establishment and management.	-Evaluate the present state of operating grid-connected Li-ion BESSs. -Analyze battery modeling, BMS architecture, and integration with power markets.	-Review and assessment of managing grid-connected Li-ion BESSs -Integration of BESSs with electrical market services
8	[51]	The study emphasizes the necessity of energy management systems (EMSs) and optimization techniques for effectively utilizing energy storage technologies as dynamic grid assets.	-An overview of grid-scale energy storage. -Review of EMS architectures and the top storage applications.	-Grid-scale energy storage devices enhance grid infrastructure's flexibility, resiliency, and robustness. -Effective utilization requires energy management and optimization methodologies.

characteristics, and guarantee safe operation, advanced control systems are used. Flywheels are the main tool used in energy management to control grid frequency, reduce oscillations, and improve grid stability [144].

When there is excess energy, water is pumped from a lower reservoir to a higher reservoir and then released through turbines to generate electricity during peak demand [145]. This process is known as pumped hydro storage. Optimizing pumping and producing schedules, regulating water flow rates, and guaranteeing effective conversion of potential energy into electrical energy are all part of energy management methods [146]. Pumped hydro storage, which offers frequency control, energy arbitrage, and grid balancing services, is essential to system stability. In order to promote grid efficiency and dependability, energy management focuses on optimizing power generation, reacting to demands on the grid, and taking part in ancillary markets [125].

3.2.4. *Green chemical energy storage management system*

Chemical energy storage systems are reversible chemical reactions that require a significant amount of energy to store energy. As with electrochemical energy storage systems, chemical energy storage systems might be grouped based on their energy consumption. Hydrogen is created in a hydrogen energy storage device by electrolysis, held in reserve, and subsequently exposed to oxygen. Hydrogen is produced by chemical processes. Hydrogen was not considered as essential a source as electricity for a long time. Electricity and hydrogen have complementary qualities. The hydrogen economy was proposed by studies and covers the production, delivery, and storage of hydrogen as well as its energy and utilization [147]. Comprehensive energy and energy assessment of green hydrogen power systems show that operating conditions, thermal integration, and electrolyzer efficiency all have a

Table 5
Comparative analysis of green technologies.

Technology	Effectiveness	Cost-Efficiency	Scalability	References
Solar Power	High efficiency in sunny areas, reliable and scalable.	Lower expenses, higher initial cost.	High scalability, appropriate for systems that are decentralized.	[53]
Wind Power	Scalable, reliable, and very efficient in windy areas.	Competitive levelized cost of energy (LCOE), high initial cost.	High scalability, requirement for a sizable amount of land or sea.	[35]
Geothermal Energy	Reliable and highly efficient baseload power.	High initial cost, low ongoing expenses.	Geographical restrictions, moderate scalability.	[90]
Biomass Energy	Adaptable feedstock with moderate efficiency.	varying expenses based on the feedstock.	High scalability combined with environmentally friendly sourcing.	[85]
Battery Storage	Crucial for intermittent renewable energy sources, reliable.	Costs decreasing but still high.	High scalability with technological advancements.	[118]
Pumped Hydro Storage	Extremely efficient for extensive storage.	High upfront cost, low ongoing expenses.	Restricted by appropriate geographic regions.	[125]
Hydrogen Storage	High energy content; beneficial for sector-coupled and seasonal storage	Moderate to Low (electrolysis is still expensive)	Medium to High	[22]
Thermal Storage	Excellent for solar thermal power plants due to its high thermal retention	High	Medium (only applicable to systems that use heat)	[23]

significant impact on system performance. These assessments provide important information to improve the overall sustainability of renewable energy systems and maximize hydrogen-based energy storage [148]. The study [149] highlights the effects on the environment, the hydrogen economy, and atmospheric conditions. effects on new electrical non-heat motor energy converter power modules used in small devices for fixed and flexible applications, in addition the decarbonization of fossil fuel power plants. Hydrogen is commonly produced through the process of water separation. Energy from renewable sources or petroleum derivatives can be used to power this technology. RES needs to be maintained for lengthy periods of time because it is sporadic and transient in nature. Because environmentally friendly power is often limited, it should be saved before being used. The authors of [150] evaluated the solar concentration system with thermochemical water-splitting process, photo conversion, solar thermal system with electrolyzer and turbine, and solar cell and electrolyzer mixture in order to produce hydrogen using sun energy.

For hydrogen fuel cell systems to operate efficiently, control and administration must be done correctly. This entails preserving ideal operating circumstances, regulating reactant flow rates, controlling humidity and temperature, and distributing power output [151]. By improving reactant usage, limiting voltage losses, and reducing parasitic losses, energy management techniques aim to maximize the performance and efficiency of fuel cells. For the purpose of preserving ideal

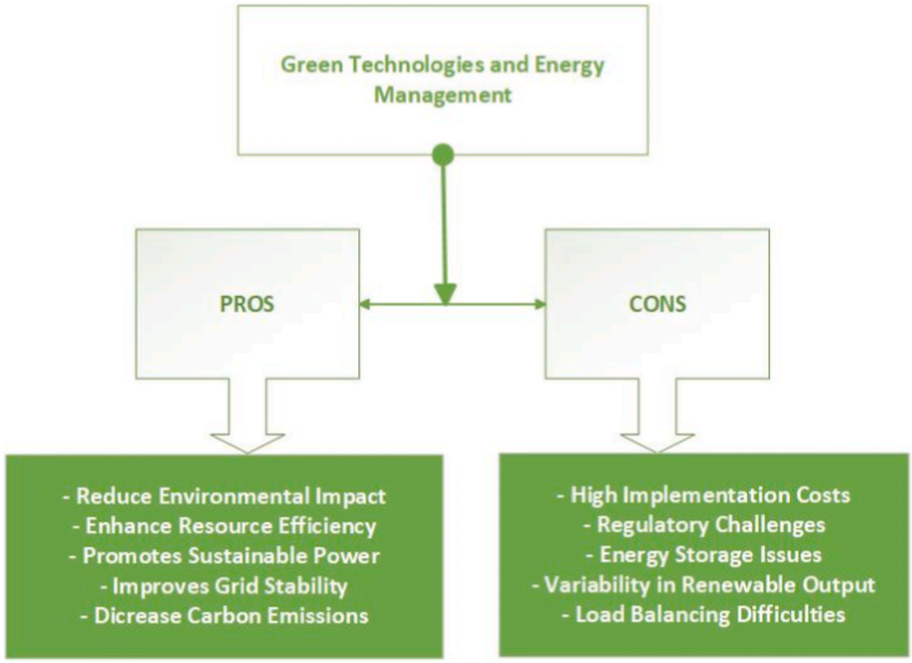

Fig. 6. Pros and cons of green technologies.

operating parameters, sophisticated control algorithms and monitoring systems are used [152]. Hydrogen fuel cell systems depend heavily on the efficient storage and transport of hydrogen. In order to guarantee a secure and effective supply of hydrogen, energy management procedures optimize hydrogen storage techniques, such as solid-state storage, cryogenic storage, and high-pressure tanks [153]. Establishing infrastructure for hydrogen production, storage, delivery, and recharging is another aspect of energy management. For fuel cell devices to be widely used, it is essential to coordinate hydrogen availability and manage the logistics of hydrogen supply chains [154].

Efficient energy management is necessary for integrating hydrogen fuel cell systems with other parts, including power electronics, energy storage, and renewable energy sources. This entails assuring smooth integration with the current energy infrastructure, optimizing power flows, and managing the operation of various system components [155]. Enhanced energy management capabilities can be obtained via hybrid systems that integrate batteries or other energy storage technologies with hydrogen fuel cells [156]. In order to effectively satisfy dynamic power demands, energy management concentrates on optimizing the supply and consumption of both hydrogen and stored electrical energy [157]. Solid-state batteries, which might be predicted to reach industrial scalability with the aid of 2025 because of developments in lithium metal anodes and sulfide electrolytes, are one instance of recent power storage breakthroughs [158]. In a comparable vein, better PEM electrolyzers and the incorporation of renewable energy resources have decreased the value of hydrogen electrolysis from $5–6/kg in 2020 to much less than $3/kg in pilot tasks through 2024 [18]. The practical application of green hydrogen technology in energy systems has been demonstrated by extensive research and demonstration programs across the EU, focusing on grid integration, electrolysis and storage powered by renewable energy sources. These programs demonstrate that hydrogen is a viable strategic energy source for achieving long-term decarbonization goals [159]. Green Energy storage technology and energy management are critical for increasing power system flexibility, efficiency, and security. They also facilitate the integration of renewable energy sources and multifunctional coordination. A variety of approaches and systems have been developed to improve energy storage and management. Table 4 lists numerous studies on energy storage technologies and the methodology utilized in each.

A thorough comparison analysis is necessary to give a greater knowledge of the advantages and disadvantages of various green technology and energy management strategies. In order to provide a current viewpoint, this section examines the effectiveness, cost-efficiency, and scalability of various technologies, depending on recent publications. This analysis shows the crucial factors influencing the adoption and integration of renewable energy sources including solar, wind, geothermal, and biomass energy together with energy storage options like battery storage and pumped hydro storage, highlighting their contributions to improving energy efficiency and lowering greenhouse gas emissions. The purpose of this thorough comparison is to educate industry experts, researchers, and policymakers on the relative benefits of each technology, enabling them to make well-informed decisions and encouraging the adoption of sustainable energy solutions. Table 5 provides an updated viewpoint by comparing the scalability, cost-effectiveness, and effectiveness of various technologies, depending on recent research.

The comparison analysis demonstrates the benefits and drawbacks of different green technologies with respect to their efficacy, affordability, and scalability. Because of economies of scale and technological developments, solar and wind power are becoming more and more cost-effective [53]. They are more appealing overall because of their scalability, which makes them appropriate for both large- and small-scale applications. In renewable energy systems, energy storage technologies like pumped hydro storage and battery storage are essential for maintaining supply and demand balance. Despite its geographic limitations, pumped hydro storage is more economical for large-scale energy storage, even though battery storage offers great flexibility and quick response times [118].

3.3. Digitalization and AI-enabled green energy management

Machine-learning (ML)–enabled control can outperform traditional rule-based dispatch in renewable-dominated systems because it can learn nonlinear relationships from historical and streaming data, update decisions under uncertainty, and co-optimize multiple interacting assets (e.g., PV, wind, batteries, hydrogen/Power-to-X units, and demand response) in high-dimensional decision spaces. Rule-based approaches (fixed thresholds, static heuristics, or pre-defined schedules) are

Table 6
Challenges, barriers, and proposed solutions in green technologies.

Green Technology	Challenges and Barriers	Proposed Solutions	References
Solar Power	High starting costs, problems with interconnection, trade regulations, land usage, erratic behavior, and a requirement for energy storage	Improvements in energy storage technology, international trade agreements, government subsidies, and greater grid integration policies.	[54]
Wind Power	Wind resource fluctuations, environmental effects (such as bat and bird mortality), large initial costs, noise pollution, and problems arising from land use	Government subsidies, improved turbine technology, wildlife-friendly turbine designs, development of hybrid renewable energy systems, and community involvement in site planning.	[48]
Geothermal Energy	Geographical constraints, exorbitant expenses for exploration and drilling, seismic hazards, depletion of resources, and regulatory obstacles.	Seismic risk monitoring, cost-cutting technology, enhanced geothermal systems, sustainable resource management, and expedited regulatory procedures.	[96]
Biomass Energy	Competition from land use changes, pollution, supply chain management, food production, and feedstock variability.	Utilization of biomass that isn't food, enhanced logistics for the supply chain, technology for reducing emissions, sustainable land management techniques, and a variety of feedstock sources.	[86]
Battery Storage	Excessive prices, problems with recycling and lifecycles, safety difficulties, scarcity of raw materials, and gradual decline in performance	The creation of affordable materials, cutting-edge recycling techniques, safety regulations, substitute raw materials, and studies to lengthen battery life.	[123]
Pumped Hydro Storage	Geographical restrictions, effects of the environment on nearby ecosystems, increased capital expenses.	Investigating subterranean pumped hydro storage, putting environmental mitigation plans into practice, offering financial incentives, and forming public-private alliances.	[146]
Thermal Energy Storage	Losses in efficiency during retrieval and storage, Integration with the energy infrastructure already in place, Initial financial obstacles.	Sophisticated system and material designs, incorporating thermal storage into already-existing plants, lowering costs by utilizing economies of scale.	[135]

typically tuned for nominal conditions and often degrade when weather volatility, degradation, and price dynamics change. ML-based forecasting improves short-term renewable and load prediction accuracy, which directly improves scheduling, reduces curtailment, and lowers reserve requirements; ML-based optimization (including reinforcement learning and hybrid model–data methods) can provide adaptive, near-real-time setpoints while still enforcing hard operational constraints when embedded within EMS architectures [30,165]. Accordingly, integrating trustworthy AI (robustness, explainability, and cybersecurity-by-design) with EMS platforms is a priority direction for scalable green energy management [164].

Beyond physical generation and storage technologies, the effectiveness of green energy management increasingly depends on digitalization of the power system—advanced metering, pervasive sensing, communication networks, and supervisory control platforms—that enable real-time visibility and coordination of distributed energy resources. Modern energy management systems for microgrids and smart grids use these digital layers to schedule renewables, storage, and flexible loads, improving operational efficiency and reliability under variable renewable generation [30,165]. In this context, digital twins and data-driven monitoring can support predictive maintenance and asset-health estimation, thereby reduce downtime and life-cycle cost while increase renewable utilization [164].

4. Challenges and barriers of green technologies

Although the shift to green technology is necessary for sustainable development, there are several obstacles in the way of their general adoption and application. These problems have several facets, including aspects related to technology, the economy, the environment, and regulations as shown in Fig. 6. For example, high initial costs continue to be a major deterrent for technologies like wind and solar power, while technological challenges like grid integration and storage efficiency are major roadblocks for battery storage solutions and renewable energy systems. The adoption of these technologies is further complicated by environmental consequences such as the ecological effects of biomass energy and the land use considerations connected with hydropower.

Table 6 offers a thorough summary of the current state of green technologies by thoroughly analyzing these issues and suggesting potential solutions.

The table illustrates the major obstacles and hurdles that impede the adoption of green technologies. High initial prices and technological restrictions are major obstacles for renewable energy technologies such as wind and solar power. But as materials and manufacturing techniques have advanced, these technologies have been becoming better all the time, cutting costs and increasing productivity [54]. Despite these obstacles, renewable energy technologies continue to enjoy widespread support because of their enormous environmental advantages and broad applicability. Cost, efficiency, and lifetime issues plague energy storage technologies including pumped hydro storage and battery storage. Recent improvements have focused on improving energy density and lowering prices, and technological advancements are essential in tackling these concerns [123]. Despite its geographical limits, pumped hydro storage is still the most established and economical option for large-scale energy storage; nevertheless, new storage options must be developed. Energy-efficient appliances, smart grids, and cutting-edge lighting technologies are all faced with market and regulatory obstacles. Incentives and policies have a big impact on encouraging the use of these technologies. Furthermore, the effectiveness and market penetration of energy management systems can be further improved by integrating digital technology [167].

Comparing green energy solutions to traditional fossil fuel-based energy sources requires a thorough grasp of their economic viability. Significant improvements in renewable technologies, especially PV and wind energy, are revealed by economic research that highlights the Levelized Cost of Energy, installation prices, and lifecycles for diverse energy sources, see Table 7. In terms of cost-effectiveness, these technologies currently frequently match or surpass fossil fuels, contingent on local resources and market dynamics.

Renewable technologies such as solar PV and onshore wind are now more expensive than coal and natural gas in terms of LCOE. Storage technologies such as pumped water and thermal energy storage provide cost-effective storage solutions, while battery storage costs gradually decrease. Compared to conventional sources such as coal and natural gas, renewables such as wind and solar reduce carbon emissions by

Table 7
Comparison of renewable energy, energy storage systems, and traditional energy sources.

Category	Technology/Source	LCOE (USD/MWh)	Efficiency (%)	Installation Cost (USD/kW)	Lifecycle (Years)	Carbon Emissions	Reference
Renewable Energy	**Solar PV**	30–60	20–25	1000–2500	25	80–90 % reduction	[17]
	Wind (Onshore)	25–50	30–40	1200–2000	20	80–90 % reduction	[17]
	Wind (Offshore)	50–90	40–50	3000–5000	25	80–90 % reduction	[17]
	Biomass	80–120	20–35	2500–5000	20–25	60–70 % reduction	[15]
	Geothermal	60–80	90–95	2500–5000	30	90 % reduction	[15]
Energy Storage	**Battery Storage (Utility)**	150–200	85–95	300–500	10	N/A	[18]
	Pumped Hydro Storage	50–100	70–85	1500–3000	40–50	N/A	[15]
	Thermal Energy Storage	10–50	50–90	10–50 (USD/kWh)	20–30	N/A	[18]
Traditional Sources	**Coal**	80–100	35–45	1000–1200	35	High (1000+ gCO2/kWh)	[15]
	Natural Gas	50–70	45–50	700–1300	30	Moderate (400–500 gCO2/kWh)	[15]

Table 8
Research gaps and directions emerging from the reviewed literature.

Theme	What the literature covers well	Remaining gap	Specific future research direction
System-level integration & interoperability	Integration of renewables with storage and basic EMS strategies; microgrid architectures; controller prototypes	Limited interoperability across multi-vendor devices and heterogeneous assets; weak alignment with standards across domains	Develop standardized, interoperable EMS architectures with clear data models and interfaces; validate across multi-vendor testbeds and real deployments
Validation and field evidence	Simulation-driven performance studies; techno-economic modeling; limited pilots	Insufficient field-scale validation under realistic uncertainties (weather, pricing, degradation, human behavior)	Prioritize living-lab deployments and open benchmarking; report reproducible datasets, sensitivity analysis, and uncertainty quantification
Digitalization, AI, and trustworthiness	Growing use of AI/ML for forecasting and optimization; digital twins concepts	Limited trustworthiness reporting (generalization, drift, explainability) and cybersecurity-by-design considerations	Establish "trustworthy AI" reporting for energy management, including robustness, drift monitoring, explainability, and security threat models
Hydrogen/Power-to-X as flexibility resource	Conceptual integration frameworks and early market discussions	Unclear operational value under real ancillary service rules and constraints; limited cross-sector co-optimization with storage and demand response	Develop co-optimization frameworks that jointly schedule Power-to-X, storage, and flexible loads with market participation constraints and verified economic value
Lifecycle sustainability and circularity	Emissions accounting often discussed qualitatively; life cycle assessment studies exist for components	Lack of unified lifecycle metrics integrated into operational decision-making	Integrate lifecycle impacts (materials, recycling, embodied carbon) into planning/dispatch optimization and compare strategies under policy scenarios
Policy, regulation, and deployment pathways	Policy drivers and incentives are discussed; qualitative roadmap narratives	Weak coupling between technical feasibility and regulatory design; limited analysis for emerging markets	Develop policy-aware techno-economic models that connect grid codes, incentives, and permitting to technology adoption and system performance

80–90 %. Energy storage systems are critical for connecting renewable energy to the grid and balancing supply and demand fluctuations without impacting carbon emissions. Geothermal energy provides the highest proportion of electricity (90–95 %), unlike intermittent sources such as the sun and wind, and produces stable electricity. Conventional fuels such as coal and natural gas provide reasonable efficiency but contribute significantly to greenhouse gas emissions.

Table 8 consolidates the principal research gaps identified across the reviewed green energy management literature and maps each gap to a targeted future research direction, thereby providing a concise, actionable agenda for the next 5–10 years and directly supporting the priorities highlighted in the Conclusion.

5. Future research directions

Several areas require focused research to advance green energy management from concept-level designs to scalable, real-world deployments. A first priority is system-level integration, where renewables, storage, smart grids, and emerging hydrogen/Power-to-X pathways must operate under unified planning and control frameworks to capture synergistic benefits and avoid fragmented optimization. At the same time, rapid progress in digitalization; including AI-driven analytics, IoT-based monitoring, and secure transactional platforms (e.g., blockchain-enabled coordination)—creates new opportunities to improve forecasting, operational decision-making, and decentralized participation. In parallel, energy storage innovation remains a central requirement; research should target higher performance and lower cost through advances in materials, scalable designs, and degradation-aware operation to support reliability under high renewable penetration. Beyond technology, wider adoption will depend on addressing economic and social constraints, including investment barriers, policy and regulatory gaps, and public acceptance, through evidence-based deployment models and stakeholder-informed design. Finally, the environmental value of these solutions should be validated through lifecycle assessment and sustainability evaluation, ensuring that material sourcing, recyclability, and end-of-life considerations support net environmental gains.

Future work should increasingly emphasize deployable solutions validated under realistic conditions. Key directions include: (i) interoperable architectures and standardized data models for coordinating multi-energy assets; (ii) rigorous validation under uncertainty through living-lab deployments, open benchmarking datasets, and uncertainty quantification; (iii) robust and explainable AI-enabled energy management with cybersecurity integrated by design; (iv) co-optimization of flexibility resources (storage, demand response, and Power-to-X) under realistic market and grid-code constraints; and (v) lifecycle-aware planning and operational optimization that incorporates circularity and embodied-carbon impacts. Progress along these directions will accelerate the transition from promising prototypes to reliable, economically viable, and scalable decarbonization pathways.

6. Conclusion

Green technologies and their integration with energy management practices have been highlighted in this review as essential enablers for sustainable power generation and utilization. The paper examined renewable energy sources (solar, wind, hydro, geothermal, and biomass) and energy storage systems as core pillars of effective green energy management, supported by enabling approaches such as smart grids and demand response. Because renewable generation is inherently variable, energy storage (e.g., batteries, pumped hydro storage, thermal storage, and hydrogen pathways) plays a central role in balancing supply and demand, reducing reliance on conventional peaking plants, improving grid stability, and strengthening energy security. Overall, effective energy management remains indispensable for reducing carbon emissions, improving resource efficiency, and achieving sustainability targets through coordinated planning, operation, and control across generation, storage, and end-use systems.

Based on the gaps synthesized, the most critical research priorities for the next 5–10 years are as follows: (1) System-level integration and interoperability that develop deployable architectures, standard data models, and interoperable interfaces that enable coordinated operation of renewables, storage, hydrogen/Power-to-X, and flexible loads across multi-vendor environments; (2) Advanced energy storage performance to accelerate improvements in cost, safety, lifetime, and scalability (including degradation-aware operation) to support high renewable penetration without compromising reliability; (3) Digitalization and trustworthy AI-enabled control which helps in advancing forecasting, optimization, and real-time control using machine learning and digital twins while ensuring robustness, explainability, cybersecurity, and safe constraint handling under uncertainty; (4) Policy, market design, and bankable deployment pathways that aims to align technical solutions with regulatory frameworks, incentives, and market mechanisms that properly value flexibility services (including storage and Power-to-X) and reduce adoption barriers; and (5) Lifecycle sustainability and social acceptance which integrates lifecycle assessment, circularity, and responsible material sourcing into planning and dispatch decisions while strengthening stakeholder engagement to improve adoption and long-term impact.

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Declaration of competing interest

We confirm that this work is original and has not been published elsewhere, nor is it currently under consideration for publication elsewhere.

All 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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Appendix A. List of Abbreviations and Symbols

Abbreviation	Definition
GHG	Greenhouse Gas
GDP	Gross Domestic Product
CO_2	Carbon Dioxide
RESs	Renewable Energy Sources
EMS	Energy Management System
EMR	Energetic Macroscopic Representation
SED	Sustainable Energy Development
PV	Photovoltaic
VAWT	Vertical Axis Wind Turbines
HAWT	Horizontal Axis Wind Turbines
CDS	Cadmium Sulfide
CDTe	Cadmium Telluride
WE	Wind Energy
GEM	Geothermal Energy Management
SMES	Superconducting Magnetic Energy Storage
LCOE	Levelized Cost of Energy
PCM	Phase Change Material
IoT	Internet of Things
WEF	Water–Energy–Food
AA-CAES	Advanced Adiabatic Compressed-gas (Air) Energy Storage
BESS	Battery Energy Storage Systems
HESS	Hybrid Energy Storage Systems

Data availability

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

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