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A COMPARATIVE STUDY TO MEASURE THE SUSTAINABILITY OF EXISTING RENEWABLE ENERGY SYSTEMS AND NON-CONVENTIONAL ENERGY SOURCES

¹Praveen Kumar*, ²Dr. Neetu Pandey, ³Vipin Saini, ⁴Mradul Saini, ⁵Ruchi Malhotra⁶Yagyavalkya Sharma, ⁷Dr. Sandeep Rout^{1,3,4,5,6}Department of Biotechnology & Microbiology, Kalp Laboratories, Mathura, Uttar Pradesh²School of Applied Chemistry and Basic Sciences, Sardar Bhagwan Singh University, Balawala, Dehradun, Uttarakhand⁷Faculty of Agriculture, Sri Sri University, Cuttack, Odisha-754006

*Correspondence Email:psingh2943@gamil.com

Abstract: The global energy landscape is undergoing a crucial shift brought on by increased fossil fuel demand, environmental damage, and the need to tackle climate change. Traditional fossil fuel and nuclear energy systems have been generally dependable in the past, although there are ever-increasing worries about carbon emissions, environmental hazards, and resource availability. Renewable energy technologies, including solar, wind, hydro, geothermal, and biomass, represent scalable, sustainable, and low-cost alternatives because of technological advancements and reduced costs. Nevertheless, challenges relating to storage capabilities, intermittency of supply, and infrastructural integration remain. Furthermore, non-conventional technologies, including tidal, wave, ocean thermal, micro-hydro, and second-generation bioenergy, are advancing and will provide additional diversity in energy sources in due course. This review highlights the performance, economics, social and environmental implications, and sustainability of traditional, renewable, and non-conventional energy systems. It is concluded that renewable energy represents the most immediate and practical pathway for sustainable energy transitions, while non-conventional technology can also be complementary as technologies and policies develop.

Keywords: Climate change mitigation, Energy transition, non-conventional energy sources, Renewable energy, Sustainable energy systems

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1. Background

Energy has historically been the cornerstone of human progress, shaping social, economic, and technological development across different stages of civilisation [1]. From the initial dependence on conventional biomass to the hegemony of fossil fuels in the Industrial Revolution, access to energy has always dictated the rate of growth and modernisation [2]. In the modern era, the world's energy system is confronted with unparalleled challenges. Accelerating growth in population, industrialisation, and urbanisation has resulted in a severe increase in energy demand, while simultaneously, the use of conventional fossil-based resources is causing climate change, environmental degradation, and resource depletion. These trends highlight the necessity to shift towards sustainable energy systems that reconcile the increasing demand for energy with long-term environmental and social factors.

Energy sources are generally classified as conventional, renewable, and non-conventional systems. Conventional energy, mainly consisting of coal, petroleum, natural gas, and nuclear energy, has historically generated most of the global energy supply [3]. While they have considerable economic

value, they are heavily linked to high carbon emissions, environmental hazards, and finite resources. Nuclear power, as a low-carbon option, is accompanied by major concerns related to radioactive waste management, safety, and economic efficiency [4]. On the other hand, sustainable energy resources like solar, wind, hydropower, biomass, geothermal, and marine power are generally considered to be more sustainable because of their abundance, inexhaustibility, and relatively low environmental impact. Non-conventional energy sources, sometimes coinciding with renewables, normally imply nascent or less market-oriented technologies like tidal, wave, and small-hydropower installations [5]. Though these sources hold much promise, they are currently constrained by technological immaturity, intermittency, and increased upfront costs.

The quest for sustainability involves a broad energy transition that takes into account economic, social, political, and environmental factors. The Paris Climate Agreement (2015) stressed this need by establishing international targets to limit temperature rise to below 2 °C (with aspirations of 1.5 °C), which will require significant reductions in reliance on fossil fuels and the swifter uptake of low-emission energy systems [6]. At the same time, energy inequalities on a global scale remain stark. Countries in the developing world still grapple with the dual challenges of energy poverty and economic growth, all while grappling with sustainability demands. Decentralised renewable energy systems like solar mini-grids and wind-powered water pumps are emerging as options for rural energy access and for stimulating local economic development [7]. Similarly, advanced energy storage, grid modernisation, smart grid, and artificial intelligence technologies are the focus for developed economies' renewable energy agendas at-scale for global change.

The review aims to provide a comparative evaluation of traditional, renewable, and non-conventional energy systems, considering their sustainability. Based on efficiency, cost competitiveness, environmental and societal effects, scalability, and ability to contribute towards energy security, the paper attempts to determine the most promising avenues for future energy transition. The comparative perspective aims to underscore opportunities and challenges, providing insights for policymakers, researchers, and practitioners in reconciling energy policy with international sustainability objectives. Overall, the transition of the global energy system is no longer a choice but imperative. The challenge is not merely increasing the deployment of renewable and non-conventional sources but transforming existing energy systems and governance frameworks to achieve long-term sustainability, equity, and resilience.

2. Energy Systems: An Overview

Energy systems are the networked systems and processes by which energy is generated, transformed, transmitted, stored, and consumed. Energy systems are the underpinning of economic activity and societal progress because a consistent and inexpensive supply of energy is a prerequisite for industrial activity, transportation, communication, health services, and domestic consumption. In the past, energy systems were dominated by centralised fossil fuel-based generation systems, especially coal, oil, and natural gas [8]. Although these sources are effective in addressing global-scale energy demands, they continue to be associated with greenhouse gas emissions, environmental degradation, and continuous resource depletion. This has created the need to transition towards green and resilient energy systems as a critical priority for the world.

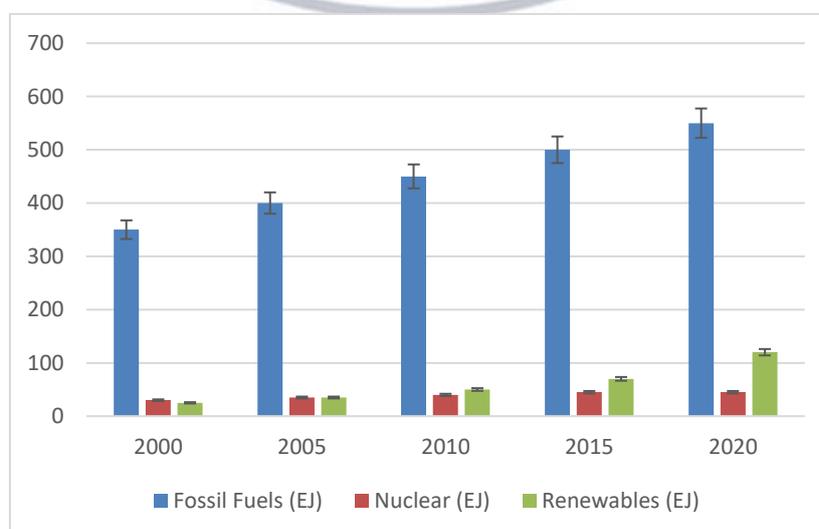
Modern energy systems are undergoing a revolutionary transformation, and the resulting transformation is driven by the emergence of renewables, which include solar photovoltaics, wind, hydropower, biomass, and geothermal energy [9]. The renewables are a low-carbon alternative to fossil fuels, but their variability and intermittency generate new technical challenges. The variability and intermittency associated with renewables will generate the need for new energy storage technology. Relevant technologies include lithium-ion batteries, pumped hydro storage, and future hydrogen technologies. At the same time, the modernisation of the grid, leveraging smart grids, managing demand-side, and real-time monitoring, is ensuring stability of the system as well as optimised energy

flows between sources and end uses. Digitalisation of energy infrastructures also represents a new dimension of energy systems [10]. The application of artificial intelligence (AI), big data analytics, and the Internet of Things (IoT) for predictive maintenance, load forecasting, and dynamic control will drive further improvements in reliability and efficiency [11]. In turn, these developments will also allow individual consumers to become "prosumers": Individuals who will now be participatory producers of energy (through solar roofs, electric vehicles, and microgrids). This decentralisation of energy supply and demand will further disrupt the existing supply - demand balance and enable deeper democratisation of access to energy.

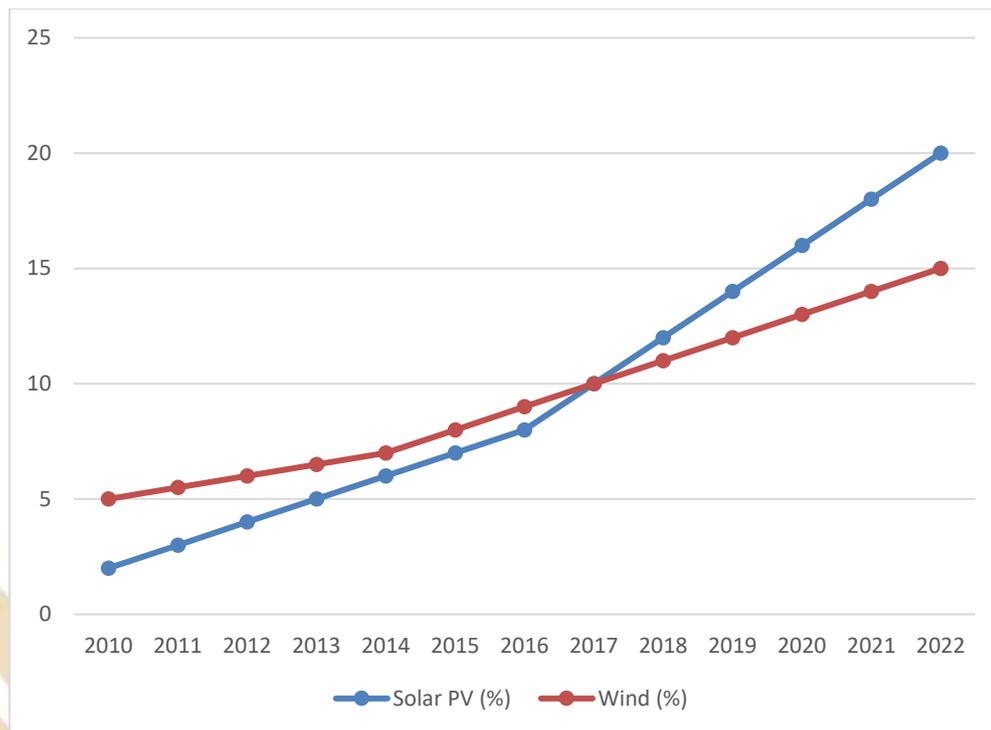
However, energy systems encompass more than their functional components. They are part of a broader set of socio-economic, political, and environmental conditions. Policy structures and regulatory and financial instruments have shaped the configuration of energy systems in significant ways. Policies like feed-in tariffs, carbon pricing, and renewable portfolio standards have all supported the spread of clean technologies, while international agreements like the Paris Accord have set long-term decarbonization benchmarks. At the same time, issues of equity, energy security, and affordability will continue to be equally important issues to address to ensure transitions are fair and reasonable. Ultimately, energy systems have evolved from old fossil fuel-based structures to more interconnected, decentralised, and low-carbon systems. Energy systems are multi-vector systems that produce and consume a mix of electricity, heat, and new vectors such as hydrogen. Knowledge of the technological developments, operational complexity, and socio-political aspects of energy systems is critical for advancing sustainable energy transitions and achieving global climate and development objectives.

3. Global Energy Consumption Trends

The rise in energy consumption for the world is directly related to global demographic and economic advances. According to the International Energy Agency (IEA), total energy use increased by over 40% during the 20 years between 2000 and 2020, and fossil fuels make up about 80% of our energy consumption (Graph 1) [12]. This degree of reliance has been critical in global carbon dioxide emissions peaking at 36 gigatons, and our global and national energy consumption patterns are primarily unchanged, as we seem to be heavily reliant on fossil fuels for energy use. While fossil fuel market share remains strong, renewable energy consumption is growing faster than any other sector of the energy market. Data provided by the World Electric Power Plants (WEPP) Global Database indicates that renewable energy's market share increased from 16% of worldwide electricity generation in 2010 to just short of 28% in 2022 (Graph 2) [13]. In keeping with the previous energy mix, solar and wind energy have experienced major increases in installed generating capacity, led by declines in technology costs and national policies.



Graph 1. Global Energy Consumption by Source (2000–2020)



Graph 1. Renewable Energy Share in Global Electricity Generation (2010–2022)

However, differences in adoption continue to be visible. Developed economies, including the European Union, have managed to reach high penetration rates of renewables, more than 40% in the generation of electricity, through positive regulatory schemes, feed-in tariffs, and carbon pricing policies [14]. Other developing countries still support a large reliance on traditional sources based on affordability, infrastructural limitations, and financial accessibility issues. However, decentralised renewable systems, including microgrids and solar home kits, are increasingly being deployed across rural and underserved communities of South Asia and Africa, holding out the prospect for inclusive energy access.

From a sustainability perspective, the world's energy system stands at a turning point. Traditional sources, as reliable, are inconsistent with both long-term climate objectives and resource preservation. Non-conventional and renewable systems offer environmentally friendly options, yet their scale-up depends on overcoming issues of intermittency, storage, and connection to traditional grids [15]. The future of world energy systems will thus be subject to technological development, enabling policies, and global collaboration focused on reconciling economic development with environmental conservation.

4. Energy classification in the world

Energy resources across the globe can be broadly divided into renewable and non-renewable forms. Non-renewable resources comprise coal, petroleum, natural gas, and nuclear energy, which have traditionally dominated global energy supply but are finite and environmentally taxing [16]. Renewable resources, on the other hand, include solar, wind, hydro, geothermal, and biomass/biogas energy, all of which are naturally replenishing and environmentally sustainable. The increasing demand for clean energy has accelerated the integration of renewables into global energy systems. This classification underscores the need for balanced utilisation of both resource types while transitioning toward sustainable energy futures. A proposed review workflow graph depicting this classification is presented in Figure 1.

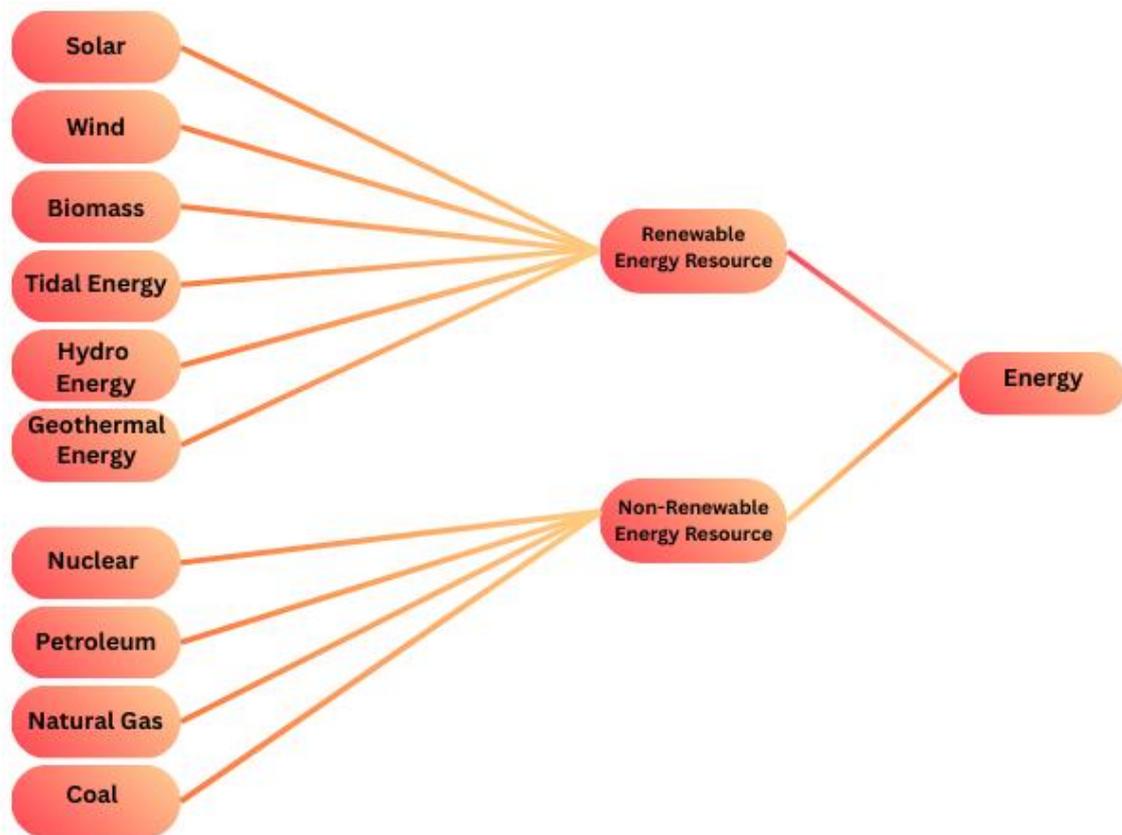


Figure 1. Flowchart of review work

4.1 Conventional and Non-Renewable Energy Sources

Conventional energy sources, primarily derived from fossil fuels, have historically served as the backbone of industrialisation and global economic growth. Coal, petroleum, natural gas, and nuclear energy collectively account for most of the global primary energy consumption [17]. Despite their critical role in supporting reliable and large-scale power generation, these sources are increasingly scrutinised for their environmental, social, and economic implications.

4.1.1 Coal

Coal is among the oldest and most widely used fossil fuels, providing approximately 27% of global primary energy supply and nearly 36% of electricity generation in 2021 [18]. It is abundant and relatively inexpensive, with established mining and power plant infrastructure. However, coal combustion is the largest single source of carbon dioxide emissions worldwide, accounting for roughly 40% of total energy-related CO₂ emissions [19]. Additionally, coal use is associated with particulate matter, sulfur dioxide, and nitrogen oxide emissions, leading to air pollution and severe public health consequences. In addition to environmental costs, coal extraction typically results in land degradation, habitat destruction, and worker safety hazards. While carbon capture, utilisation, and storage (CCUS) technologies have been proposed to mitigate these impacts, utilisation remains limited due to high costs and technical challenges.

4.1.2 Petroleum

Petroleum remains a dominant global energy source, especially in the transportation and petrochemical sectors. It accounted for nearly one-third of global energy consumption in 2020 [20]. Crude oil and its derivatives—such as gasoline, diesel, and jet fuel—are valued for their high energy density and ease of transport. However, petroleum extraction, refining, and consumption present significant sustainability challenges. Oil spills, greenhouse gas emissions, and dependence on geopolitically

volatile regions have raised concerns about energy security. Moreover, the burning of petroleum products is a major contributor to urban air pollution and climate change [21]. While advances in electric mobility and alternative fuels are gradually reducing petroleum dependence, the transition remains uneven across regions.

4.1.3 Natural Gas

Natural gas is often described as a “bridge fuel” due to its lower carbon intensity compared to coal and oil. It supplies around 24% of global energy demand and is widely used for electricity generation, heating, and as an industrial feedstock. Liquefied natural gas (LNG) has enabled long-distance trade, increasing its global significance. Nonetheless, natural gas is not without drawbacks. Methane leakage during extraction and transport poses serious climate risks, as methane is over 25 times more potent than CO₂ as a greenhouse gas over a 100-year horizon [22]. Hydraulic fracturing (fracking), a common extraction method, has further raised environmental concerns, including groundwater contamination and induced seismicity.

4.1.4 Nuclear Energy

Nuclear power is often considered a conventional but low-carbon energy option. As of 2022, it accounted for approximately 10% of global electricity generation [23]. Its advantages include high energy density, low operational greenhouse gas emissions, and reliability as a baseload power source. However, nuclear power faces critical challenges. Radioactive waste disposal remains unresolved, with storage solutions requiring robust, long-term management strategies. The catastrophic accidents at Chernobyl (1986) and Fukushima (2011) have also intensified public opposition and raised questions regarding nuclear safety [24]. Additionally, the high capital costs and long construction timelines for nuclear plants limit their competitiveness relative to rapidly expanding renewable alternatives.

4.1.5 Environmental and Economic Implications

Together, traditional and non-renewable resources regulate today's energy system but pose high hurdles to sustainability. Their production causes climate change, environmental impairment, and health hazards, whereas their limited availability poses long-term energy security issues. In economic terms, these sources continue to be competitive in most areas because of the deep-rooted infrastructure, subsidies, and well-established markets. Nevertheless, the unreliability of fossil fuel prices and rising regulatory pressures due to carbon emissions further diminish their future role.

In summary, although coal, oil, natural gas, and nuclear energy are still the foundation of global energy supply, their sustainability gaps create a justified need for a transition to cleaner, renewable, and non-conventional sources. The comparison of systems with renewables only emphasises our obligation to ensure an energy mix that reduces ecological impacts while providing assured access to energy without unnecessary degradation.

4.2 Renewable Energy Sources

Renewable energy (RE) sources are derived from continuously replenishing flows of energy such as sunlight, wind, water cycles, biomass, geothermal heat, and the movements of oceans [25]. They are almost unlimited in comparison to fossil fuels and normally do not emit greenhouse gases when in operation. Thus, they form the basis of sustainable development and the transition to low-carbon energy systems. In this section, we summarise the major renewable energy sources, their use, benefits, and obstacles.

4.2.1 Solar Energy

Solar energy is the most abundant renewable resource, with the Earth receiving more energy from the sun in one hour than humanity consumes in an entire year [26]. Solar technologies are primarily

classified into **photovoltaic (PV)** systems, which directly convert sunlight into electricity, and **concentrated solar power (CSP)** systems, which use mirrors or lenses to focus sunlight and produce heat for electricity generation [27]. The global deployment of solar PV has grown exponentially due to declining costs, with the levelized cost of electricity (LCOE) decreasing by nearly 85% between 2010 and 2020 [28]. Solar applications range from small-scale rooftop systems to large utility-scale plants, as well as thermal uses such as solar cookers and water heaters. However, challenges include intermittency, land requirements for large solar farms, and the environmental footprint of PV manufacturing and recycling.

4.2.2 Wind Energy

Wind energy harnesses the kinetic energy of moving air to generate electricity through wind turbines. Technological improvements and economies of scale have positioned wind power as one of the most competitive renewable sources. As of 2022, global wind capacity exceeded 830 GW, with both onshore and offshore developments expanding rapidly [29]. Offshore wind, in particular, offers higher capacity factors due to stronger and more consistent winds. Wind energy is relatively mature, cost-competitive, and scalable. Nevertheless, it faces limitations such as intermittency, noise and visual concerns, ecological impacts on bird and bat populations, and the need for advanced grid integration.

4.2.3 Hydropower

Hydropower is the oldest and most widely used renewable energy technology, providing approximately 16% of global electricity in 2020 [30]. Large hydropower plants generate electricity by using the kinetic energy of flowing water to turn turbines, while small-scale and run-of-river projects provide decentralised options. Hydropower offers reliable baseload capacity and the ability to provide energy storage through pumped hydro systems. However, environmental and social impacts are significant. Large reservoirs can cause habitat loss, disrupt river ecosystems, and displace communities. Methane emissions from reservoirs also raise concerns about their overall climate benefits.

4.2.4 Biomass Energy

Biomass energy derives from organic materials such as agricultural residues, forestry by-products, animal waste, and energy crops. It can be converted into electricity, heat, or biofuels through combustion, gasification, fermentation, and anaerobic digestion. Bioenergy accounted for nearly 9% of global energy demand in 2020 [31]. A key advantage of biomass is its potential to utilise waste streams, thereby contributing to circular economy strategies. However, bioenergy raises critical sustainability debates, particularly regarding food security, land use change, and biodiversity loss when energy crops compete with food production [32]. Sustainable bioenergy requires careful resource management and lifecycle assessments to ensure climate benefits.

4.2.5 Geothermal Energy

Geothermal energy exploits heat stored beneath the Earth's surface to produce electricity or provide direct heating. High-temperature geothermal reservoirs are used for power generation, while low- to medium-temperature sources are widely applied in district heating, agriculture, and industrial processes [33]. Geothermal plants operate with high-capacity factors and low emissions, offering reliable baseload energy. Global installed capacity reached over 15 GW by 2020. Yet, geothermal deployment is geographically constrained to regions with suitable geological conditions, such as the "Ring of Fire." Exploration and drilling costs also remain significant barriers to large-scale adoption.

4.2.6 Marine and Tidal Energy

Marine energy encompasses tidal, wave, and ocean thermal energy conversion (OTEC). Tidal energy exploits predictable movements of ocean tides, while wave energy captures surface wave motion [34]. OTEC utilises the temperature difference between warm surface water and cold deep water to generate

power. Although marine energy offers vast theoretical potential, technological development is still in its early stages. High installation costs, environmental concerns, and technical reliability issues have restricted large-scale deployment. Current projects are mostly in demonstration phases, concentrated in Europe, East Asia, and North America.

4.3 Non-Conventional Energy Sources (NCES)

Non-conventional energy sources (NCES) are renewable technologies that are still in the process of being widely commercialised, technically developed, or connected to the main energy systems [35]. Although NCES are highly associated with renewable energy, they are usually differentiated by their new, small-scale, or developing characteristics. They are tidal and wave energy, ocean thermal energy conversion (OTEC), micro- and pico-hydropower, decentralised solar and wind, and advanced bioenergy systems. These resources, although presently underutilised, have great potential to diversify the world's energy mix and meet the challenges of sustainability.

NCES are especially significant in areas where large-scale traditional infrastructure is not available or possible. For example, micro-hydropower and stand-alone solar technology have been effectively implemented in rural areas of Asia and Africa to offer decentralised electrification alternatives [36]. Likewise, tidal and wave power schemes in the United Kingdom, South Korea, and Portugal are examples of marine-based technologies that are viable, though high initial costs and technology immaturity continue to pose obstacles. Advanced bioenergy- including next-generation biofuels that can be produced from non-food biomass and algae- is a possible solution to the food versus fuel problem experienced by first-generation biofuels, but commercial production that prioritises costs, efficiency, and yield is still lacking [37].

There are economic, technical, infrastructural, and regulatory challenges to NCES development and integration. Economic challenges can range from the high cost of development and limited access to funding, particularly in developing countries. Technical challenges include intermittency and variability in resources, as well as a lack of standardised designs in small-scale systems or systems that use multiple energy sources. Further, inadequate energy infrastructures at most locations are a barrier to the deployment of NCES at scale. Policy and regulatory systems do not support or sufficiently incentivise adoption either [38]. Environmental issues also remain, since tidal barrages have the potential to distort marine ecosystems, and large-scale bioenergy activities can compete for land and water resources for agriculture.

In spite of these difficulties, prospects for NCES are good. Continued research in materials science, hybrid renewable systems, and energy storage is continuously increasing the efficiency and lowering the costs of these technologies. Hybrid systems that integrate traditional renewables with NCES, such as solar-wind or tidal-solar, are being developed to increase reliability and efficiency. Additionally, global cooperation, policy-specific incentives, and capacity development are anticipated to drive NCES mainstreaming faster, particularly in emerging economies where access to energy continues to be a challenge.

5. Comparative Analysis of Energy Systems

The evaluation of energy systems requires a holistic framework that accounts for technical efficiency, economic viability, environmental consequences, social acceptability, and long-term sustainability [39]. Conventional, renewable, and non-conventional energy sources each present distinct advantages and limitations. While conventional systems have historically dominated global energy supply due to their reliability and mature infrastructure, they pose significant challenges for sustainability. In contrast, renewable and non-conventional energy systems have less environmental impact but deal with technical challenges, including intermittency, affordability, and system integration [40]. A comparative assessment of these energy systems is instrumental in mapping the potential pathways for an equitable and sustainable global energy transition.

5.1 Efficiency and Reliability

Conventional energy systems—coal, petroleum, and natural gas—offer high energy density and reliable baseload power, making them well-suited for large-scale and continuous demand. Nuclear power also provides high efficiency and steady output, although safety concerns persist. By contrast, renewable sources such as solar and wind are intermittent, depending on weather and seasonal variations. Hydropower and geothermal systems, however, provide relatively stable output and can serve as baseload or backup energy [41]. Non-conventional sources, particularly marine energy and advanced biofuels, remain in experimental or small-scale phases and have yet to demonstrate efficiency on par with mature technologies.

5.2 Economic Competitiveness

Historically, fossil fuels have been the cheapest energy option due to established supply chains and subsidies. However, recent decades have witnessed a sharp decline in the costs of renewable technologies. Solar PV and onshore wind are now competitive with, and in many cases cheaper than, new coal and gas plants. Hydropower and geothermal, though capital-intensive upfront, offer low operational costs. Non-conventional sources, such as tidal and wave power, remain expensive due to high capital requirements and limited economies of scale. Economic viability, therefore, favours established renewables, while NCES requires policy incentives and technological innovation to reach competitiveness [42].

5.3 Environmental and Social Impacts

Conventional energy systems are the largest contributors to greenhouse gas emissions, air pollution, and ecological degradation. Coal mining and oil drilling are particularly destructive, causing habitat loss, land subsidence, and risks of oil spills. Nuclear power avoids direct carbon emissions but generates hazardous radioactive waste. Renewable systems generally have a smaller environmental footprint, though challenges persist. Large hydropower projects, for example, can disrupt ecosystems and displace communities, while bioenergy may compete with food production and biodiversity conservation [43]. Non-conventional resources, such as tidal and wave energy, may affect marine ecosystems, but their impacts are less studied given the limited deployment. Socially, renewables and NCES provide decentralised energy access, creating employment and enhancing local resilience, whereas fossil fuel dependence often concentrates benefits and risks in resource-rich regions [44].

5.4 Scalability and Sustainability

Conventional systems are already embedded in global infrastructures and can be scaled readily, but their finite reserves limit long-term sustainability. Renewables, particularly solar and wind, have demonstrated rapid scalability, with global capacity growing at double-digit rates annually. Their sustainability is strengthened by inexhaustibility, though material demands (e.g., rare earths for turbines, metals for PV cells) present resource challenges. Non-conventional energy sources have substantial theoretical potential, particularly marine energy, but remain constrained by immaturity and integration barriers. In terms of sustainability across economic, social, environmental, and political dimensions, renewables score higher, while NCES represent promising supplements if technological hurdles are overcome.

Table 1. Comparative Summary of Energy Systems

Criteria	Conventional (Coal, Oil, Gas, Nuclear)	Renewable (Solar, Wind, Hydro, Geothermal, Biomass)	Non-Conventional (Tidal, Wave, OTEC, Micro-hydro, Advanced Biofuels)
Efficiency/Reliability	High efficiency, reliable baseload	Variable (solar/wind), stable for hydro & geothermal	Emerging, often low efficiency, site-dependent
Economic Viability	Historically cheapest; price volatile	Costs declining rapidly; competitive in many markets	High capital costs, limited economies of scale
Environmental Impact	High emissions, pollution, and habitat loss	Low emissions, some ecological/social trade-offs	Relatively low but under-researched; localised ecological risks
Scalability	Mature infrastructure, finite reserves	Rapidly scalable; resource-constrained in some cases	Limited scalability: pilot and demo projects dominate
Sustainability	Unsustainable long-term	High sustainability if managed responsibly	Promising future role, but technologically immature

6. Impact of Renewable and Non-Conventional Energy on Climate Change Mitigation

Climate change, driven largely by the combustion of fossil fuels, is one of the most pressing global challenges of the twenty-first century. Energy production and consumption account for nearly three-quarters of global greenhouse gas (GHG) emissions. Consequently, transforming the energy sector is central to achieving international climate targets, particularly those outlined in the **Paris Agreement (2015)**, which seeks to limit the rise in global average temperature to well below 2 °C, with efforts to remain below 1.5 °C [45]. Renewable and non-conventional energy systems play a pivotal role in this transformation, as they provide low-carbon alternatives capable of reducing dependence on conventional fossil-based energy sources.

6.1 Renewable Energy and Emissions Reduction

Renewable energy technologies, including solar, wind, hydropower, geothermal, and biomass, are universally recognised as critical interventions for reducing GHG emissions. Under a direct scenario of displacing fossil fuels for electricity, heating, and transport, renewables lead to a reduction in CO₂ emissions. Solar photovoltaics and wind technology generate negligible emissions during their operation and are increasingly cost-competitive with fossil fuels for widespread decarbonization [46]. Hydropower and geothermal resources are more limited geographically, but are loads of low-carbon consistency that are aligned with variable renewables.

Bioenergy is more complicated in terms of its emissions performance in a climate change context. It can reduce dependence on fossil fuels, but unsustainable management practices for energy crops can contribute to land-use change, loss of biodiversity, and indirect emissions of CO₂. In order to be considered an appropriate mitigation option, bioenergy needs to be sourced from sustainable management practices, including prioritising the feedstocks of waste and residues to direct and indirect emissions from food crops. Global expansion of renewables is already contributing to direct reductions

of emissions. Between 2010 and 2020, the rapid increase in capacity of wind and solar power displaced an estimated 2.1 gigatons of CO₂ per year [47]. A continued investment in renewables supply with energy efficiency will lead to more than half of the reductions of emissions required by mid-century, under the scenarios net-zero, through direct replacements.

Table 2. Estimated CO₂ Emissions Avoided by Renewable Energy Deployment (2010–2020)

Technology	Estimated CO ₂ Avoided Annually (Gt)	Key Source
Solar PV	~0.9 Gt	IRENA (2021)
Wind	~1.0 Gt	IRENA (2021)
Hydropower	~0.15 Gt	IEA (2021)
Geothermal	~0.02 Gt	IEA (2021)
Bioenergy	~0.03 Gt	IPCC (2019)
Total	~2.1 Gt annually	Global Estimate

6.2 Non-Conventional Energy and Climate Benefits

Non-conventional energy sources (NCES), while being in earlier stages of deployment, provide further avenues for climate mitigation. Tidal and wave power, for example, are predictable and sustained in relation to solar and wind and therefore can be used to help stabilise the grid while replacing fossil-fuel-based generation [48]. Ocean thermal energy conversion (OTEC) also has long-term potential in the tropics, though commercialisation has been constrained. Small hydropower and small-scale decentralised solar and wind systems are particularly effective in rural electrification scenarios. By offering clean alternatives in places otherwise dependent on diesel generators or biomass, NCES can lower localised emissions and enhance public health outcomes.

Next-generation bioenergy technologies, such as second-generation biofuels from lignocellulosic biomass and algae, can help decarbonise hard-to-abate sectors like shipping and aviation. Though still commercially limited, their successful deployment would overcome the shortcomings of first-generation biofuels and minimise the use of liquid fuels from fossil sources.

6.3 Broader Mitigation Potential

Beyond direct emissions reductions, renewable and non-conventional energy systems enhance climate resilience and adaptive capacity. Decentralised renewable systems strengthen energy security in vulnerable regions by reducing reliance on imported fuels and by providing access to reliable, clean energy. This, in turn, supports sustainable development goals, such as poverty reduction and improved health, thereby creating co-benefits for climate adaptation.

However, the climate mitigation potential of renewables and NCES is not without challenges. Intermittency of solar and wind requires advances in energy storage, grid flexibility, and demand-side management [49]. The material demands of renewable technologies, particularly rare earth elements, raise questions about lifecycle emissions and resource sustainability. Non-conventional sources, while promising, still face technological immaturity and cost barriers that limit their near-term contribution.

7. Policy, Governance, and Economic Perspectives

The transition from conventional fossil-based systems to renewable and non-conventional energy sources is not only a technological challenge but also a political, regulatory, and economic undertaking.

Policy frameworks, governance structures, and market mechanisms play decisive roles in shaping the speed and direction of energy transitions [50]. Without supportive policies and coordinated governance, even the most advanced technologies risk underutilization. This section explores the global policy landscape, governance mechanisms, and economic considerations influencing renewable and non-conventional energy development.

7.1 Global Policy Frameworks

At the international level, the Paris Agreement (2015) is the foundation of global climate and energy policy. The Agreement commits countries to keeping global warming below 2 °C, and preferably to 1.5 °C, which implicitly requires a rapid decrease in fossil fuels and a more rapid shift to renewables. The Sustainable Development Goals (SDGs), and in particular Goal 7 (“Affordable and Clean Energy”), highlight access to energy for all, and support renewables and energy efficiency [51].

Multilateral mechanisms, such as the International Renewable Energy Agency (IRENA) and the Clean Energy Ministerial, have helped promote knowledge exchange, capacity building, and coordinated action [52]. However, the effectiveness of international agreements depends on national pledges to act, which vary greatly in their commitment, implementation, and enforcement in different parts of the world.

7.2 National Policies and Instruments

National governments play the most direct role in advancing renewable and non-conventional energy systems. A wide range of policy instruments has been employed globally, including:

- **Regulatory measures** such as renewable portfolio standards (RPS), which mandate a minimum share of renewable energy in the power mix.
- **Economic incentives** like feed-in tariffs (FiTs), tax credits, and subsidies, which lower financial barriers and attract private investment [53].
- **Market-based mechanisms** such as carbon pricing and emissions trading schemes, which internalise the environmental costs of fossil fuels and improve the competitiveness of low-carbon alternatives.
- **Public investments** in research and development (R&D) to promote technological innovation, particularly in emerging non-conventional sources.

Countries such as Germany (Energiewende), Denmark (wind energy leadership), and China (solar and hydropower expansion) illustrate how coherent policy frameworks can accelerate renewable adoption. In contrast, inconsistent policies and fossil fuel subsidies in some regions hinder progress and perpetuate carbon lock-in.

7.3 Governance and Institutional Dimensions

Effective governance is essential for harmonising the dimensions of the energy transition. Governance structures must simultaneously engage in energy security, equity, and environmental sustainability [50]. Decentralised governance structures - local authorities, communities, are pertinent, particularly for renewable non-conventional and small-scale projects. Community engagement that ensures social acceptance will increase the chances of projects being sustained in the long-term. Institutional barriers, fragmented regulatory frameworks, limited technical capacity, and weak enforcement remain prevalent in many developing nations. Addressing these issues requires strengthening institutions, improving coordination and coherency of policy across sectors, and accommodating energy planning into broader development planning.

7.4 Economic Considerations

The economics of energy transition contain opportunities and challenges. On the one side, the cost of renewables is dropping drastically, with solar PV and onshore wind being among the lowest-cost electricity resources globally. There is also a considerable amount of renewable-sector employment, with 12 million people employed globally in renewable energy industries in 2021 [54]. On the other side, non-conventional energy systems remain economically constrained by high initial costs, limited commercialisation, and a lack of economies of scale. In addition, phasing out fossil fuels will have economic consequences for countries highly reliant on hydrocarbon revenue. In this sense, a framework for a 'just transition' is important - this means ensuring that the workers and communities that depend on fossil industries have access to reskilling, social safety nets, or alternative employment.

8. Future Perspectives

The next decades will be crucial for achieving a sustainable global energy future. Renewable and non-conventional energy systems are anticipated to grow rapidly, driven by technology innovation, reduced cost, and favourable legislation. Advances in storage technology, smart grids, and digital technologies (e.g., artificial intelligence and IoT) will improve system reliability and increase integration of intermittent renewables, including solar and wind. Hybrid systems that bring together several forms of resources will improve stability and efficiency. Non-conventional sources, including tidal, wave, and advanced bioenergy sources, will play a more significant role as they technologically and economically mature. Policy systems need to make a behavioural shift, putting greater emphasis on carbon pricing, phasing out fossil subsidies, and increasing investment in research and development. Ensuring that this transition is equitable is also essential, and policymakers need to make protecting workers in fossil industries a priority. Global collaboration on technology transfer, finance, and capacity building will be vital to narrowing global divides and supporting equitable and gender-responsive energy transitions.

Conclusion

This review emphasises the significance of traditional, renewable, and non-conventional energy systems in energy transitions towards a sustainable energy future. Traditional energy systems provide a reliable capacity but have negative impacts on the environment and diminish finite resources. Renewable energy is scalable, affordable, and effective at reducing the impacts of climate change. Non-conventional energy systems offer a potential means of expanding energy diversity in the future. Sustainable energy requires a reliable energy mix that considers environmental implications, is supported by successful technical innovations, policies, good governance, and equitable economic systems. The energy transition should not only be regarded as an environmental necessity but also as an opportunity to develop resilient and equitable societies. Dependency on fossil fuels can be reduced, the adoption of renewable energy can be increased, and new technologies can be developed. Global cooperation is also necessary to support the transition to power systems that provide a long-term, secure, and climate-resilient electricity supply. Ultimately, the path to sustainability is through diversity, equity, and innovation integrated into energy systems.

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