

A Comparative Study of Conventional and Renewable Energy Systems with Advanced Computer Science Applications for Sustainable Power Generation

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Abstract

The growing demand for reliable electricity and the urgent need to mitigate climate change have intensified global interest in evaluating both conventional and renewable energy systems for sustainable power generation. This study presents a comprehensive comparative analysis of major energy sources, including coal, natural gas, nuclear, hydropower, wind, solar, and biomass. Each energy system is examined in terms of its operational characteristics, environmental impact, economic feasibility, reliability, and long-term sustainability. While conventional sources such as coal and natural gas provide stable and dispatchable power, they are associated with significant greenhouse gas emissions and environmental concerns. Renewable technologies offer low-carbon alternatives but face challenges related to intermittency, land use, and storage dependency. Nuclear energy occupies a unique position, delivering high-capacity-factor low-carbon electricity while encountering economic and public acceptance constraints. Beyond technological comparison, this review highlights the critical role of advanced computer science applications—including machine learning-based forecasting, smart grid optimization, digital twins, predictive maintenance, and cybersecurity frameworks—in enhancing efficiency, reliability, and data-driven decision-making across modern energy systems. By integrating multidisciplinary insights, the study demonstrates that sustainable power generation requires balanced energy portfolios supported by computational intelligence and system-level optimization rather than reliance on a single energy source.

Keywords: Sustainable power generation; Renewable and conventional energy; Lifecycle assessment; Energy system optimization; Artificial intelligence; Smart grids; Digital twins; Decarbonization.

1. INTRODUCTION

The global energy sector is undergoing a major structural transformation driven by rising electricity demand, rapid industrialization, digitalization, and the intensifying impacts of climate change. Global electricity consumption continues to increase as economies expand and technological infrastructure grows, placing additional pressure on existing power systems [1], [5]. At the same time, international climate assessments emphasize that the power sector remains one of the largest contributors to greenhouse gas emissions and must undergo rapid decarbonization to meet global temperature stabilization targets [2], [16]. International policy frameworks, including the Sustainable Development Goals, further underscore the importance of affordable, reliable, and sustainable energy systems for long-term socio-economic development [4]. These global pressures have intensified the need for comprehensive evaluation of both conventional and renewable energy technologies.

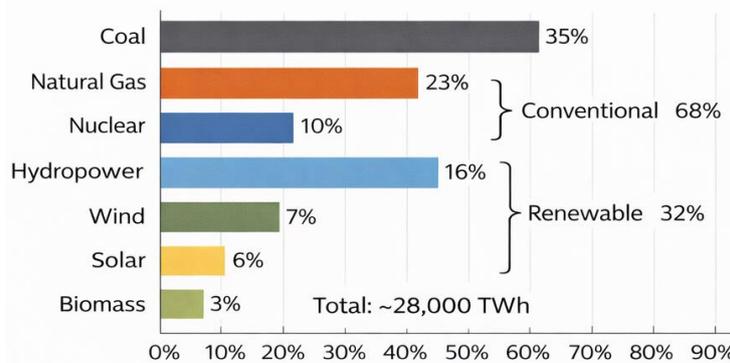


Fig. 1. Global electricity generation by energy source (adapted from [1], [5]).

Historically, coal and natural gas have dominated electricity generation due to their dispatchable nature, established infrastructure, and relatively predictable output [5], [25]. Coal-fired power plants have provided large-scale baseload power for decades; however, they are associated with high carbon dioxide emissions and significant environmental impact [2], [10]. Natural gas, often considered a transitional fuel, produces lower emissions than coal and offers flexible ramping capabilities that support grid balancing [25]. Nevertheless, methane leakage and continued fossil dependency limit its compatibility with long-term net-zero pathways [2], [16]. As climate policies tighten, reliance on fossil-based generation is increasingly questioned.

In response to environmental concerns, renewable energy technologies—including wind, solar photovoltaic, hydropower, and biomass—have expanded significantly in recent years. Global renewable capacity additions have accelerated, supported by declining technology costs and policy incentives [3], [6]. Wind and solar energy, in particular, have experienced substantial cost reductions and rapid deployment across multiple regions [6], [24]. Despite their environmental advantages, variable renewable energy sources introduce operational challenges related to intermittency, storage dependency, and grid integration complexity [7], [9]. System-level studies indicate that high renewable penetration requires complementary flexible generation or advanced storage solutions to maintain reliability [8], [18]. Therefore, renewable expansion must be accompanied by systemic grid transformation.

Nuclear energy occupies a distinct position within low-carbon electricity options. Nuclear power plants provide continuous, high-capacity-factor electricity generation with minimal direct greenhouse gas emissions [11], [12]. Lifecycle assessments demonstrate that nuclear energy's carbon intensity is comparable to wind power and significantly lower than fossil-based generation [10], [13]. Moreover, nuclear energy's high energy density results in relatively low land-use requirements compared to many renewable technologies. However, nuclear development involves high upfront capital investment, extended construction timelines, and complex regulatory frameworks [14], [15]. Public perception and long-term waste management considerations further influence deployment decisions.

While numerous studies examine individual energy sources separately, increasing research emphasizes the importance of portfolio-based approaches to energy planning. Deep decarbonization analyses highlight that combining variable renewables with firm low-carbon resources can reduce system cost and improve grid reliability under net-zero scenarios [16], [18]. This evolving perspective suggests that sustainable power generation should not be framed as a competition between technologies but rather as an optimization challenge involving complementary integration.

Simultaneously, advances in computer science have become central to modern energy system management. Machine learning algorithms enhance renewable forecasting accuracy and reduce operational uncertainty [19], [23]. Smart grid architectures and distributed control frameworks enable real-time system optimization [22]. Digital twin technologies support lifecycle modeling and performance optimization of energy infrastructure [20]. In addition, cybersecurity frameworks are increasingly necessary to protect interconnected power systems from digital vulnerabilities [21]. These computational tools improve efficiency, reliability, and data-driven decision-making across both conventional and renewable energy systems.

This study therefore presents a comparative evaluation of conventional and renewable energy systems, including coal, natural gas, nuclear, hydropower, wind, solar, and biomass. By synthesizing authoritative institutional reports and peer-reviewed research, the paper analyzes environmental impact, economic feasibility, technical reliability, and social considerations across these technologies. The study further examines how advanced computer science applications contribute to improving energy system efficiency and sustainability. Through structured comparison and interdisciplinary synthesis, the objective is to provide a balanced and evidence-based perspective on sustainable power generation supported by computational intelligence.

2. LITERATURE SURVEY

A. Coal Energy

Coal has historically been the dominant source of electricity generation worldwide and continues to contribute significantly to global power production, particularly in developing and industrial economies [1], [5]. Coal-fired power plants operate by combusting pulverized coal to generate high-pressure steam, which drives turbine generators in Rankine cycle systems. The widespread adoption of coal is primarily attributable to its abundant global reserves, established supply chains, and ability to provide continuous, dispatchable baseload electricity. According to global energy outlook assessments, coal remains a substantial contributor to electricity generation despite increasing renewable penetration [1], [5].

From a technical perspective, coal plants are capable of stable long-duration operation and high output consistency, making them reliable components of centralized grid systems. However, coal combustion produces the highest lifecycle greenhouse gas emissions among major electricity sources, with substantial carbon dioxide intensity per kilowatt-hour generated [2], [10]. In addition to CO₂ emissions, coal plants emit sulfur dioxide, nitrogen oxides, mercury, and particulate matter, contributing to air pollution, acid rain, and public health risks. Environmental impact assessments further highlight the ecological consequences of coal mining, including land degradation, water contamination, and habitat destruction [2].

Economic evaluations reveal that while coal infrastructure is often already amortized in many countries, increasing carbon regulation and emission penalties reduce its long-term competitiveness [16]. Furthermore, modernization requirements, pollution control technologies, and potential carbon capture systems significantly increase operational costs. Although carbon capture and storage (CCS) has been proposed as a mitigation strategy, large-scale implementation remains limited due to high capital expenditure and uncertain economic viability [16]. As global decarbonization commitments strengthen, coal's role in future electricity systems is increasingly constrained by environmental policy objectives.

Overall, literature consensus indicates that while coal provides operational stability and energy security in resource-rich regions, its environmental footprint and climate impact substantially undermine its compatibility with sustainable power generation pathways [2], [16].

Table 1: Strengths and Weaknesses of Coal Energy

Strengths	Weaknesses
Reliable baseload generation [1]	Highest lifecycle CO ₂ emissions [10]
Mature infrastructure and supply chain	Severe air pollution and environmental degradation [2]
Domestic energy security in coal-rich regions	Increasing carbon regulation and climate incompatibility [16]

Strengths	Weaknesses
Dispatchable and stable output	Mining-related ecological damage

B. Natural Gas Energy

Natural gas has emerged as a significant component of global electricity generation, particularly in regions seeking to transition away from coal while maintaining grid reliability [1], [5]. Electricity generation from natural gas primarily occurs through gas turbine systems or combined-cycle gas turbine (CCGT) plants. Combined-cycle systems improve thermal efficiency by utilizing waste heat from the gas turbine to generate additional steam power, resulting in higher overall conversion efficiency compared to conventional coal-fired plants [25]. This higher efficiency, combined with lower carbon dioxide emissions per unit of electricity generated relative to coal, has positioned natural gas as a transitional fuel within many national energy strategies [2].

One of the principal technical advantages of natural gas power plants is their operational flexibility. Gas turbines can ramp up or down rapidly, making them particularly suitable for balancing intermittent renewable generation such as wind and solar power [9]. As renewable penetration increases, the need for flexible backup generation becomes more pronounced, and natural gas plants frequently serve this balancing role. This flexibility enhances short-term grid stability and supports renewable integration without requiring immediate large-scale storage deployment.

Despite these operational strengths, natural gas remains a fossil fuel and contributes to greenhouse gas emissions. While its carbon intensity is lower than coal, lifecycle assessments demonstrate that natural gas emissions remain significantly higher than nuclear and most renewable energy technologies [10]. Additionally, methane leakage during extraction, processing, and transportation poses a substantial environmental concern. Methane is a potent greenhouse gas with a significantly higher global warming potential than carbon dioxide over shorter time horizons [2]. Therefore, the climate benefit of switching from coal to natural gas depends heavily on controlling upstream methane emissions.

Economic considerations further complicate natural gas deployment. Although natural gas plants generally require lower capital investment than nuclear facilities and have shorter construction timelines, they remain subject to fuel price volatility and geopolitical supply dependencies [1]. Regions reliant on imported natural gas may experience price fluctuations and supply risks influenced by global market conditions. Long-term decarbonization modeling studies suggest that while natural gas may facilitate short-term emission reductions relative to coal, its continued use without carbon mitigation technologies may conflict with deep net-zero targets [16].

In summary, literature indicates that natural gas offers important operational advantages, particularly in supporting renewable integration through flexible generation. However, its ongoing carbon emissions, methane leakage risks, and exposure to fuel market volatility limit its suitability as a long-term standalone solution for sustainable power generation [2], [10], [16].

Table 2: Strengths and Weaknesses of Natural Gas Energy

Strengths	Weaknesses
Lower CO ₂ emissions than coal [10]	Still carbon-intensive [2]
High thermal efficiency (combined cycle) [25]	Methane leakage risks
Rapid ramping capability for renewable balancing [9]	Fuel price volatility [1]
Lower capital cost than nuclear	Geopolitical supply dependency
Supports grid flexibility	Incompatible with long-term net-zero without CCS [16]

C. Nuclear Energy

Nuclear energy generates electricity through controlled nuclear fission reactions in which heavy atomic nuclei, typically uranium-235 or plutonium-239, are split to release substantial thermal energy. This heat is used to produce steam that drives turbine generators in a manner similar to conventional thermal power plants. Nuclear power plants operate as centralized, high-capacity facilities capable of continuous electricity generation over extended operational cycles. According to global energy assessments, nuclear power remains one of the largest sources of low-carbon electricity worldwide [1], [11]. Unlike fossil fuel-based systems, nuclear plants produce negligible direct greenhouse gas emissions during operation, making them significant contributors to decarbonization strategies.

From a lifecycle perspective, nuclear energy exhibits carbon intensity comparable to wind energy and significantly lower than coal and natural gas [10], [13]. Lifecycle assessments account for mining, fuel processing, plant construction, operation, and decommissioning, and consistently classify nuclear as a low-carbon technology. Furthermore, nuclear plants demonstrate exceptionally high capacity factors, often exceeding 85–90%, which indicates sustained and reliable electricity output throughout the year [11], [12]. This high capacity factor distinguishes nuclear from intermittent renewable technologies such as wind and solar. In addition, nuclear energy’s high energy density results in relatively low land-use requirements per unit of electricity generated, offering spatial advantages in regions with limited land availability [13].

Despite these strengths, nuclear energy faces significant economic and institutional challenges. Construction of nuclear power plants requires substantial upfront capital investment and long development timelines, often extending beyond a decade due to regulatory approval processes, safety compliance requirements, and financing complexity [14]. Delays and cost overruns have been observed in several large-scale nuclear projects globally, increasing financial risk. Moreover, radioactive waste management remains a long-term governance issue. Although technological solutions for spent fuel storage and

geological disposal have been developed, political and societal acceptance of waste repositories remains contentious [15].

Public perception further influences nuclear deployment. Historical accidents and safety incidents have shaped societal attitudes toward nuclear power, even though modern reactor designs incorporate multiple redundant safety systems and passive cooling technologies [15]. Regulatory oversight for nuclear energy is necessarily stringent due to the potential consequences of severe accidents, which adds to development complexity and cost. Nevertheless, many decarbonization studies emphasize the value of firm low-carbon resources such as nuclear energy in achieving reliable net-zero electricity systems [16].

Overall, literature consensus suggests that nuclear energy provides a highly reliable, low-carbon, and land-efficient electricity source. However, its expansion depends on addressing capital cost challenges, strengthening regulatory efficiency, and improving public confidence in long-term safety and waste management [14], [15], [16].

Table 3: Strengths and Weaknesses of Nuclear Energy

Strengths	Weaknesses
Very low lifecycle carbon emissions [10], [13]	High upfront capital cost [14]
Very high capacity factor (reliable baseload) [11], [12]	Long construction timelines
Low land use per unit of electricity [13]	Radioactive waste management challenges [15]
Strong grid stability contribution	Public perception and regulatory complexity [15]
Long operational lifespan	Financing and cost overrun risks

D. Hydropower Energy

Hydropower is one of the most mature and widely deployed renewable energy technologies, utilizing the kinetic and potential energy of flowing or stored water to generate electricity. Large-scale hydropower plants typically operate through dam-based reservoir systems, where stored water is released to drive turbines connected to generators. Run-of-river systems provide an alternative configuration with limited storage capacity. Globally, hydropower contributes a substantial share of renewable electricity generation and plays a key role in many national energy portfolios [1], [3]. Due to its long operational life and relatively low operating costs once constructed, hydropower remains a foundational renewable resource in several regions.

From an environmental standpoint, hydropower exhibits low lifecycle greenhouse gas emissions compared to fossil fuels [10]. However, lifecycle assessments indicate that emissions can vary depending on geographic conditions, reservoir size, and vegetation decomposition in flooded areas [10]. Technically,

hydropower offers significant advantages in grid stability. Reservoir-based hydropower plants can provide dispatchable and flexible generation by adjusting water release, making them valuable for balancing demand fluctuations and integrating variable renewable energy sources [3]. Pumped-storage hydropower systems further enhance grid flexibility by functioning as large-scale energy storage facilities.

Despite these benefits, hydropower development is associated with ecological and social trade-offs. Construction of large dams can lead to displacement of communities, alteration of river ecosystems, sedimentation changes, and impacts on aquatic biodiversity [2]. Environmental assessments emphasize that river fragmentation and habitat disruption may have long-term ecological consequences. Moreover, hydropower generation depends heavily on hydrological conditions and precipitation patterns. Climate variability and prolonged drought events can significantly reduce electricity output, as observed in several regions experiencing water scarcity [2]. Therefore, while hydropower provides reliable and low-emission electricity under stable hydrological conditions, its performance is sensitive to climatic and geographic factors.

Economic considerations also influence hydropower deployment. Initial capital investment for dam construction and infrastructure development is substantial, although operating costs are relatively low over extended lifespans [1]. Expansion potential is geographically constrained to suitable river basins, limiting universal scalability. Consequently, hydropower represents a valuable renewable resource where geographic conditions permit, but its global expansion capacity is finite.

Overall, literature suggests that hydropower plays a critical role in renewable energy systems by providing both low-carbon generation and grid flexibility. However, environmental impact, social displacement, and climate sensitivity require careful planning and regulatory oversight [2], [10].

Table 4: Strengths and Weaknesses of Hydropower

Strengths	Weaknesses
Low lifecycle emissions [10]	Ecosystem disruption and river alteration [2]
Dispatchable with reservoir control [3]	Community displacement risks
Supports grid balancing and storage	Vulnerable to drought and climate variability [2]
Long operational lifespan	High initial capital investment
Low operating cost after construction	Geographic limitation

E. Wind Energy

Wind energy converts the kinetic energy of moving air masses into electricity through turbine-generator systems. Modern wind turbines capture wind flow through aerodynamic blades connected to a rotor and generator assembly. Over the past two decades, wind power has experienced substantial technological

advancement and cost reduction, resulting in rapid global capacity expansion [3], [6]. Both onshore and offshore wind installations contribute to electricity generation portfolios in many regions, with offshore systems generally achieving higher capacity factors due to stronger and more consistent wind resources.

From an environmental perspective, wind energy produces negligible direct greenhouse gas emissions during operation. Lifecycle assessments demonstrate that wind power ranks among the lowest carbon-intensity electricity technologies when construction, manufacturing, and decommissioning stages are considered [10]. As a result, wind energy is widely recognized as a cornerstone of decarbonization strategies [16]. Technologically, wind systems are modular and scalable, enabling deployment at varying scales from small distributed installations to large utility-scale farms.

Despite these advantages, wind energy is inherently intermittent and dependent on meteorological conditions. Variability in wind speed results in fluctuating generation output, which introduces operational challenges for grid stability [7]. High penetration of wind energy requires improved forecasting, flexible backup generation, expanded transmission networks, or energy storage systems to maintain reliability [8], [18]. Without such integration mechanisms, variability can lead to curtailment or imbalance between supply and demand.

Land use and spatial footprint also present considerations. Onshore wind farms require significant land area, although agricultural activities can often coexist with turbine installations. Offshore wind projects reduce land competition but involve higher capital investment and complex marine engineering requirements. Additionally, wind installations may generate local opposition due to visual impact, noise concerns, or potential effects on wildlife such as bird and bat populations.

Economically, wind energy has become increasingly competitive due to technological innovation and economies of scale [6]. However, system-level cost assessments indicate that as wind penetration increases, integration costs rise due to transmission expansion and balancing requirements [18]. Therefore, while wind energy provides substantial environmental benefits and scalability, its contribution to sustainable power generation depends heavily on coordinated grid management and complementary resources.

Overall, literature consensus indicates that wind energy is a critical low-carbon resource capable of large-scale deployment, yet its intermittency necessitates advanced forecasting, storage integration, and system-level planning to ensure reliability [7], [8], [16].

Table 5: Strengths and Weaknesses of Wind Energy

Strengths	Weaknesses
Very low lifecycle emissions [10]	Intermittent and weather-dependent [7]
Rapid global deployment [3]	Requires storage or backup generation [8]
Declining technology costs [6]	Transmission and grid integration challenges [18]

Strengths	Weaknesses
Modular and scalable	Land use and visual impact concerns
Supports decarbonization goals [16]	Wildlife and ecological considerations

F. Solar Energy

Solar energy generates electricity by converting sunlight directly into electrical power through photovoltaic (PV) cells composed of semiconductor materials. When exposed to sunlight, these materials produce an electric current via the photovoltaic effect. Over the past decade, solar photovoltaic technology has experienced rapid technological advancement and substantial cost reductions, resulting in widespread global deployment across residential, commercial, and utility-scale applications [3], [6]. Solar energy is particularly attractive due to its abundance, geographic accessibility, and modular scalability, allowing distributed generation through rooftop installations as well as centralized large-scale solar farms.

From an environmental perspective, solar PV systems produce negligible direct greenhouse gas emissions during operation. Lifecycle assessments indicate that solar energy exhibits very low carbon intensity compared to fossil fuel technologies, although slightly higher than wind and nuclear due to manufacturing and material processing stages [10]. These lifecycle impacts include extraction of raw materials such as silicon, aluminum, and rare metals, as well as energy-intensive panel manufacturing processes. Nevertheless, solar energy remains a central component of decarbonization pathways outlined in global energy transition scenarios [16].

Despite its environmental advantages, solar generation is inherently dependent on solar irradiance and is limited to daylight hours. Diurnal and seasonal variability introduce predictable but unavoidable intermittency [7]. High penetration of solar energy in electricity systems increases the need for storage technologies, flexible generation resources, or demand-side management strategies to maintain supply-demand balance [8], [18]. In regions with high solar adoption, mid-day overgeneration can occur, leading to curtailment if grid flexibility is insufficient.

Land use considerations also influence solar deployment. Utility-scale solar farms require significant surface area to generate large amounts of electricity. While rooftop installations reduce land competition, large-scale ground-mounted systems may compete with agricultural or ecological land use. Additionally, end-of-life panel recycling and waste management are emerging sustainability concerns as early-generation installations approach decommissioning [10].

Economically, solar power has achieved significant cost competitiveness, particularly in regions with high solar irradiance [6], [24]. However, system-level cost analyses demonstrate that as solar penetration increases, integration costs associated with storage, transmission reinforcement, and grid flexibility also rise [18]. Therefore, while solar energy is one of the fastest-growing and most scalable renewable technologies, its long-term contribution to sustainable power systems depends on coordinated infrastructure planning and advanced system management.

Overall, literature indicates that solar energy plays a critical role in global decarbonization strategies due to its scalability and declining cost trends. However, effective integration requires forecasting accuracy, storage deployment, and grid modernization to mitigate intermittency challenges [7], [8], [16].

Table 6: Strengths and Weaknesses of Solar Energy

Strengths	Weaknesses
Very low lifecycle emissions [10]	Daylight-dependent and intermittent [7]
Rapid cost reduction and deployment [6], [24]	Requires storage at high penetration [18]
Modular and scalable	Large land footprint for utility-scale farms
Suitable for distributed generation	Manufacturing and recycling impacts [10]
Central to decarbonization pathways [16]	Grid integration challenges

G. Biomass Energy

Biomass energy involves the conversion of organic materials—such as agricultural residues, forestry waste, energy crops, and municipal solid waste—into electricity through combustion, gasification, or biochemical processes. Unlike fossil fuels, biomass derives from recently living biological matter, which allows it to be considered potentially carbon-neutral under certain conditions. During plant growth, carbon dioxide is absorbed from the atmosphere through photosynthesis, and when biomass is combusted for energy, this carbon is released back into the atmosphere, theoretically creating a balanced carbon cycle [10]. However, lifecycle sustainability depends heavily on feedstock sourcing, land management practices, and supply chain efficiency.

From a technical standpoint, biomass power plants operate similarly to conventional thermal plants and are capable of providing dispatchable electricity generation. This controllability distinguishes biomass from intermittent renewable technologies such as wind and solar. Biomass systems can therefore contribute to grid stability and complement variable renewable resources. Additionally, biomass energy can support waste management strategies by utilizing agricultural byproducts and municipal waste streams, thereby contributing to circular economy objectives.

Despite these advantages, biomass energy presents several environmental and governance challenges. Lifecycle assessments indicate that carbon neutrality is not automatically guaranteed; emissions associated with cultivation, harvesting, transportation, and processing may reduce net climate benefits [2], [10]. Unsustainable biomass production may lead to deforestation, biodiversity loss, soil degradation, and competition with food production. Land-use change effects can significantly alter lifecycle carbon accounting outcomes. Moreover, large-scale biomass deployment may require extensive feedstock supply chains, increasing transportation emissions and operational costs.

Economic viability varies depending on feedstock availability and regional resource conditions. In agricultural economies with abundant biomass residues, electricity generation from biomass may be economically feasible. However, in regions without sufficient sustainable feedstock supply, biomass may not scale efficiently. Furthermore, long-term sustainability requires careful regulation to ensure that biomass harvesting rates do not exceed natural regeneration capacity.

Overall, literature suggests that biomass energy offers dispatchable renewable electricity potential and waste utilization benefits. However, its environmental performance and scalability depend critically on sustainable feedstock management, lifecycle assessment transparency, and regulatory oversight [2], [10], [16].

Table 7: Strengths and Weaknesses of Biomass Energy

Strengths	Weaknesses
Potential carbon neutrality under sustainable management [10]	Lifecycle emissions vary depending on feedstock [2]
Dispatchable renewable generation	Risk of deforestation and land-use change
Supports waste utilization and circular economy	Competes with food and agricultural land
Can stabilize renewable-heavy grids	Supply chain and transportation emissions
Provides rural economic opportunities	Limited scalability in some regions

3. COMPARATIVE EVALUATION OF ENERGY SYSTEMS

A comprehensive comparison of conventional and renewable energy systems reveals that each technology presents distinct trade-offs across environmental, economic, technical, and societal dimensions. Sustainable power generation therefore depends not on the dominance of a single source but on balanced evaluation and integration strategies.

From an environmental standpoint, coal exhibits the highest lifecycle greenhouse gas emissions among major electricity sources, contributing substantially to global carbon dioxide output [2], [10]. Natural gas produces lower emissions than coal but remains carbon-intensive, particularly when methane leakage is considered [2], [10]. In contrast, nuclear energy, wind, solar, and hydropower demonstrate very low lifecycle emissions, making them central to decarbonization pathways [10], [13]. Biomass occupies an intermediate position, as its carbon neutrality depends heavily on feedstock sustainability and lifecycle management [10]. Consequently, deep decarbonization strategies prioritize low-emission technologies while phasing down high-carbon fuels [16].

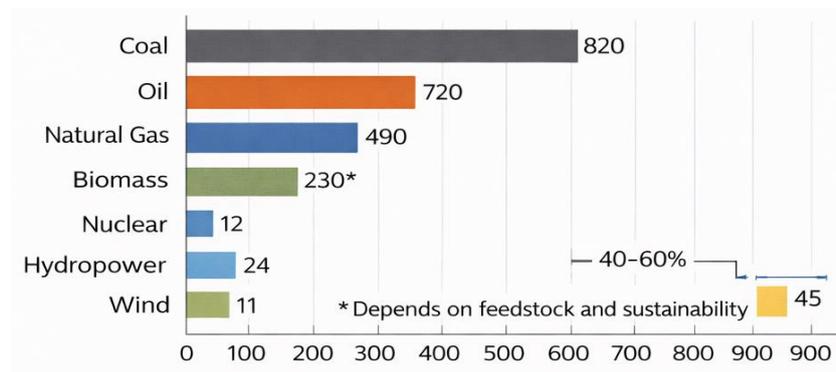


Fig. 2. Lifecycle greenhouse gas emissions of major electricity generation technologies (adapted from [10], [13]).

Economic evaluation further differentiates these systems. Fossil-based generation benefits from established infrastructure but faces increasing regulatory and carbon pricing pressures [1], [16]. Nuclear energy involves high upfront capital investment and long development timelines, which increase financial risk [14]. However, its long operational lifespan and high capacity factor may provide cost stability over time [11]. Wind and solar technologies have experienced significant cost reductions and are increasingly competitive for new installations [6], [24]. Nevertheless, system-level studies demonstrate that high renewable penetration increases integration costs due to storage requirements, transmission expansion, and grid reinforcement [8], [18]. Therefore, project-level cost comparisons alone are insufficient to determine overall system affordability.

Technical reliability represents another critical comparison criterion. Coal, natural gas, nuclear, and reservoir-based hydropower provide dispatchable and controllable electricity generation [11], [25]. Nuclear energy, in particular, exhibits one of the highest capacity factors among all major energy sources [11]. Natural gas offers operational flexibility and rapid ramping capability, which supports renewable integration [9]. Wind and solar generation, while technologically mature, remain weather-dependent and introduce variability into grid systems [7]. High renewable shares therefore require forecasting improvements, flexible backup capacity, and energy storage to maintain grid stability [8], [18]. This highlights the importance of complementary system design rather than isolated technology evaluation.

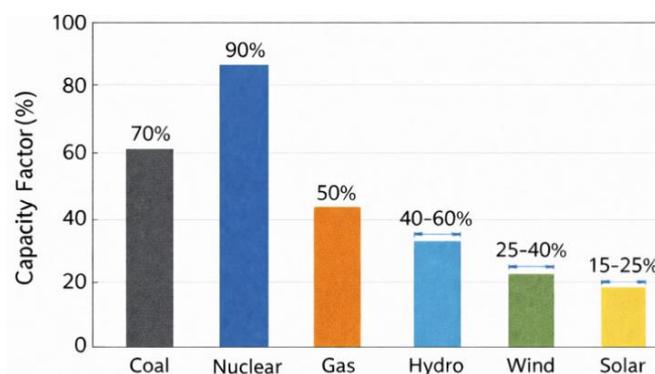


Fig. 3. Typical capacity factors of major energy sources (adapted from [11], [25]).

Land use and spatial footprint also vary considerably among energy systems. Nuclear power’s high energy density results in relatively low land requirements per unit of electricity generated [13]. Fossil fuel plants occupy limited plant areas but impose significant upstream environmental impacts through extraction processes. Wind and solar installations require larger land or offshore areas to achieve comparable energy output, particularly at utility scale. Hydropower reservoirs may occupy extensive geographical areas and alter ecosystems [2]. Biomass cultivation can compete with agricultural land and biodiversity. Thus, regional geography and land availability strongly influence technology feasibility.

Social acceptance and governance further shape energy deployment decisions. Coal faces increasing societal opposition due to environmental and health impacts [2]. Nuclear energy, despite its low-carbon advantages, encounters public perception challenges and regulatory scrutiny [15]. Renewable technologies generally receive strong policy support, although local opposition may arise due to land use or aesthetic concerns. These non-technical factors significantly affect implementation timelines and investment risk.

Table 8: Integrated Comparative Assessment of Major Energy Sources

Energy Source	Lifecycle Emissions	Dispatchability	Capital Intensity	Land Use	Long-Term Sustainability
Coal	Very High [10]	High	Moderate	Moderate	Declining under climate policy [16]
Natural Gas	High [10]	Very High (Flexible) [9]	Moderate	Low	Transitional role
Nuclear	Very Low [10], [13]	Very High [11]	Very High [14]	Very Low [13]	Strong firm low-carbon candidate
Hydropower	Very Low [10]	High	High	High	Geographic constraints [2]
Wind	Very Low [10]	Variable [7]	Moderate	High	Core renewable technology
Solar	Very Low [10]	Variable [7]	Moderate	High	Rapidly expanding renewable
Biomass	Variable [10]	High	Moderate	Moderate	Sustainability depends on feedstock

Overall, comparative analysis demonstrates that no single energy source optimizes environmental sustainability, economic viability, technical reliability, and societal acceptance simultaneously. Fossil fuels provide dispatchability but conflict with climate targets. Renewable technologies support decarbonization but require integration solutions to address intermittency. Nuclear energy offers reliable low-carbon generation but involves economic and political complexity. Therefore, diversified energy

portfolios combining complementary technologies provide a more resilient pathway toward sustainable power generation [16], [18].

4. ROLE OF COMPUTER SCIENCE IN ENERGY SYSTEM OPTIMIZATION AND MANAGEMENT

The transformation of modern energy systems extends beyond technological diversification and increasingly depends on advanced computational intelligence. As electricity networks become more complex due to the integration of variable renewable resources and distributed generation, computer science applications play a central role in ensuring efficiency, reliability, and security. Digital technologies such as machine learning, artificial intelligence, smart grid architectures, big data analytics, digital twins, and cybersecurity frameworks enable data-driven management of both conventional and renewable energy systems [19], [22], [23].

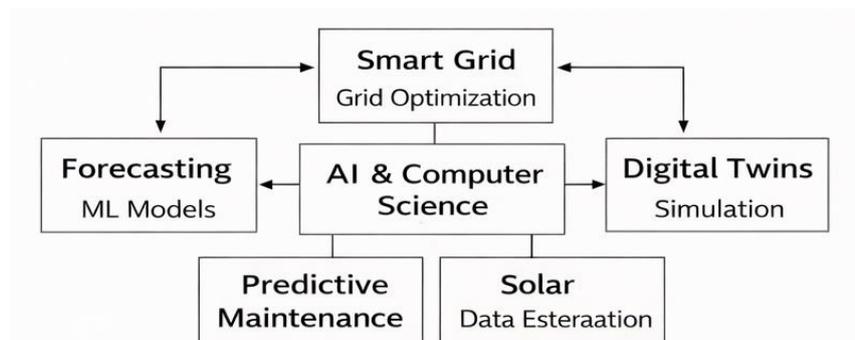


Fig. 4. Role of artificial intelligence, smart grid systems, digital twins, and cybersecurity in modern energy infrastructure (adapted from [19], [20], [21], [22], [23]).

One of the most significant contributions of computer science in energy systems is forecasting optimization. Wind and solar energy are inherently dependent on meteorological conditions, and accurate prediction of generation output is essential for maintaining grid stability. Machine learning models have demonstrated substantial improvements in renewable energy forecasting accuracy, reducing uncertainty and lowering reserve requirements [19], [23]. Enhanced forecasting enables more efficient scheduling of backup generation from natural gas, hydropower, or nuclear facilities, thereby minimizing operational costs and reducing curtailment losses.

Smart grid technologies further enhance coordination across interconnected energy infrastructures. Distributed control systems and real-time optimization algorithms allow dynamic balancing of supply and demand across multiple energy sources [22]. Through sensor networks and advanced communication protocols, smart grids facilitate integration of distributed renewable installations, electric vehicles, and storage systems. These computational systems improve grid resilience and reduce transmission losses, particularly in renewable-heavy networks.

Digital twin technology represents another transformative advancement. A digital twin is a high-fidelity virtual model of physical infrastructure that enables simulation, predictive analysis, and performance

optimization [20]. In nuclear power plants, digital twins can support safety analysis, maintenance scheduling, and operational efficiency. Similarly, digital modeling can be applied to wind farms, solar installations, and hydropower facilities to monitor performance degradation and detect anomalies before system failures occur. Predictive maintenance algorithms reduce downtime, extend equipment lifespan, and improve cost efficiency across all major energy systems [23].

Cybersecurity has become increasingly critical as energy infrastructure becomes digitally interconnected. The integration of smart meters, automated control systems, and remote monitoring introduces vulnerabilities that must be addressed through secure architecture design and threat detection frameworks [21]. Cybersecurity protocols protect critical infrastructure from data breaches, operational disruption, and malicious interference. Ensuring secure communication between distributed energy resources is particularly important in decentralized renewable systems.

Beyond operational optimization, data analytics supports long-term energy planning and policy evaluation. Large-scale datasets on generation patterns, demand fluctuations, emissions performance, and cost metrics enable comparative modeling and scenario analysis [23]. These analytical tools help policymakers assess trade-offs among coal, natural gas, nuclear, and renewable technologies under different climate and economic scenarios. Computational modeling therefore complements technological diversification by providing evidence-based decision support.

Overall, computer science functions as an enabling layer across all energy technologies rather than as an independent energy source. Artificial intelligence enhances renewable integration, digital twins improve nuclear and thermal plant safety, smart grids coordinate distributed systems, and cybersecurity protects digital infrastructure. Sustainable power generation in the modern era thus depends not only on selecting appropriate energy sources but also on leveraging computational intelligence to optimize performance, minimize risk, and enhance system resilience.

5. CONCLUSION

This study presented a structured comparative evaluation of conventional and renewable energy systems, including coal, natural gas, nuclear, hydropower, wind, solar, and biomass, through a multi-dimensional sustainability framework encompassing environmental performance, economic feasibility, technical reliability, land use, and governance considerations. The detailed analysis demonstrates that no individual energy source independently satisfies all criteria necessary for long-term sustainable power generation. Fossil fuels provide dispatchable and flexible electricity but remain constrained by high lifecycle emissions and climate incompatibility. Renewable technologies such as wind and solar enable large-scale decarbonization yet introduce intermittency and integration challenges at high penetration levels. Nuclear energy offers firm low-carbon baseload generation with high capacity factors but faces economic and regulatory complexity, while hydropower and biomass present region-specific opportunities influenced by ecological and resource conditions. The comparative synthesis confirms that diversified energy portfolios combining complementary technologies provide greater resilience, stability, and sustainability than single-technology approaches. Furthermore, advanced computer science applications—including machine learning forecasting, smart grid optimization, digital twins, predictive maintenance, and cybersecurity frameworks—serve as essential enablers for enhancing operational efficiency and

integration across modern energy systems. Sustainable power generation therefore requires integrated technological planning supported by computational intelligence and evidence-based policy coordination to achieve long-term decarbonization and energy security objectives.

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