

## RENEWABLE AND SUSTAINABLE ENERGY SYSTEMS FOR A LOW-CARBON FUTURE: SOURCES, SUSTAINABILITY DIMENSIONS, AND FUTURE CHALLENGES

Muhammad Raza Punjwani<sup>1</sup>, Jaweed Ali Thaheem<sup>2</sup>, Muhammed Ahsan Niaz<sup>3</sup>,  
Ali Zain Ul Abdeen<sup>4</sup>, Shafique Ahmed Soomro<sup>\*5</sup>, Mansoor<sup>6</sup>

<sup>1,2, \*5</sup>Faculty of Engineering Science and Technology, Department of Electrical Engineering, Indus University, Karachi, 75850, Pakistan.

<sup>3</sup>A professional working in a pharmaceutical facility as the Head of Utilities and HVAC. Karachi, 75850, Pakistan

<sup>4</sup>Manager Campus France Karachi Organization: Campus France, Karachi, 75850, Pakistan.

<sup>6</sup>A professional working in a pharmaceutical facility as the Assistant Manager Engineering. Karachi, 75850, Pakistan

<sup>1</sup>raza.punjwani@indus.edu.pk <sup>2</sup>jaweed.thaheem@indus.edu.pk

<sup>3</sup>ahsanniaz@outlook.com; <sup>4</sup>zainqureshi340@gmail.com; <sup>5</sup>shafiq.soomro@indus.edu.pk,

<sup>6</sup>mangriomansoor92@gmail.com

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Corresponding Author: \*

Shafique Ahmed Soomro

### Abstract

Renewable and sustainable energy systems are essential for addressing global challenges such as climate change, energy insecurity, and environmental degradation while enabling a transition to a low-carbon future. Renewable energy refers to energy derived from naturally replenished resources, including solar, wind, hydropower, biomass, and geothermal energy. Sustainable energy extends this concept by emphasizing the efficient, equitable, and environmentally responsible production and use of energy to meet present needs without compromising the ability of future generations to meet their own. This study provides a comprehensive overview of major renewable energy sources and examines their environmental, economic, and social benefits within the broader framework of sustainability dimensions. It further analyzes key challenges associated with large-scale deployment, including resource intermittency, storage limitations, lifecycle impacts, policy constraints, and market barriers. In addition, a case example from Pakistan the Noriabad Jamshoro Wind Power Project is highlighted to demonstrate the practical application and benefits of renewable energy in a developing country context. The study concludes that advancements in technology, supportive policies, and global cooperation are accelerating the adoption of clean energy systems. Ultimately, transitioning to renewable and sustainable energy is critical for reducing greenhouse gas emissions, strengthening energy security, promoting inclusive economic growth, and achieving long-term sustainable development goals.

### 1. INTRODUCTION

In the previous time, the twin concepts of sustainability and renewable energy have emerged as a defining imperative of humanity that is situated at the nexus of science, technology, culture, economics, policy and the environment

[1] These concepts are framed as a means to mitigate the negative impacts of natural resource depletion, energy consumption, water consumption and climate changing greenhouse gas emissions associated with human activities [1]. It is important to understand that the words

"renewable" and "sustainable" have very different meanings and should not be used interchangeably [2]. Renewable energy sources are naturally restored over time and use replenish able resources, meaning there is always the potential to generate more [2]. These sources are extracted from natural processes that are continuously renewed, such as sunshine and wind that persistently radiate and gust (Abildtrup et al., 2024)(Irawan et al., 2024). Renewable energy includes solar energy, wind energy, hydropower, geothermal energy, bioenergy, and marine energy (Meng et al., 2018)(Y et al., 2023). Sustainable energy, on the other hand, is energy that in its production or consumption has minimal negative impacts on human health and the healthy functioning of vital ecological systems, including the global environment (Omer, 2017)(Abdeen, 2012)(Omer, 2021). More specifically, sustainable energy pertains to energy resources that can fulfill existing energy requirements while preserving the capacity of future generations to meet their own energy needs (Lv, 2023). It supplies current consumption with insignificant influence on future energy and minimal or no negative impact on ecology, economy, and society (Meng et al., 2018).

For renewable energy sources to be considered sustainable as shown in Figure 1, they must meet four key criteria: they must be economically viable, politically supported, socially equitable, and environmentally acceptable [2]. A renewable resource may be sustainable if used in moderation, but if the consumption rate exceeds the replenishing rate, its continuous use will not be sustainable [2]. For example, biofuels produced through ethanol fermentation can be unsustainable due to competition with the food chain, while most renewable sources like solar, wind, geothermal, hydro, and tidal are sustainable as they are stable and available in abundance [2]. (Hosseini et al., 2014) (Sekoai et al., 2016) (Sekoai et al., 2016)(Guney, 2019)(Owusu et al., 2016)(Kumar, 2020)(Obidike et al., 2021)(Sekoai et al., 2017).

The growing importance of renewable and sustainable energy is closely connected with wider global development priorities. In the modern world, energy is not only required for electricity

generation, transportation, and industrial production, but it is also essential for education, healthcare, communication, agriculture, and overall human well-being. As a result, the quality, availability, and sustainability of energy systems directly influence the social and economic progress of nations. Clean and renewable energy technologies offer a practical pathway to reduce dependence on fossil fuels, which are finite in nature and highly responsible for environmental pollution and greenhouse gas emissions. By shifting toward cleaner energy systems, countries can strengthen energy security, reduce vulnerability to fuel price fluctuations, and decrease reliance on imported energy resources. At the same time, renewable energy can improve public health by reducing harmful air pollutants that cause respiratory and cardiovascular diseases. In addition, the renewable energy sector creates employment opportunities in manufacturing, installation, maintenance, research, and technical services, thereby contributing to inclusive economic growth and local development. These technologies also support rural electrification and improved energy access for remote and underserved communities, helping to reduce energy poverty and social inequality. Furthermore, renewable and sustainable energy play a vital role in achieving international climate goals and advancing the Sustainable Development Goals (SDGs), particularly SDG 2 (Zero Hunger), SDG 4 (Quality Education), and SDG 7 (Affordable and Clean Energy). Renewable energy supports agriculture through irrigation, food preservation, and processing systems, contributes to better educational opportunities by providing electricity for schools and digital learning, and directly ensures access to affordable, reliable, sustainable, and modern energy for all. As population growth, urbanization, and industrial expansion continue to increase global energy demand, the need for affordable, reliable, accessible, and environmentally responsible energy systems will become even more urgent. Therefore, renewable and sustainable energy are no longer optional alternatives; they are essential components of future development and long-term global stability.

Against this background, the present study aims to provide a broader and deeper understanding of renewable and sustainable energy by examining their major sources, analyzing their environmental, economic, and social benefits, and exploring future opportunities and challenges related to their large-scale implementation. The study seeks to explain how different forms of renewable energy, such as solar, wind, hydropower, geothermal, biomass, and marine energy, contribute to cleaner and more sustainable energy systems. It also aims to assess the ways in which these energy sources can help reduce greenhouse gas emissions, mitigate the effects of climate change, strengthen national and global

energy security, and promote more efficient and responsible use of natural resources. In addition, this study will consider the broader role of clean energy technologies in supporting sustainable economic development, improving quality of life, and ensuring intergenerational equity by preserving environmental and resource stability for future generations. By bringing together discussions on sources, benefits, sustainability concerns, and future prospects, the study intends to present a comprehensive view of why renewable and sustainable energy have become one of the most important priorities of the twenty-first century.

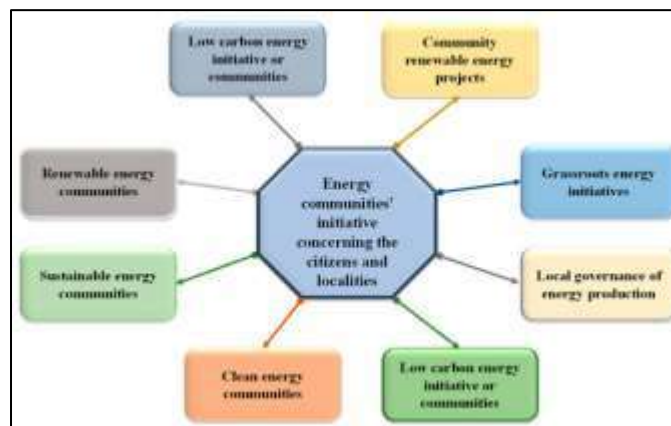


Fig. 1. Typology of energy communities involving citizens and localities

### TYPES OF RENEWABLE ENERGY SOURCES

The main categories of renewable energy sources are widely recognized in the literature as solar energy, wind energy, hydropower, geothermal energy, bioenergy, and marine energy (Meng et al., 2018; Koochi-Fayegh et al., 2020; Duggan, 2025). These resources originate from natural processes that are continuously replenished by the earth and its surrounding environment, such as solar radiation, atmospheric motion, the water cycle, biological growth, and geothermal heat from the earth's interior (Abildtrup et al., 2024). Unlike fossil fuels, which require millions of years to form and are depleted through extraction and use, renewable energy resources are naturally restored over shorter time scales, making them more suitable for long-term and sustainable energy

planning. Each renewable energy source has its own method of energy conversion, technical characteristics, advantages, and limitations, but together they represent the foundation of the global transition toward cleaner and more resilient energy systems [1]-[3].

Among these sources, **solar energy** is one of the most abundant and promising forms of renewable energy. It harnesses the inexhaustible power of the sun to produce both electricity and heat through two major technological pathways: photovoltaic (PV) systems and solar thermal systems (Oluwadamilare et al., 2023). Photovoltaic cells convert sunlight directly into electricity through the photovoltaic effect, while solar thermal technologies capture the sun's heat for water heating, industrial processes, or steam generation to drive turbines for electricity production

(Oluwadamilare et al., 2023). Solar energy is considered a virtually inexhaustible and pollution-free resource because the sun continuously provides radiant energy without direct emission of harmful pollutants during operation (Santosh et al., 2024). In recent years, improvements in solar panel efficiency, falling installation costs, and supportive policies have made solar power one of the fastest-growing renewable energy technologies worldwide. It is especially useful in remote areas and regions with high solar radiation, where it can provide decentralized and off-grid electricity access.

**Wind energy** is another major renewable energy source that converts the kinetic energy of moving air into electrical power through wind turbines. As the wind moves the turbine blades, rotational mechanical energy is generated and then transformed into electricity by a generator (Oluwadamilare et al., 2023). Wind energy is widely regarded as one of the most sustainable and environmentally favorable sources of power, and it has become one of the most cost-effective renewable technologies in many regions of the world due to declining capital costs and low operational emissions (Abildtrup et al., 2024). Wind farms may be developed onshore or offshore, depending on geographic and climatic conditions. Offshore wind, in particular, often offers stronger and more stable wind speeds, though it involves higher installation and maintenance costs. Despite its advantages, wind power is intermittent in nature because electricity generation depends on wind speed and weather conditions, which makes grid integration and storage important considerations [4].

**Hydropower** is one of the oldest and most established forms of renewable energy generation. It harnesses the energy of flowing or falling water to produce electricity, usually through dams, reservoirs, or run-of-river systems (Oluwadamilare et al., 2023). In a typical hydropower plant, water flows through turbines, creating mechanical motion that is converted into electricity. Hydropower has long been valued for its reliability, efficiency, and ability to provide baseload electricity as well as flexible peak-load support (Santosh et al., 2024). Large-scale

hydropower projects can contribute significantly to national electricity supply, while small-scale and micro-hydropower systems can serve rural and remote communities. However, although hydropower is renewable, it may also raise environmental and social concerns, such as ecosystem disruption, changes in river flow, displacement of local populations, and impacts on aquatic biodiversity. Therefore, its sustainability depends not only on electricity generation but also on careful planning and management.

**Geothermal energy** is derived from the internal heat of the earth and is considered a stable and relatively underutilized renewable resource (Santosh et al., 2024). This form of energy can be used both for electricity generation and for direct heating applications. In geothermal power plants, steam or hot water from underground reservoirs is brought to the surface to drive turbines and generate electricity. In other cases, geothermal heat can be used directly for district heating, greenhouse agriculture, drying processes, and industrial applications. Because geothermal resources can provide continuous energy output regardless of weather or time of day, they are generally more reliable than intermittent sources such as solar and wind. Geothermal energy is often considered the second most sustainable renewable source after wind in some comparative analyses (Abildtrup et al., 2024). However, its use is geographically limited to areas with suitable geological conditions, and initial exploration and drilling can be costly. As shown in Figure 2, **biomass and bioenergy** have served humanity since ancient times and remain important components of the renewable energy mix. Traditionally, biomass has been used for cooking, heating, steam production, and small-scale power generation (Nalbant et al., 2025). Biomass energy is derived from organic materials such as wood, agricultural residues, animal waste, municipal waste, and dedicated energy crops. Since plant growth depends on solar radiation, biomass may be understood as a stored form of solar energy in organic matter (Nalbant et al., 2025). Bioenergy can be converted into useful forms such as heat, electricity, biogas, biodiesel, and bioethanol. One of the key advantages of biomass is its versatility

and potential to utilize waste materials that might otherwise create disposal problems. However, biomass is not automatically sustainable in all cases. Unsustainable harvesting, land-use changes, deforestation, and competition with food

production can undermine its environmental and social benefits. Therefore, the sustainability of biomass depends heavily on responsible sourcing, efficient conversion technologies, and balanced resource management [5].

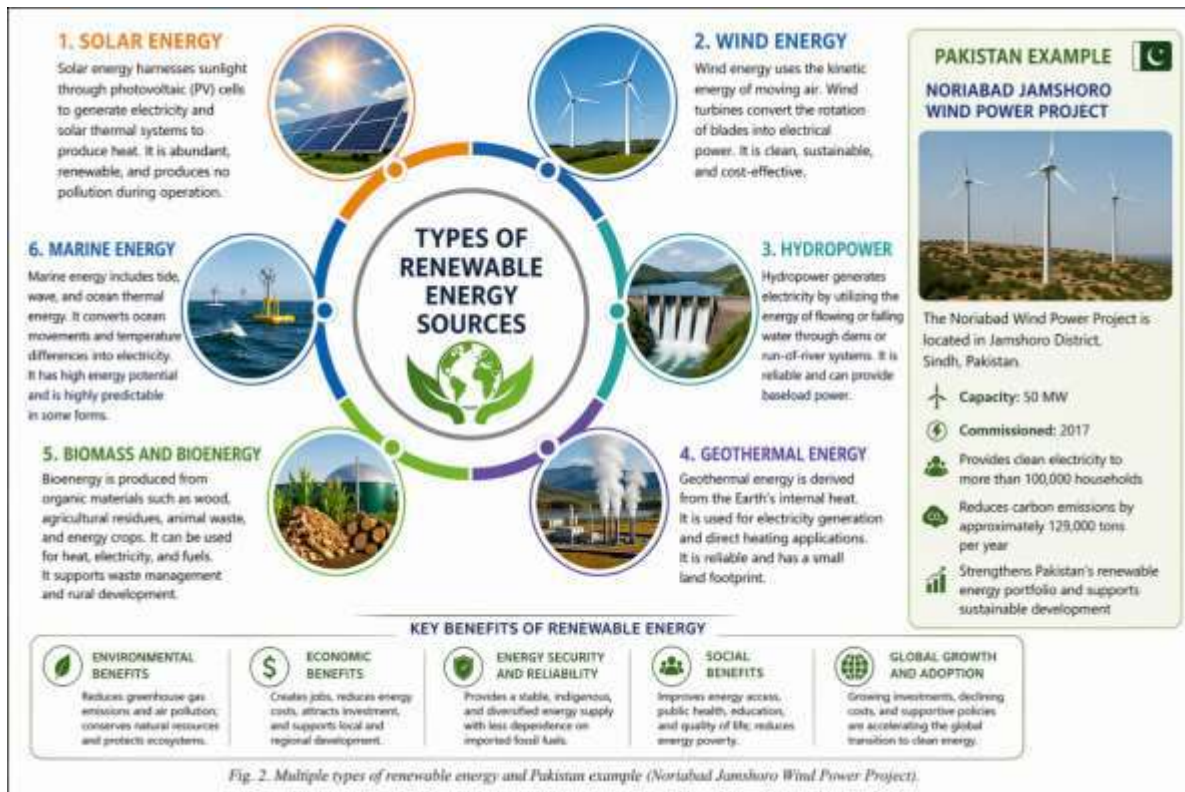


Fig. 2. Overview of major renewable energy sources with a Pakistan case example: the Noriabad Jamshoro Wind Power Project

**Marine energy** represents another important but relatively less developed category of renewable energy. It includes several ocean-based technologies such as tidal energy, wave energy, and ocean thermal energy conversion (Koohi-Fayegh et al., 2020; Margoum et al., 2024). Tidal energy is particularly promising because tides are highly predictable and regular, making this source more dependable than some other variable renewables. It converts the movement of ocean water caused by gravitational interactions into useful mechanical and electrical energy (Margoum et al., 2024; Chowdhury et al., 2020). Wave energy, on the other hand, captures the energy generated by surface waves, while ocean thermal systems exploit temperature differences between warm surface

water and colder deep water. Marine energy offers significant long-term potential, especially for coastal and island regions, but its commercial deployment remains limited due to technological, economic, and infrastructure challenges. Harsh marine environments, corrosion, high installation costs, and maintenance complexity continue to slow its large-scale adoption. Renewable energy sources can also be classified according to their operational characteristics, especially in relation to continuity and controllability of power generation (Duggan, 2025). Solar photovoltaic and wind power are commonly described as intermittent or variable energy sources because their output depends on weather conditions, daylight availability, and seasonal changes. In contrast,

geothermal energy, biomass, and hydropower offer varying degrees of dispatch ability, meaning that their electricity generation can be adjusted or scheduled more easily according to demand (Duggan, 2025). This distinction is highly important for power system operation, market design, and grid stability. Intermittent renewable sources require support from energy storage systems, flexible backup generation, demand-side management, and smart grid technologies to ensure reliable electricity supply. Therefore, understanding the technical behavior of different renewable energy sources is essential for effective

energy planning and successful integration into modern electricity markets.

Overall, the diversity of renewable energy sources provides a strong foundation for reducing dependence on fossil fuels and building a cleaner, more secure, and more sustainable energy future. Each source contributes in a different way depending on resource availability, technological maturity, cost, and regional suitability. A balanced combination of solar, wind, hydropower, geothermal, biomass, and marine energy can help countries diversify their energy mix, improve energy resilience, and support long-term sustainable development.

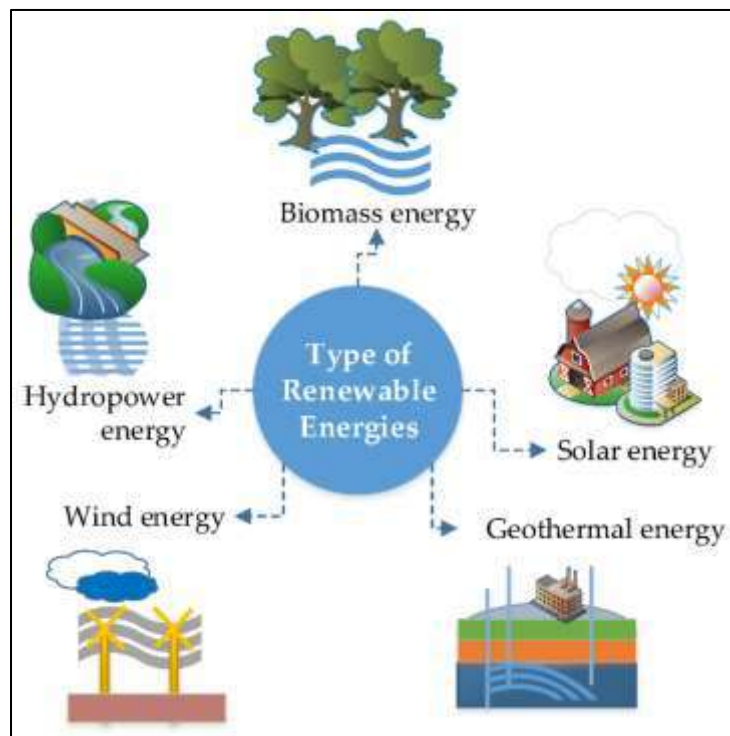


Fig.3. Multiple types of Renewable energy

### BENEFITS OF RENEWABLE ENERGY

Renewable energy provides substantial environmental benefits that are essential for addressing climate change, environmental degradation, and ecological imbalance. Unlike fossil fuels, renewable energy sources such as solar, wind, and hydropower generate electricity with little to no greenhouse gas emissions during operation, making them significantly cleaner alternatives (Rashid et al., 2024; Alismail et al.,

2023). This reduction in emissions directly contributes to mitigating global warming and limiting climate change impacts. In addition, renewable energy systems help reduce air and water pollution, which are major causes of environmental damage and public health problems. By decreasing dependence on fossil fuels, renewable energy minimizes issues such as acid rain, oil spills, and harmful particulate emissions that affect ecosystems and biodiversity

(Musa et al., 2022; Ndayishimiye et al., 2019). The environmentally friendly characteristics of these technologies, along with their ability to produce energy sustainably, make them a key solution for long-term environmental protection and ecological stability (Domazetovska et al., 2023)[5]. The economic benefits of renewable energy are equally significant and continue to grow as technologies advance. One of the most notable advantages is the creation of employment opportunities across multiple sectors, including manufacturing, installation, operation, maintenance, and research and development (Uzondu et al., 2024; Becchetti et al., 2025). The renewable energy sector has become a major source of job creation globally, supporting both skilled and unskilled labor. Moreover, renewable energy reduces long-term energy costs by decreasing reliance on imported fossil fuels, which are subject to price fluctuations and geopolitical risks. Investments in renewable energy infrastructure are largely focused on initial capital costs, after which operational expenses remain relatively low due to the free availability of natural resources such as sunlight and wind (Musa et al., 2022). Renewable projects also promote local economic development by utilizing local materials, workforce, and services, thereby strengthening regional economies (Becchetti et al., 2025). Furthermore, technological improvements have significantly reduced the cost of renewable energy; for example, the global levelized cost of electricity from solar photovoltaics declined by approximately 89% between 2010 and 2020, making it one of the most competitive energy sources available today (Becchetti et al., 2025). Energy security and reliability represent another major advantage of renewable energy systems. Traditional fossil fuel-based energy systems are highly dependent on limited resources and are often influenced by international market fluctuations and geopolitical tensions. In contrast, renewable energy sources such as solar radiation, wind, and water are naturally abundant and continuously replenished, providing a more stable and secure energy supply (Rashid et al., 2024). By diversifying the energy mix and reducing dependence on imported fuels, renewable energy

enhances national energy independence and resilience (Doric, 2024; Lodhi et al., 2024). This diversification also reduces the risks associated with energy shortages and price volatility, making renewable energy a reliable option for long-term energy planning (Musa et al., 2022). Additionally, the integration of renewable energy with modern technologies such as energy storage systems and smart grids further improves system reliability and efficiency. Beyond environmental and economic advantages, renewable energy also delivers important social benefits. It plays a crucial role in reducing energy poverty by providing access to electricity in remote and underserved regions where traditional grid infrastructure is unavailable or unreliable. Off-grid and decentralized renewable energy systems, particularly solar-based solutions, offer affordable and sustainable electricity for rural communities, thereby improving living standards and supporting socio-economic development (Rashid et al., 2024). Access to reliable energy enhances education, healthcare services, communication, and overall quality of life. Renewable energy projects also contribute to community development by creating jobs, encouraging local participation, and fostering social cohesion (Uzondu et al., 2024; Becchetti et al., 2025). In addition, reduced air pollution leads to improved public health outcomes, lowering the incidence of respiratory and cardiovascular diseases associated with fossil fuel use[6].

The rapid growth and global adoption of renewable energy further highlight its importance in the modern energy landscape. Over the past few decades, renewable energy has experienced significant expansion in both capacity and investment. It has emerged as one of the fastest-growing energy sectors, with nearly one-fifth of global electricity generation coming from renewable sources, making it the second-largest power source after coal (Omer, 2017). By 2015, renewable energy accounted for approximately 17.5% of global final energy consumption, with modern renewable technologies contributing a growing share to electricity generation (Garrido et al., 2020). Financial investment in renewable energy has also increased substantially, rising from

177 billion USD in 2008 to nearly 288.9 billion USD in 2018, while a large number of countries have adopted national renewable energy targets and policies to accelerate the transition (Lin et al., 2020). This continuous growth reflects increasing global awareness of the need for sustainable energy solutions and demonstrates the strong potential of renewable energy to reshape the future of energy systems worldwide [7][8][9].

Overall, the environmental, economic, social, and strategic benefits of renewable energy make it a vital component of sustainable development. Its ability to reduce emissions, create jobs, enhance energy security, and improve quality of life positions renewable energy as a key driver of global progress toward a cleaner, more resilient, and sustainable future.

## 2. SUSTAINABILITY AND CHALLENGES

The distinction between renewable energy and sustainable energy becomes especially important when evaluating long-term energy strategies, because not every renewable resource automatically satisfies sustainability requirements [2]. A renewable resource is generally defined by its ability to regenerate naturally over time, whereas sustainability involves a broader evaluation of whether that resource can be produced, managed, and consumed without causing unacceptable environmental, social, economic, or political harm. For renewable energy sources to be considered truly sustainable, they must satisfy four major pillars: they must be economically viable, politically supported, socially equitable, and environmentally acceptable [2]. In addition, a renewable resource may only remain sustainable when it is used at a rate that does not exceed its natural replenishment capacity. If consumption becomes greater than the rate of renewal, long-term use can no longer be regarded as sustainable [2]. This makes sustainability a more comprehensive and demanding concept than renewability alone.

The sustainability challenges associated with biomass provide a clear example of this complexity. Biomass and biofuels are often classified as renewable because they originate from organic materials that can be regrown or

replenished. However, their sustainability depends heavily on how they are produced and used. The production of biofuels through processes such as ethanol fermentation may become unsustainable when it competes with food crops, increases pressure on agricultural land, or contributes to deforestation and water stress [2] (Sekoai et al., 2016; Sekoai et al., 2016). This demonstrates that a renewable energy source may still fail to meet wider sustainability criteria when its environmental or social costs are high. By contrast, most other renewable sources, including solar, wind, geothermal, hydro, and tidal energy, are generally regarded as more sustainable because they are naturally abundant, relatively stable, and less directly linked to food security concerns [2]. Technical and operational challenges also present major barriers to the sustainability of renewable energy systems. [9][10] A key objective of renewable energy development is to reduce reliance on fossil fuels while ensuring reliable and adequate energy supply for growing populations and industries (Nzeanorue et al., 2024). However, several renewable technologies are affected by variability in resource availability. Solar energy depends on sunshine, wind power depends on wind speed, and hydropower may be influenced by rainfall patterns, river flow, and seasonal climatic changes. Such variability can make it difficult to guarantee a constant supply of electricity without additional support systems. As a result, renewable energy projects often require advanced hardware, improved forecasting models, energy storage systems, smart grids, and flexible backup generation in order to maintain reliability and efficiency (Kumar, 2020). These technical requirements can raise costs and complicate large-scale deployment, especially in developing regions with limited infrastructure [11].

Recent research has also drawn attention to the so-called “dark side” of renewable energy, which highlights that renewable systems can sometimes create hidden negative effects that weaken sustainability goals (Tian et al., 2024). Although renewable energy is widely promoted as a solution to environmental and developmental challenges, some technologies may create trade-offs in land use, biodiversity conservation, raw material

extraction, social acceptance, and waste generation. For example, large solar farms may require extensive land areas, hydropower projects may disrupt ecosystems and local communities, and renewable technology manufacturing may involve intensive mining of rare materials. These concerns do not negate the value of renewable energy, but they show that its sustainability must be assessed carefully across multiple dimensions. This broader understanding raises an important question: whether renewable energy systems always promote sustainable development, or whether in some cases they may enable progress in one area while creating problems in another (Tian et al., 2024). Market and systemic barriers further hinder the sustainability and expansion of renewable energy deployment. Despite major technological progress and increasing global awareness, fossil fuels continued to dominate electricity production in 2022–2023, accounting for approximately 62–63.5% of global power generation, while renewables contributed only around 29–30% (Poorvashree et al., 2024). This indicates that the global energy transition is still incomplete and faces strong structural resistance. Many countries remain dependent on existing fossil-fuel infrastructure, subsidies, and market arrangements that favor conventional energy systems. In addition, renewable energy expansion is often slowed by financing constraints, grid limitations, policy uncertainty, land acquisition problems, and weak institutional coordination. Therefore, the shift toward a global energy system dominated by renewables requires not only technological innovation but also coordinated policy support, regulatory reform, and international cooperation (Doric, 2024).

Another important aspect of sustainability is the lifecycle performance of renewable energy technologies. A renewable energy project cannot be considered fully sustainable based only on its operational phase; its entire lifecycle must be evaluated, including raw material extraction, manufacturing, transportation, installation, maintenance, and end-of-life disposal or recycling.

Sustainability conditions require that renewable energy systems demonstrate neutral or ideally negative carbon dioxide emissions over their lifecycle, while also minimizing other environmental and social harms (Petrescu et al., 2017). This means that true sustainability must integrate environmental quality, economic feasibility, human health, cultural context, and regulatory compliance. Renewable energy development must therefore align with national laws, international environmental standards, and broader social expectations if it is to support sustainable development in a meaningful way (Petrescu et al., 2017). Finally, the long-term transition toward sustainable energy requires continuous investment in research, innovation, public awareness, and policy implementation. Renewable energy systems must become not only cleaner but also more efficient, affordable, reliable, and socially acceptable if they are to replace fossil fuels at scale. This transition depends on the development of better storage technologies, smarter grids, improved conversion systems, stronger public education, and policy frameworks that encourage adoption and investment (Doric, 2024). At the same time, the growing pressures of climate change, environmental degradation, and resource depletion are forcing global economies to decarbonize more rapidly and adopt cleaner development pathways (Becchetti et al., 2025). For this reason, the future of renewable energy depends not only on the natural availability of resources but also on how effectively societies can manage the technical, environmental, political, and economic challenges associated with their widespread use.

Overall, while renewable energy offers major opportunities for a cleaner and more secure future, its long-term success depends on whether these resources can be developed and managed in ways that are truly sustainable. The relationship between renewability and sustainability is therefore not automatic but conditional, requiring balanced planning, responsible governance, and continuous innovation.

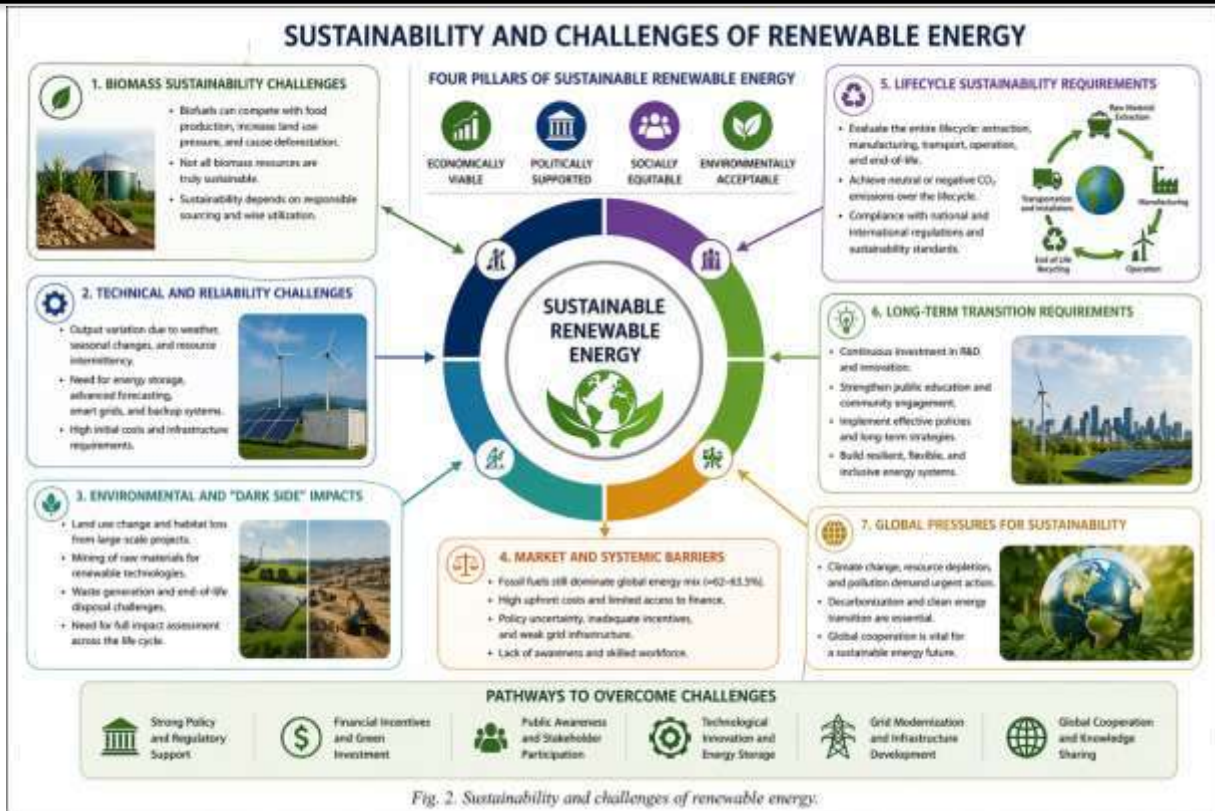


Fig. 4. Sustainability dimensions and major challenges of renewable energy, including technical, environmental, economic, and systemic factors.

### 3. Conclusion and discussions

1) Renewable energy sources significantly reduce greenhouse gas emissions and environmental pollution, making them essential for combating climate change and promoting sustainable development.

2) The widespread adoption of renewable energy enhances energy security by diversifying energy sources and reducing dependence on finite and volatile fossil fuels.

3) Renewable energy technologies provide strong economic benefits through job creation, cost reduction, and support for local and regional development.

4) Not all renewable energy sources are inherently sustainable; sustainability depends on economic viability, social equity, environmental impact, and responsible resource management.

5) Technical challenges such as intermittency, grid integration, and lifecycle impacts remain key barriers to large-scale renewable energy deployment.

6) Long-term sustainability of renewable energy systems requires supportive policies, continuous research and development, improved infrastructure, and global cooperation.

### 4. Future Recommendations

#### 1. Strengthening Policy and Regulatory Frameworks

Governments should develop stable, long-term policies and incentives that encourage investment in renewable energy technologies, grid modernization, and energy storage systems to ensure reliability and market integration.

#### 2. Advancing Research and Development

Continuous investment in research is essential to improve efficiency, reduce costs, and address intermittency issues through advanced energy storage, smart grids, and hybrid renewable systems.

#### 3. Lifecycle Sustainability Assessment

Future renewable energy projects should incorporate comprehensive lifecycle assessments to ensure minimal environmental impact, reduced

carbon footprints, and compliance with sustainability standards.

#### 4. Enhancing Grid Infrastructure and Energy Storage

Upgrading transmission networks and expanding energy storage solutions will help manage the variability of intermittent sources such as solar and wind, ensuring stable and secure power supply.

#### 5. Promoting Sustainable Biomass Utilization

Biomass energy development should prioritize waste-based and non-food feedstocks to avoid competition with food resources and enhance overall sustainability.

6. **Capacity Building and Public Awareness** Education, training, and public engagement programs should be strengthened to build technical capacity, increase social acceptance, and encourage community participation in renewable energy projects.

#### 7. International Cooperation and Investment

Global collaboration, technology transfer, and financial support mechanisms are crucial, particularly for developing countries, to accelerate the transition toward sustainable and low-carbon energy systems.

By addressing these recommendations, renewable energy can move beyond simple resource replacement and evolve into a truly sustainable energy system capable of supporting economic growth, social well-being, and environmental protection for future generations.

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