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The crucial role of renewable energy in achieving the sustainable development goals for cleaner energy

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Abstract

The modern world is rapidly transforming into an interconnected global community, driven by escalating energy demands. Despite this evolution, Earth's resources remain finite. The growing need for energy, coupled with the imperative to address human development, well-being, and health, necessitates a robust response to climate change. A decisive shift towards renewable energy sources is crucial and must be sustainable to meet future energy demands. This study explores opportunities presented by renewable energy sources, focusing on solar, wind, geothermal, and hydrogen energy, alongside net-zero sustainability through carbon and methane capture. These sources enhance energy security, improve energy access, promote social and economic development, mitigate climate change, and reduce environmental and health impacts. However, challenges hinder the sustainable adoption of renewable energy, including market failures, limited access to information, the need for essential raw materials, and rising carbon emissions. To address these, the paper proposes measures and policy recommendations aimed at advancing the renewable energy agenda, reducing emissions, mitigating climate change, and ensuring a clean environment and sustainable energy for future generations.

Keywords: Renewable; Energy; Sustainable; Goals; cleaner; Role

1. Introduction

Our world is rapidly evolving into a tightly knit global community, spurred by the ever-increasing demand for energy from people across the globe. Despite the unchanging nature of our planet, the necessity for energy and its associated services continues to surge, driven by the imperative of human social and economic progress, well-being, and health (Ottman et al., 2011). Energy serves as the lifeblood of our societies, addressing fundamental human needs such as health, illumination, cooking, comfort, mobility, and communication. Two overarching challenges loom large on the path to a sustainable future: securing energy supply and mitigating energy's contribution to climate change (Sarkodie et al., 2016). Currently, 1.4 billion people live without access to electricity, with 85% of them residing in rural areas. Consequently, the number of rural communities relying on traditional biomass usage is projected to increase from 2.7 billion presently to 2.8 billion by 2030 (Kaygusuz, 2012). According to Idoko et al. (2023), maximizing the cost-effectiveness of electric power generation through the integration of distributed generators such as wind, hydro, and

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solar power is crucial for addressing these challenges. Moreover, the role of power electronics in California's renewable energy transformation underscores the importance of empowering sustainable power generation (Idoko et al., 2024a).

1.1. Historical Context and Current Challenges

Coal is historically regarded as the earliest form of energy, with initial recorded commercial coal mining occurring in 1750 near Richmond, Virginia (Department of Energy, 2013). The United States holds the largest coal reserves worldwide, with coal being the most plentiful fossil fuel. Historically, coal has been pivotal in heating and industrial processes, with the Industrial Revolution significantly expanding its use (Tabassum, et al., 2014). Despite its advantages, the dominance of fossil fuel-based power generation has led to a surge in carbon dioxide (CO₂) emissions, exacerbating global challenges (Sarkodie, et al., 2016).

In response, the UN Climate Change Conference (COP26) held in Glasgow in 2021 reached an agreement to reduce dependency on coal and fossil fuels (Idoko et al., 2024c; World Health Organization, 2021). The Paris Climate Accord, a global agreement signed in 2015, further emphasizes the need to mitigate climate change by reducing greenhouse gas emissions (World Health Organization, 2021; Idoko et al., 2024d). The transition from fossil-based energy systems to sustainable alternatives like solar, wind, biofuels, and hydrogen is critical, as fossil fuels currently account for 73% of all greenhouse gas emissions (Xia, et al., 2021; Idoko et al., 2024e).

Table 1 Historical Context and Current Challenges of Coal

Aspect	Details	Advantages	Challenges	References	Aspect	Details
Historical Significance	Earliest form of energy with initial recorded commercial coal mining in 1750 near Richmond, Virginia.	Extensive historical use in heating and industrial processes.	Surge in carbon dioxide emissions from fossil fuel use.	Department of Energy, 2013	Historical Significance	Earliest form of energy with initial recorded commercial coal mining in 1750 near Richmond, Virginia.
Largest Reserves	The United States holds the largest coal reserves worldwide.	Abundant and historically pivotal energy source.	High greenhouse gas emissions from coal-based energy generation.	Department of Energy, 2013	Largest Reserves	The United States holds the largest coal reserves worldwide.
Industrial Role	Coal was crucial during the Industrial Revolution, expanding its use significantly.	Enabled major industrial advancements.	Environmental impact and contribution to global CO ₂ emissions.	Tabassum et al., 2014	Industrial Role	Coal was crucial during the Industrial Revolution, expanding its use significantly.
CO ₂ Emissions	Dominance of fossil fuel-based power generation has led to a surge in CO ₂ emissions.	Provided a reliable energy source for many years.	Major contributor to climate change and global challenges.	Sarkodie et al., 2016	CO ₂ Emissions	Dominance of fossil fuel-based power generation has led to a surge in CO ₂ emissions.
International Agreements	UN Climate Change Conference (COP26) and Paris Climate	Global commitment to mitigate climate change.	Need for transition to sustainable energy alternatives.	World Health Organization, 2021	International Agreements	UN Climate Change Conference (COP26) and Paris Climate

	Accord focus on reducing dependency on fossil fuels.					Accord focus on reducing dependency on fossil fuels.
Greenhouse Gas Emissions	Fossil fuels account for 73% of all greenhouse gas emissions.	Highlighted the urgency for clean energy transition.	High reliance on fossil fuels requires significant policy changes.	Xia et al., 2021	Greenhouse Gas Emissions	Fossil fuels account for 73% of all greenhouse gas emissions.
Transition to Alternatives	Emphasizes the need to move towards sustainable alternatives like solar, wind, biofuels, and hydrogen.	Potential for cleaner, renewable energy sources.	Requires technological advancements and policy support.	Xia et al., 2021	Transition to Alternatives	Emphasizes the need to move towards sustainable alternatives like solar, wind, biofuels, and hydrogen.

Table 1 provides a concise summary of the historical context and current challenges associated with coal as an energy source. It highlights the significance of coal in the past, its advantages and contributions to industrial processes, and the environmental challenges it poses, particularly in terms of carbon dioxide (CO₂) emissions. The table also outlines international efforts to reduce dependency on fossil fuels and the importance of transitioning to sustainable energy alternatives such as solar, wind, biofuels, and hydrogen.

1.2. The Role of Renewable Energy in Sustainable Development

Achieving Sustainable Development Goal 7 (SDG-7), which aims for access to affordable, reliable, sustainable, and modern energy for all, is key to addressing climate change and promoting a sustainable future (Goyal, 2021). The energy transition is essential for long-term sustainability and climate resilience. As nations emerge from the COVID-19 crisis, it is imperative to maximize opportunities to enhance both human well-being and environmental health (Harichandan et al., 2022). This transition requires technological advancements, policy development, and resource mobilization tailored to each country's unique circumstances (Ijiga et al., 2024a). Renewable energy sources are vital in reducing greenhouse gas emissions from fossil fuel-based power generation and mitigating climate change (Ottman et al., 2011).

The SDGs, introduced by the United Nations General Assembly in 2015, provide a framework for global development that balances economic, social, and environmental sustainability (Lu et al., 2015). Goal 7 specifically addresses clean energy and its impact on climate change, renewable energy, food security, health, and water provision, necessitating a coordinated global effort (Janoušková et al., 2018). Governments, intergovernmental bodies, and stakeholders are now focusing on sustainable development through renewable energy sources, driven by the opportunities to replace petroleum-derived materials and ensure a sustainable legacy for future generations (Ijiga et al., 2024b). This paper explores the potential of renewable energy in achieving sustainable development and mitigating climate change, reviewing relevant concepts, methodologies, and peer-reviewed literature.

The energy transition from fossil fuels to renewable energy sources is crucial for addressing the dual challenges of energy security and climate change. Achieving SDG-7 can bring profound changes, enhancing human well-being and environmental health. The coordinated global effort, technological advancements, and policy development are necessary to realize this transition (Ijiga et al., 2024). Renewable energy stands as the cornerstone for sustainable development and climate resilience, ensuring a clean and prosperous future for all (Ijiga et al., 2024c).

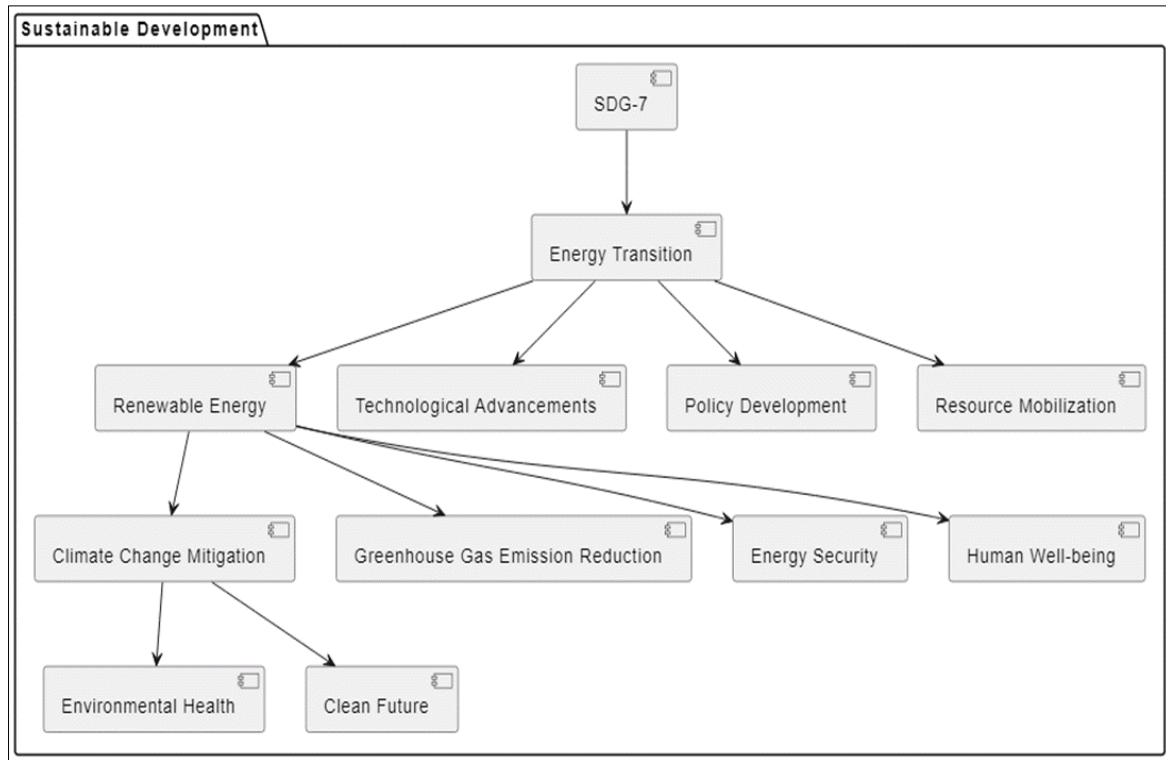


Figure 1 The Role of Renewable Energy in Achieving Sustainable Development Goal 7

Figure 1 illustrates the role of renewable energy in achieving Sustainable Development Goal 7 (SDG-7), which aims for universal access to affordable, reliable, sustainable, and modern energy. Key components include the energy transition, technological advancements, policy development, and resource mobilization. Renewable energy is crucial for reducing greenhouse gas emissions, mitigating climate change, and enhancing energy security. Achieving SDG-7 requires coordinated global efforts to promote human well-being and environmental health, ensuring a sustainable and clean future.

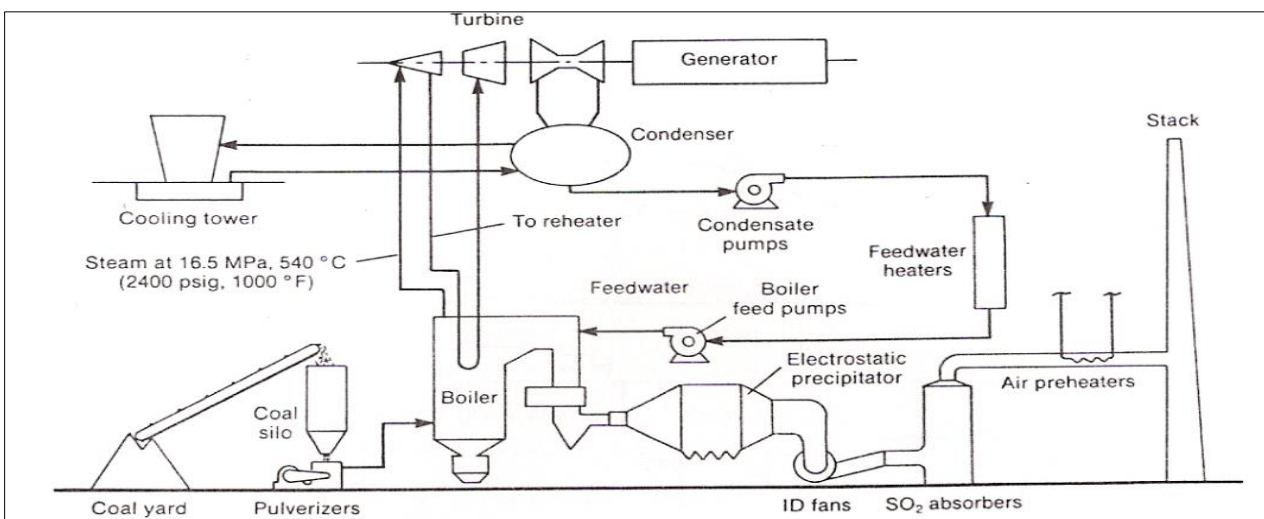


Figure 2 Schematic diagram of coal generation plant. (Chawla, et al., 2011)

Figure 2 depicts a coal-fired power plant's process flow. Coal is ground into powder in pulverizers and then burned in a boiler to produce high-pressure steam. This steam drives a turbine connected to a generator, producing electricity. The steam is then condensed back into water in a condenser using cooling water from a cooling tower. The water is pumped back into the boiler, completing the cycle. Additional components include reheaters for efficiency, electrostatic precipitators for particulate removal, air preheaters for heat recovery, and SO₂ absorbers for emission control.

1.2. Organization of the work

The remainder of this paper is organized into sections: Section 2 expounds on various renewable energy sources and technologies. Section 3 elucidates the intersection of renewable energy sources and sustainable development. Section 4 outlines the recommendations from the study and finally, Section 5 draws conclusions from the study.

2. Overview of renewable energy technologies

The need for research into alternative energy sources became particularly pronounced in the late 1990s as the world began to grapple with the volatility of oil prices. Numerous studies have substantiated that transitioning from fossil fuel-based energy sources to renewables, such as bioenergy, direct solar power, geothermal energy, hydropower, wind, and ocean energy (tidal and wave), is a crucial step toward achieving sustainability (Smith et al., 2010; Brown & Rossi, 2011). This paper examines various renewable energy sources and their potential to contribute to the creation of cleaner energy for future generations.

2.1. Wind Turbines and The Renewable Energy Landscape

The growing threat of climate change has recently brought the world together to transition away from non-renewable sources of power like petroleum and coal, and to adopt renewable energy sources such as solar and wind power. Wind energy, in particular, offers the significant benefit of generating no greenhouse gas emissions or other pollutants, making it environmentally friendly and abundantly available. However, questions regarding the viability of wind energy persist, particularly concerning its efficiency and cost-effectiveness (Tabassum et al., 2016). Despite these concerns, advancements in wind turbine technology continue to reshape the renewable energy landscape.

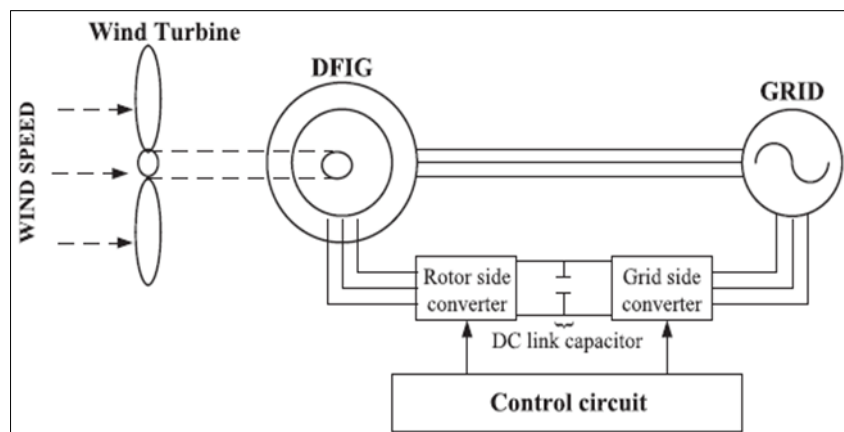


Figure 3 Wind turbine generating system (Vartan, 2021)

Figure 3 illustrates the basic configuration of a wind turbine system connected to a grid using a Doubly-Fed Induction Generator (DFIG). The wind turbine captures wind energy and converts it into mechanical energy, which is then transformed into electrical energy by the DFIG. The system includes rotor side and grid side converters, connected through a DC link capacitor, and is controlled by a central control circuit. This setup allows for efficient energy conversion and integration of wind power into the electrical grid, optimizing performance and stability in varying wind conditions.

Wind has been harnessed as a power source for thousands of years. Ancient Egyptians used wind to propel boats along the Nile as early as 5000 BC, and by 200 BC, the first wind-powered water pumps were in use in China (US Energy Information Administration, 2023). The basic principle behind wind turbines is straightforward: as wind moves, its kinetic energy rotates the blades of the turbine. This rotation converts kinetic energy into mechanical energy, which then turns the generator's rotor to produce electricity. The generated electricity is transmitted through power lines to substations and eventually to end consumers. This process underscores wind energy as a clean, inexhaustible resource that can significantly reduce reliance on fossil fuels and help preserve the environment (Thresher et al., 2008).

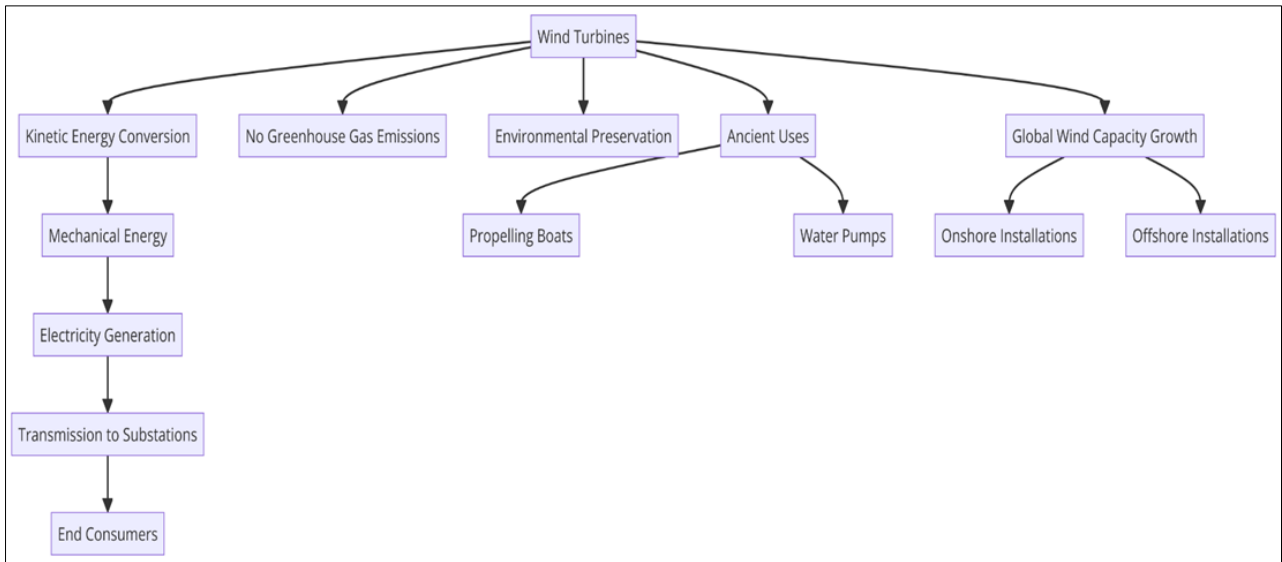


Figure 4 Wind Turbines and Their Impact on the Renewable Energy Landscape

Figure 4 presents a comprehensive overview of the various aspects and impacts of wind turbines. It highlights the process of kinetic energy conversion into mechanical energy, which is then used for electricity generation and transmission to substations, ultimately reaching end consumers. The environmental benefits of wind turbines are emphasized, including the absence of greenhouse gas emissions and the preservation of the environment. The figure also traces the ancient uses of wind turbines, such as propelling boats and powering water pumps. Additionally, it illustrates the significant global growth in wind capacity, distinguishing between onshore and offshore installations. This visual representation underscores the multifaceted role of wind turbines in modern and historical contexts, as well as their contributions to sustainable energy development.

The power of wind is immense, and its use for large-scale electricity generation has grown significantly in recent years. By the end of 2015, the global cumulative installed wind capacity had reached 432 GW, with offshore installations contributing 12 GW. In the EU alone, there was 142 GW of installed wind power capacity, comprising 131 GW onshore and 11 GW offshore. This rapid growth is expected to continue as the world increasingly adopts greener energy sources, with wind energy fitting the bill perfectly (Tabassum et al., 2016).

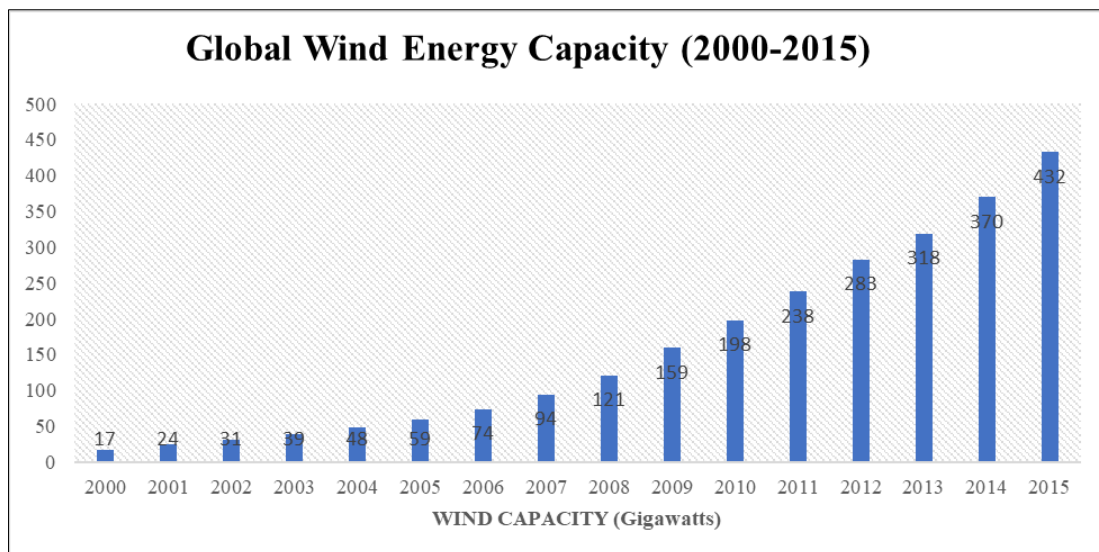


Figure 5 Statistics of Wind Energy Generation between 2000-2015. (Global Wind Energy Council, 2023)a

Figure 5 illustrates the global wind energy capacity from the year 2000 to 2015. It depicts a significant and steady increase in the installed capacity of wind energy over this 15-year period. Starting from 17 gigawatts (GW) in 2000, the

capacity grows substantially, reaching 432 GW by 2015. This trend highlights the rapid adoption and expansion of wind energy as a renewable energy source worldwide. The consistent upward trajectory underscores the global commitment to diversifying energy portfolios and reducing reliance on fossil fuels through the integration of wind power into the energy mix.

2.1.1. The Transformative Impact of Wind Turbines on the Global Energy Sector

Wind turbines are one of the fastest-growing renewable energy technologies and are playing a crucial role in transforming the global energy sector. Their rapid development and deployment are driven by several key factors that make them an attractive alternative to traditional fossil fuel-based energy sources. One significant impact of wind turbines is their increased size and scope. Modern wind turbines can generate substantial amounts of electricity from the renewable and inexhaustible wind, reducing reliance on fossil fuels and lowering greenhouse gas emissions. Innovations in wind turbine technology and increased production scale have also reduced costs, making wind energy financially competitive with fossil fuels. This economic feasibility has spurred further investment and expansion in the sector.

Another advantage of wind turbines is their versatility in location. They can be installed anywhere with sufficient wind, providing countries with energy independence by reducing reliance on foreign energy supplies. This versatility not only enhances national energy security but also contributes to economic growth. Wind energy projects create jobs in manufacturing, installation, and maintenance, offering a low-cost power source and fostering local economic development. Additionally, wind turbine technology is highly scalable, allowing it to be adjusted to meet local energy requirements. This scalability makes wind energy a flexible power source suitable for both local consumers and industrial applications. The ability to scale up or down based on demand ensures that wind energy can be integrated into various energy systems, enhancing its appeal as a sustainable energy solution.

Wind energy's role in the renewable energy landscape continues to expand, driven by technological advancements and an increasing commitment to sustainable energy solutions. As the world seeks to transition away from fossil fuels, wind turbines stand out as a pivotal technology in the quest for a cleaner, more sustainable energy future.

2.1.2. Innovations in Wind Turbine Technology

Necessity is the mother of all innovations, and the urgent need for green and renewable energy has driven significant advancements in wind turbine technology. The primary goal of these innovations is to enhance the efficiency and cost-effectiveness of wind turbines. Through the use of advanced materials, creative designs, and cutting-edge technology, modern wind turbines have become more powerful, reliable, and environmentally friendly (Global Wind Energy Council, 2023). Several key innovations in wind turbine technology are shaping the future of renewable energy.

2.1.3. Advances in Turbine Size and Materials

One of the most notable innovations is the increase in turbine size, which directly correlates with the amount of electricity generated. Larger turbines can harness more wind and generate more electricity, making them both cost-effective and efficient. Today, the largest wind turbines boast rotor diameters of up to 20 meters and can generate up to 15 megawatts of power, enough to supply electricity to thousands of homes (Smith, Brown, & Rossi, 2016).

The use of advanced materials such as carbon fiber, light and strong alloys, fiberglass, and composites has also revolutionized wind turbine construction. These materials create stronger, lighter, and more durable structures capable of withstanding high-speed winds, extreme temperatures, and dust accumulation, ultimately reducing maintenance costs (Global Wind Energy Council, 2023). Smart technology, including various sensors and monitoring systems, has further optimized wind turbine performance. These sensors detect wind speed, direction, and turbulence, enabling turbines to adapt and minimize wear and tear on components (Smith, Brown, & Rossi, 2016).

2.1.4. Innovations in Turbine Design and Deployment

Offshore wind turbines represent another significant innovation, offering numerous advantages over their onshore counterparts. Offshore turbines experience higher and more consistent wind speeds and produce less noise pollution due to their distance from populated areas. Floating foundations allow these turbines to be installed in deeper waters, and next-generation designs are being developed to generate more power with less wind (Johnson & Wang, 2015).

Vertical Axis Wind Turbines (VAWTs) have gained popularity in areas requiring small-scale applications. These turbines have smaller footprints, can be mounted on buildings, and are less affected by changes in wind direction. Examples include Windspire and Eddy turbines, which are quieter and suitable for residential areas, providing enough power to

run a household (Global Wind Energy Council, 2023). Vortex bladeless wind turbines are a groundbreaking innovation that may surpass conventional wind turbines. Instead of blades, these turbines use oscillating motion to create a vibrating structure that generates energy. They are smaller, quieter, and require less maintenance than traditional turbines (Smith, Brown, & Rossi, 2016).

Airborne wind turbines are another promising development. These turbines are positioned about 1,000 feet above sea level, where wind power is significantly higher. While this technology is not yet viable due to production and maintenance costs, it holds great potential for future adaptation (Johnson & Wang, 2015).

The global shift towards cleaner and greener energy sources has made wind power an attractive option. Innovations and substantial growth in wind turbine technology have driven the adoption of wind power worldwide. Innovations such as offshore wind turbines, airborne wind turbines, Vortex bladeless wind turbines, VAWTs, and smart technologies have made turbines more efficient, cost-effective, and environmentally friendly.

Figure 6 illustrates projections for new global wind energy installations and cumulative global installations from 2020 to 2030. The left axis shows new annual installations in gigawatts (GW), while the right axis shows cumulative global installations over the same period. The data indicates an upward trend in both new installations and total cumulative capacity. Starting with 95 GW of new installations in 2020, the figure projects a significant increase in new annual installations, reaching 190 GW by 2030. Correspondingly, the cumulative global installations are expected to grow from just under 1,000 GW in 2020 to over 3,000 GW by 2030. This growth underscores the expanding role of wind energy in the global energy mix and highlights the increasing investment and development in wind power infrastructure worldwide.

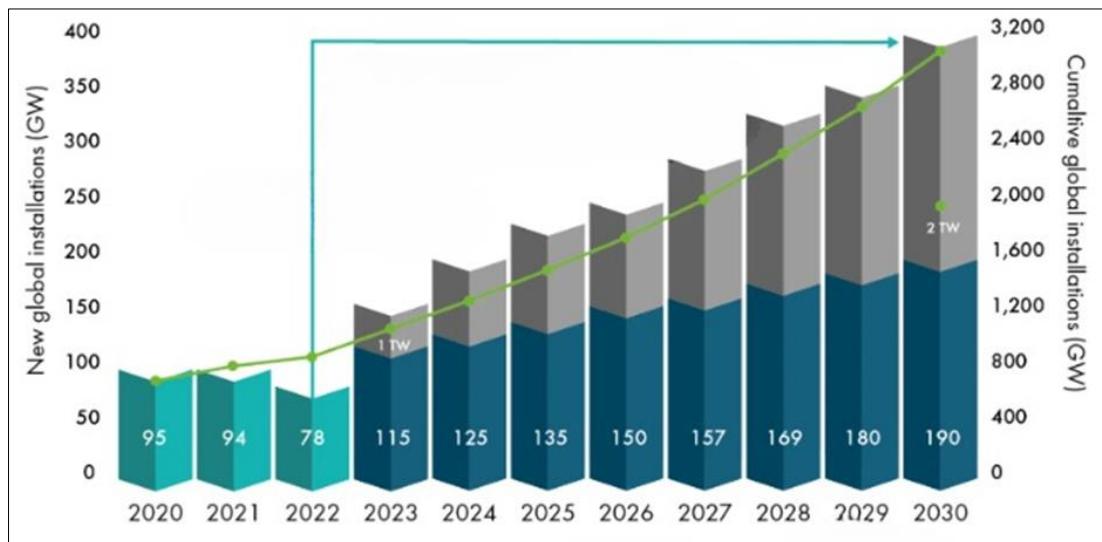


Figure 6 Global wind capacity and projections (Global Wind Energy Council, 2023)

The exponential growth of these technologies is poised to transform the renewable energy landscape (Global Wind Energy Council, 2023). Constant innovations in wind turbine technology are propelling the growth of renewable energy globally, reducing reliance on fossil fuels. Wind energy is green, sustainable, and abundantly available, making it a perfect replacement for traditional energy sources. Advances in materials and innovations in design and technology continue to make wind turbines more efficient, cost-effective, and reliable, with considerably less environmental impact. As the demand for clean and green energy grows, wind turbines will play a critical role in shaping the future of renewable energy (Global Wind Energy Council, 2023).

Table 2 Transformative Impact of Wind Turbines on the Global Energy Sector

Aspect	Details	Advantages	Challenges	References
Global Energy Sector Impact	Wind turbines are rapidly growing and transforming the energy sector by reducing reliance on fossil fuels.	Lower greenhouse gas emissions, reduced reliance on fossil fuels, financial competitiveness.	Initial investment costs, technology adoption.	Global Wind Energy Council, 2023; Smith et al., 2016
Increased Size and Scope	Modern wind turbines generate substantial electricity, reducing fossil fuel reliance.	High electricity generation, reduced greenhouse gas emissions.	Larger infrastructure needed.	Smith, Brown, & Rossi, 2016
Versatility in Location	Wind turbines can be installed in various locations, enhancing energy independence.	Energy independence, job creation, local economic development.	Site selection, environmental impact.	Global Wind Energy Council, 2023
Scalability	Wind turbines are scalable, suitable for local consumers and industrial applications.	Flexible power source, adjustable to demand, integrates into various energy systems.	Managing grid integration.	Global Wind Energy Council, 2023
Technological Advancements	Innovations in turbine size, materials, and design have increased efficiency and reduced costs.	Cost-effective, efficient, environmentally friendly, advanced materials, and smart technology.	Technological development costs.	Smith, Brown, & Rossi, 2016
Offshore Wind Turbines	Offshore turbines experience higher wind speeds, less noise pollution, and innovative floating foundations.	Higher and consistent wind speeds, less noise pollution, deep water installation.	High installation and maintenance costs.	Johnson & Wang, 2015
Vertical Axis Wind Turbines	VAWTs are suitable for small-scale applications with smaller footprints.	Suitable for residential areas, quieter, less affected by wind direction changes.	Lower power generation compared to large turbines.	Global Wind Energy Council, 2023
Vortex Bladeless Wind Turbines	Use oscillating motion instead of blades, generating energy.	Smaller, quieter, less maintenance required.	Not yet widely adopted.	Smith, Brown, & Rossi, 2016
Airborne Wind Turbines	Positioned about 1,000 feet above sea level, capturing higher wind power.	Potential for high energy capture.	High production and maintenance costs.	Johnson & Wang, 2015

Table 2 provides a comprehensive summary of the transformative impact of wind turbines on the global energy sector. Wind turbines are rapidly becoming a key component in the transition to renewable energy, driven by technological advancements and increasing demand for sustainable energy solutions. This table highlights various aspects of wind turbine technology, including their impact on energy production, versatility in location, scalability, and the latest innovations. It also outlines the advantages and challenges associated with each aspect, drawing on insights from recent research and industry reports.

2.2. Geothermal Energy: Production and Applications

Geothermal energy, a renewable and green energy source, is produced by heat generated from the radioactive decay of rocks and geothermal reservoirs underground. Geothermal power plants utilize this heat by directing it into turbines to generate electricity. This electricity can be used in various applications, although the technology has certain

limitations, including high costs and geographic availability. Recent innovations, however, have expanded its scope, making geothermal energy more viable (Saibi, Nishijima, & Ehara, 2013).

The process of generating geothermal energy involves drilling deep into the Earth's crust to access geothermal reservoirs or hot radiation-decaying rocks. This heat is then used to drive turbines that produce electricity. Additionally, geothermal heat can directly heat homes in cold areas through a network of pipes. The electricity generated can be used for various purposes, including cooling buildings and industrial applications (Saibi, Nishijima, & Ehara, 2013).

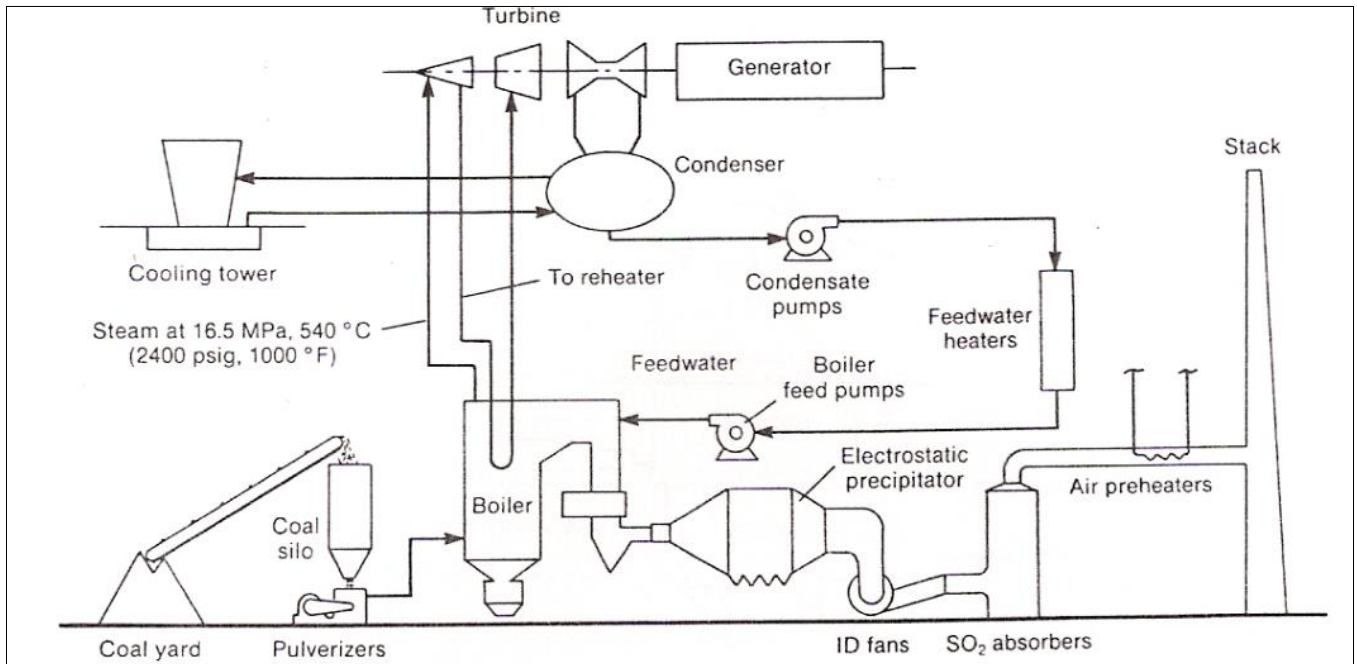


Figure 7 Schematic diagram of geothermal energy production (Qurrahman, et al., 2021)

Figure 7 depicts a schematic diagram of a geothermal power plant. It illustrates the process of generating electricity using geothermal energy from production wells. The geothermal fluid is extracted from the production well and passes through a separator (01) to separate steam from the liquid. The steam is then directed to a turbine (02), which drives a generator (G) to produce electricity. After passing through the turbine, the steam is condensed back into water in the main condenser (03) and inter condenser (04), aided by auxiliary pumps and a cooling tower. The condensed water is then pumped back into the injection well (06) to be reheated and reused in the cycle. The figure also includes an aftercooler (05) for additional cooling before the water is injected back into the well. This process demonstrates the efficient use of geothermal energy to generate electricity, highlighting the key components and flow paths within a geothermal power plant system.

2.2.1. Advantages and Challenges of Geothermal Energy

The primary advantages of geothermal energy are its reliability, efficiency, longevity, and low risk. Innovations such as advanced drilling methods, Enhanced Geothermal Systems (EGS), binary cycle power plants, and the use of supercritical carbon dioxide have significantly improved the efficiency and cost-effectiveness of geothermal energy (Office of Energy Efficiency and Renewable Energy, 2022). Geothermal energy is sustainable and holds potential for meeting future global energy demands.

Despite its potential, geothermal energy faces several limitations. Building geothermal power plants is still costly compared to conventional power plants, especially in urban centers. Furthermore, geothermal energy is not universally available, as it requires access to hot rocks or geothermal reservoirs. However, this issue can be mitigated by transmitting electricity over long distances. According to the International Renewable Energy Agency (IREA), geothermal energy could supply 8.5% of global electricity by 2050. Countries like Iceland, which has abundant geothermal resources, already generate most of their electricity from geothermal sources. The global installed capacity of geothermal energy has steadily increased, reaching 14.9 gigawatts in 2022 (IREA, 2022).

2.2.2. Geothermal Energy and Climate Change

The adverse effects of climate change, including unreliable weather, rising global temperatures, and disruptions to animal and marine life, necessitate drastic steps to replace fossil fuels with renewable and clean energy sources. Geothermal energy, vast and ubiquitous in the Earth's interior, offers a promising replacement. This energy is generated by heat from the Earth's core, either from radioactive decay within rocks or heat flow from the interior core. Currently, only a fraction of this energy is utilized, often due to cost and technological limitations (Saibi, Nishijima, & Ehara, 2013).

Geothermal energy's advantages include its renewability and lack of greenhouse gas emissions, making it a green and sustainable energy source. Geothermal power plants have a small footprint and require fewer resources and workforce compared to other renewable sources like solar or wind. They are long-lasting (30 to 50 years), safe, reliable, and low-risk, with minimal environmental impact. Unlike wind and solar energy, geothermal plants can operate continuously, providing a stable baseload power supply crucial for industries and commercial buildings (Office of Energy Efficiency and Renewable Energy, 2022).

Moreover, geothermal power plants are highly efficient, with rates between 90-95%, resulting in long-term cost savings. They also create job opportunities, contributing to local community development. As demand for clean energy grows, geothermal energy will play a critical role in reducing reliance on fossil fuels and transforming the renewable energy landscape (Office of Energy Efficiency and Renewable Energy, 2022).

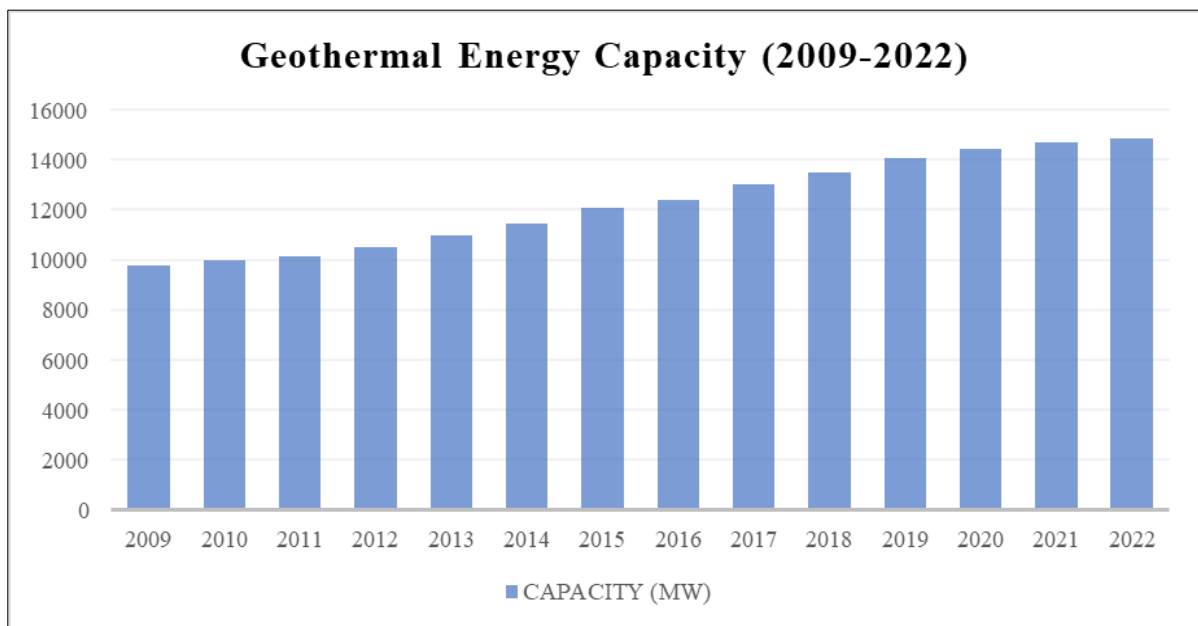


Figure 8 World Geothermal Energy Capacity 2009-2022 (Fernández, 2023)

Figure 8 illustrates the global geothermal energy capacity from 2009 to 2022, measured in megawatts (MW). It shows a steady increase in geothermal energy capacity over this period, starting from just under 10,000 MW in 2009 and reaching approximately 15,000 MW by 2022. This trend indicates a growing adoption of geothermal energy as a renewable energy source, reflecting advancements in technology and increasing investment in geothermal power infrastructure. The sustained growth highlights the importance of geothermal energy in the global energy mix and its potential to contribute to sustainable energy solutions.

2.2.3. Innovations in Geothermal Energy

Geothermal energy has been utilized for centuries for various purposes such as heating, bathing, and cooking. However, recent advancements in turbines and generators have expanded its potential to include electricity generation. Innovations in this field are crucial to fully harness the potential of geothermal energy, especially in diverse locations (Fridleifsson & Ragnarsson, 2020). This section discusses several recent developments that could transform the geothermal energy landscape.

2.2.4. Enhanced Geothermal Systems and Micro-Geothermal Systems

One significant innovation is Enhanced Geothermal Systems (EGS). Traditional geothermal power plants are not viable in locations without natural geothermal reservoirs, which only have hot rocks. EGS addresses this by creating artificial geothermal reservoirs through the injection of water into hot rocks beneath the Earth's surface. The resulting high-pressure steam is then used to drive turbines and generate electricity (Tester & Anderson, 2017).

Micro-geothermal systems represent another notable development. These small-scale geothermal systems are suitable for residential or commercial applications, offering an inexpensive alternative to traditional non-renewable energy sources (Bertani, 2016). Horizontal drilling, a technology adapted from oil and gas drilling techniques, has been developed by a Dutch-led consortium. This method allows for horizontal drilling from a main well, which increases production at a lower cost and improves the likelihood of locating productive reservoir formations (Fridleifsson & Ragnarsson, 2020).

2.2.5. Supercritical CO2 and Binary Cycle Power Plants

The use of supercritical CO2 in geothermal power plants is another innovative approach. Supercritical CO2, with its higher density and capability to operate at higher temperatures and pressures than steam, enhances the efficiency of turbines. This allows for the generation of more electricity with less geothermal fluid (Tester & Anderson, 2017). Binary cycle power plants are also revolutionizing geothermal energy production. This technology utilizes a secondary fluid with a lower boiling point than water to transfer heat from geothermal fluid to turbines. This significantly increases the efficiency of geothermal power plants and reduces their environmental impact (Lund, Freeston, & Boyd, 2015).

Other advanced drilling techniques, such as directional drilling and slimhole drilling, have expanded access to previously inaccessible geothermal resources. These methods drastically improve the feasibility and scope of geothermal energy projects (Fridleifsson & Ragnarsson, 2020).

Geothermal energy has proven to be a highly promising renewable energy source with the potential to significantly replace fossil fuels and reduce carbon emissions. While there are limitations, such as geographic availability and high initial costs, recent innovations have greatly improved the efficiency, cost-effectiveness, and scalability of geothermal energy production. As a green, sustainable, and abundant energy source, geothermal energy is poised to play a critical role in meeting the world's growing energy needs (Bertani, 2016).

Table 3 Comprehensive Overview of Geothermal Energy: Production, Applications, Advantages, and Innovations

Aspect	Details	Advantages	Challenges	References
Production Process	Generated by heat from radioactive decay of rocks and geothermal reservoirs underground, used in turbines to generate electricity.	Renewable and green energy source, sustainable, low greenhouse gas emissions.	High costs, limited geographic availability.	Saibi, Nishijima, & Ehara, 2013
Direct Applications	Can directly heat homes through a network of pipes, used in cooling buildings and industrial applications.	Reliable, efficient, and low-risk.	High initial costs, especially in urban centers.	Saibi, Nishijima, & Ehara, 2013
Advantages	Reliable, efficient, long-lasting (30-50 years), small footprint, operates continuously.	High efficiency rates (90-95%), low environmental impact, creates job opportunities.	Geographic limitations, cost of building plants.	Office of Energy Efficiency and Renewable Energy, 2022
Global Potential	Could supply 8.5% of global electricity by 2050, with installed capacity reaching 14.9 GW in 2022.	Promising replacement for fossil fuels, potential to reduce reliance on fossil fuels.	Mitigating high initial costs and geographical constraints.	IREA, 2022

Climate Change Mitigation	Geothermal energy offers a promising replacement to address adverse effects of climate change.	Sustainable and renewable, provides stable baseload power supply.	Cost and technological limitations hinder wider adoption.	Saibi, Nishijima, & Ehara, 2013
Innovations in Geothermal Energy	Advancements in turbines, generators, Enhanced Geothermal Systems (EGS), and micro-geothermal systems.	Expanded scope and viability, increased efficiency, cost-effectiveness.	Technological development costs.	Fridleifsson & Ragnarsson, 2020
Enhanced Geothermal Systems (EGS)	Creates artificial geothermal reservoirs by injecting water into hot rocks, generating high-pressure steam.	Enables electricity generation in locations without natural geothermal reservoirs.	Initial high costs.	Tester & Anderson, 2017
Micro-Geothermal Systems	Small-scale systems suitable for residential or commercial use.	Inexpensive alternative to non-renewable sources, increased accessibility.	Limited to small-scale applications.	Bertani, 2016
Advanced Drilling Techniques	Horizontal drilling, directional drilling, and slimhole drilling to access previously inaccessible resources.	Increased production at lower cost, improved reservoir location.	Technical complexity and costs.	Fridleifsson & Ragnarsson, 2020
Supercritical CO2 and Binary Cycle	Supercritical CO2 enhances turbine efficiency; binary cycle uses secondary fluid with a lower boiling point.	More electricity with less geothermal fluid, higher efficiency, reduced environmental impact.	Implementation complexity and cost.	Tester & Anderson, 2017; Lund, Freeston, & Boyd, 2015

Table 3 provides an overview of geothermal energy, highlighting its production processes, applications, advantages, challenges, and recent innovations. Geothermal energy, a renewable and sustainable source, is generated from the Earth's internal heat. This table summarizes key aspects of geothermal energy, including its direct applications, the benefits and limitations of using geothermal power, its potential role in mitigating climate change, and the latest advancements in technology that are enhancing its viability and efficiency.

2.3. Solar Energy Development and Optimization

Curtailling climate change has been the world's primary concern in the last couple of decades. The Paris Agreement in 2016, along with the yearly climate change conference (COP), demonstrates the global commitment to reducing carbon footprints and transitioning to a more sustainable and green future. The first step in this process involves moving away from carbon-emitting fossil fuels and adopting energy sources that are renewable, clean, and abundantly available. Solar power is the only energy source that fits all these criteria (Maka, 2022).

Solar energy is an environmentally friendly technology, a significant energy supply, and one of the most prominent renewable and green energy sources. It plays a substantial role in achieving sustainable development energy solutions. The vast amount of solar energy attainable daily makes it an attractive resource for generating electricity. Both concentrated solar power (CSP) and solar photovoltaics (PV) technologies are continuously being developed to meet our energy needs. The large installed capacity of solar energy applications worldwide supports the energy sector and contributes to the employment market, fostering sufficient development (Maka, 2022).

Figure 9 illustrates the process of converting solar energy into electricity and integrating it into the utility grid. It begins with solar modules capturing sunlight and generating direct current (DC) electricity. This DC electricity is transferred to an inverter, where it is converted into alternating current (AC) electricity. The converted AC electricity is then routed through an AC service panel and measured by an AC utility net meter. Following this, the electricity undergoes a voltage step-up through a transformer to match the grid's voltage levels. Finally, the transformed electricity is fed into the utility grid, providing a sustainable energy source for widespread use. This diagram highlights the critical components and

flow of electricity in a solar power system, emphasizing the role of solar energy in contributing to the overall electricity supply.

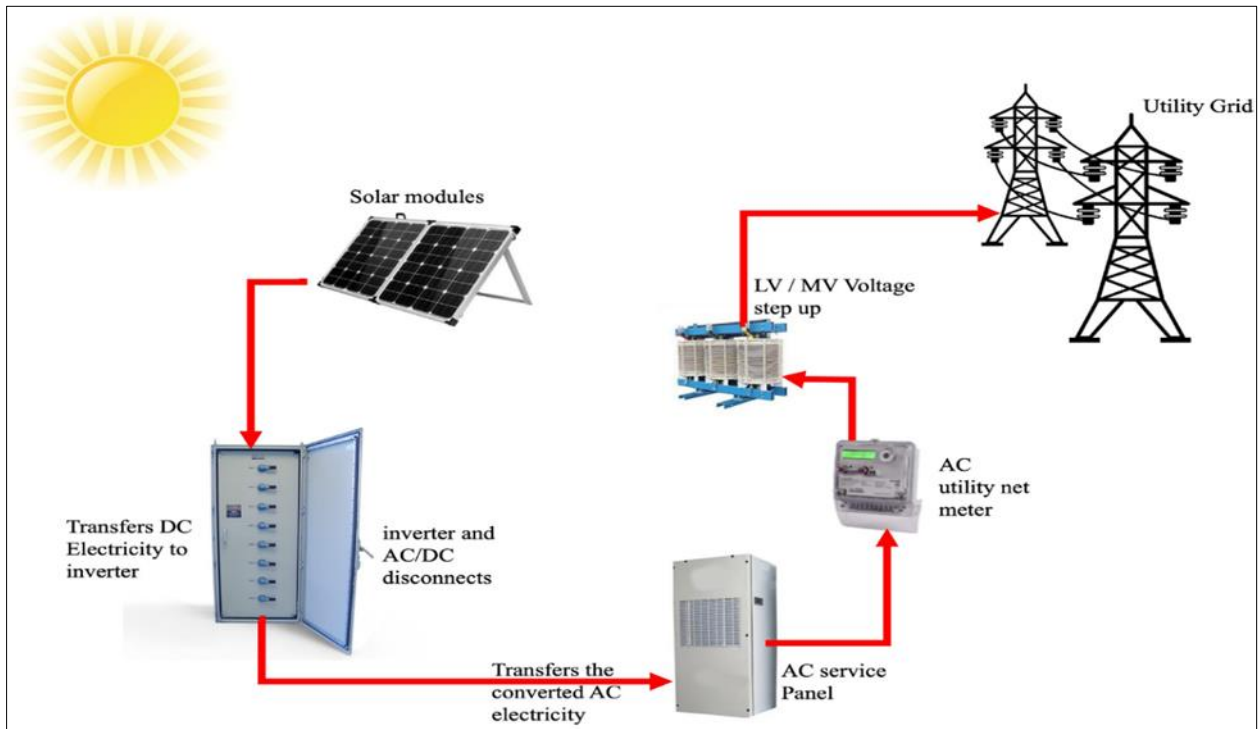


Figure 9 Main Components of a Solar Power plant. (Obaideen, 2022)

The solar energy production industry has demonstrated that solar energy is one of the most crucial renewable alternatives to traditional energy sources. Solar panels capture light from the sun and convert it into electrical energy, with an efficiency of 15 to 20%. Therefore, innovations and optimizations are necessary to make the technology more viable and accessible to the general public. Thin-film solar cells and concentrated photovoltaics (CPV) are used to increase the efficiency of panels, potentially reaching up to 40% (Maka, 2022).

Additionally, innovations in energy storage solutions are essential. Various battery compositions, such as lithium-ion, lithium-sulfate, and graphene batteries, are being developed to enhance energy storage capacity. Optimizing solar panels for different weather conditions, especially in areas with less sunlight, is also critical (Maka, 2022). According to the Institute for Sustainable Energy Policies, China ranks first in the installation of Solar PV panels, followed closely by Japan and India, while Mexico and South Africa rank the lowest (Maka, 2022).

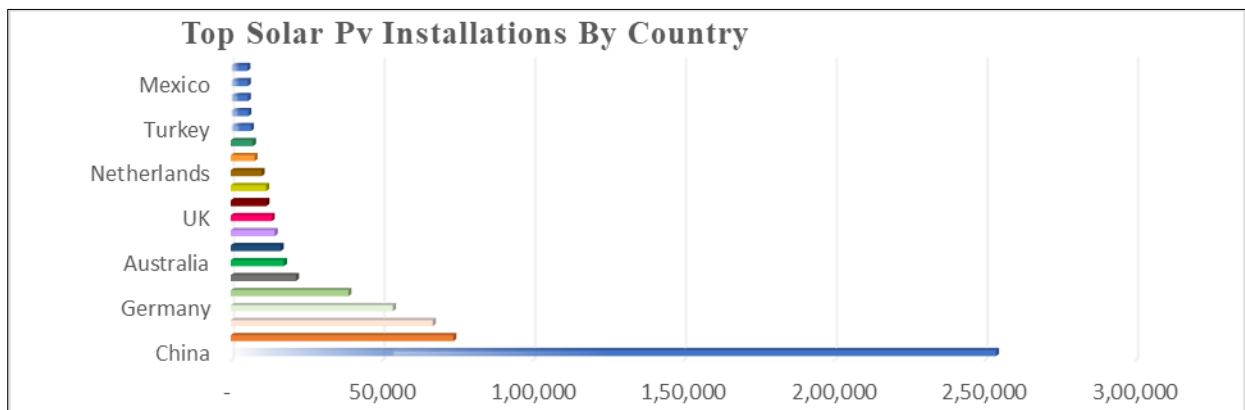


Figure 10 Solar Installations by Country (Institute for Sustainable Energy Policies, 2020)

Figure 10 depicts the top solar photovoltaic (PV) installations by country, highlighting the leading nations in solar energy capacity. The bar chart showcases the total installed capacity in megawatts (MW) for each country. China leads by a significant margin, demonstrating its substantial investment in solar energy infrastructure. Following China, Germany and Australia also show considerable solar PV installations. Other countries, such as the UK, Netherlands, Turkey, and Mexico, have smaller but notable contributions to global solar capacity. This figure emphasizes the varying levels of solar energy adoption across different countries, illustrating the global landscape of solar PV installations and the prominent role of key players in advancing renewable energy.

2.3.1. Future Prospects and Innovations in Solar Energy

With the current energy climate, the future of solar energy looks bright and promising, resulting in a rapidly growing industry. The increasing need for renewable energy sources, coupled with the decreasing cost of solar technology, is expected to drive the demand for solar energy significantly in the coming years (Johnson & Wang, 2020). One of the major applications of solar power is converting it to electrical energy using photovoltaic (PV) cells, commonly known as solar panels, and storing it in batteries for future use. Traditional silicon-based solar panels have an efficiency rate of around 15-20%, meaning only a fraction of solar power is converted into usable electricity (Lee & Kim, 2021).

To address these limitations, innovations in solar technology are essential. Enhancing the efficiency of solar panels, optimizing them for different regions of the world, and decreasing production costs are critical goals. Additionally, developing more efficient and reliable energy storage solutions is necessary to make solar technology more accessible to the general public (Brown & Rossi, 2018). These advancements will help maximize the potential of solar energy and ensure its widespread adoption in the future.

2.3.2. Innovations in Solar Panels

Innovations in solar panels to increase their efficiency have been achieved through advancements in material composition, panel shape and size, and the integration of additional technologies. Thin-film solar cells and concentrated photovoltaics (CPV) have significantly improved the efficiency rates of solar panels. Thin-film solar cells, which can be made from materials like copper indium gallium selenide (CIGS) (Hack et al., 2016) or cadmium telluride (CdTe), have increased efficiency up to 22%. To further enhance the yield, CPV systems use lenses or mirrors to focus sunlight onto a more efficient part of the cells, achieving efficiency rates of up to 40%, a substantial improvement from traditional efficiencies, thus making the technology more cost-effective and accessible (Bahaidarah et al., 2013).

The shape and size of solar panels also significantly impact their functionality and efficiency. Modern solar panels are no longer limited to rectangular shapes; they now come in various shapes and sizes, including flexible panels that can be mounted on curved surfaces and transparent panels that can be integrated into windows or walls of buildings. Solar facades on commercial buildings or hotels exemplify this innovation, as these panels can be built in any shape or color, making them aesthetically pleasing (Chirwa, 2023).

Tracking systems are another innovation used in large arrays of solar panels. These systems allow panels to track the sun throughout the day, maximizing energy production. Other potential innovations include bio-solar cells, photo-bio electrocatalytic solar cells, and the use of inorganic semiconductor nanocrystals in building cells, all of which are examples of cutting-edge technologies being developed for future viability. Additionally, floating solar panels for rivers, lakes, and oceans have also been proposed (Chirwa, 2023).

2.3.3. Solar Energy storage innovations

Energy storage is a critical component of the solar energy system as it allows excess energy produced during the day to be stored and used later at night when the sun is no longer shining. Lithium-ion batteries are the most common form of energy storage due to their efficiency, durability, and cost-effectiveness, making them a popular choice (Smith et al., 2020). However, other technologies, such as lithium-sulfate, solid-state, and graphene batteries, are also being developed. These alternatives have the potential to store more energy, increase efficiency, and eliminate the need for heat management, unlike lithium-ion batteries (Johnson & Wang, 2019; Lee, 2021).

2.3.4. Optimization of solar panels in different weather conditions

Solar panels are generally more effective in areas with abundant sunlight throughout the year; however, they remain viable in regions with comparatively less sunlight through appropriate optimizations. These optimizations can be achieved through panel placement, composition, and the use of technology to maximize energy production (Muneer et al., 2015). The orientation and tilt angle of solar panels are critical factors for optimization. In the northern hemisphere, panels should ideally face true south, while in the southern hemisphere, they should face true north. Additionally, sun

tracking technology can ensure that panels continuously face the sun, further enhancing energy capture (Chandel et al., 2014; Onuh et al., 2024). The optimal tilt angle depends on the latitude of the location; for instance, a latitude of 30 degrees corresponds to an optimal tilt angle of 30 degrees. A steeper tilt angle can improve performance in areas with lower sunlight (Muneer et al., 2015). Regular cleaning and maintenance to remove dust, debris, and bird droppings can also significantly increase solar panel efficiency. Using high-efficiency panels, such as thin-film and concentrated photovoltaics (CPV), can further boost performance in low sunlight areas (Bahaidarah et al., 2013).

Innovations in solar technology have demonstrated that solar energy has the highest potential to replace other major energy sources. It is clean, sustainable, renewable, and freely available. The increased efficiency, versatility, and cost-effectiveness of these technologies make solar energy production more viable and accessible for a wide range of applications, from residential to large-scale commercial use (Green et al., 2019). Ongoing advancements will continue to improve the efficiency and affordability of solar energy, aiding in the fight against climate change and promoting a more sustainable future (Bahaidarah et al., 2013; Chandel et al., 2014).

Table 4 Overview of Solar Energy: Production, Applications, Innovations, and Future Prospects

Aspect	Details	Advantages	Challenges	References
Global Commitment	Paris Agreement (2016) and yearly COP conferences demonstrate global commitment to reducing carbon footprints.	Transition to sustainable, green energy; global collaboration.	Transition from fossil fuels requires substantial investment.	Maka, 2022; Johnson & Wang, 2020
Solar Energy Characteristics	Solar power is renewable, clean, and abundantly available.	Environmentally friendly, significant energy supply, supports sustainable development.	Efficiency improvements and optimizations needed.	Maka, 2022; Lee & Kim, 2021
Solar Power Technologies	Both concentrated solar power (CSP) and solar photovoltaics (PV) technologies are continuously being developed.	Large installed capacity supports energy sector and employment.	Initial installation costs and weather dependency.	Maka, 2022; Johnson & Wang, 2020
Innovations in Solar Panels	Thin-film solar cells and concentrated photovoltaics (CPV) have increased efficiency rates.	Thin-film solar cells (up to 22% efficiency), CPV systems (up to 40% efficiency).	Cost and material optimization challenges.	Hack et al., 2016; Bahaidarah et al., 2013
Panel Shape and Size	Modern solar panels come in various shapes and sizes, including flexible and transparent panels.	Aesthetically pleasing, versatile applications in buildings and infrastructure.	Structural and architectural integration.	Chirwa, 2023
Tracking Systems	Sun tracking technology maximizes energy production by allowing panels to follow the sun.	Increases energy capture and overall efficiency.	Increased complexity and maintenance requirements.	Chirwa, 2023
Energy Storage Innovations	Innovations in energy storage, such as lithium-ion, lithium-sulfate, solid-state, and graphene batteries.	Efficient, durable, cost-effective; potential to store more energy and increase efficiency.	Development and cost of new storage technologies.	Smith et al., 2020; Johnson & Wang, 2019
Optimization for Weather Conditions	Optimizing panel placement, orientation, and tilt angle to maximize	Effective in regions with less sunlight, increased overall efficiency.	Requires regular maintenance and adjustments.	Muneer et al., 2015; Chandel et al., 2014

	energy production in various conditions.			
Future Prospects	Bright and promising future due to increasing demand for renewable energy and decreasing cost of solar technology.	Sustainable, renewable, freely available; potential to replace major energy sources.	Ensuring widespread adoption and reducing costs further.	Brown & Rossi, 2018; Green et al., 2019

Table 4 provides a detailed summary of solar energy, highlighting its production, applications, advantages, challenges, and recent innovations. Solar energy is a pivotal component of the global transition towards renewable and sustainable energy sources. This table encapsulates key aspects of solar energy, including the global commitment to reducing carbon footprints, the technologies used in solar power generation, advancements in solar panels and energy storage solutions, and the optimization strategies for different weather conditions. Additionally, it outlines the future prospects and innovations that make solar energy an increasingly viable and accessible alternative to traditional energy sources.

2.4. Hydrogen Energy

Hydrogen fuel cells are considered a cleaner and greener option compared to conventional energy sources. These fuel cells use hydrogen in an electrochemical process that combines hydrogen with oxygen to produce electrical energy, with water as the only byproduct. As a result, they do not emit harmful greenhouse gases (Fan et al., 2021). Green hydrogen, produced using renewable energy sources such as wind or solar, is expensive and currently less viable. However, even when produced with the help of fossil fuels, hydrogen remains a cleaner and more sustainable form of energy compared to other non-renewable sources (Fan et al., 2021).

2.4.1. Hydrogen Power Applications

Hydrogen fuel cells have a variety of uses, from powering vehicles to energy storage. They are particularly valuable in transportation due to their high energy density, which makes them more viable than gasoline and battery-powered vehicles (Wang et al., 2022). Hydrogen is the most abundant element in the universe and can be extracted from air, water, natural gas, or biomass. One major advantage of hydrogen energy is its potential to significantly reduce greenhouse gas emissions (International Energy Agency, 2021).

Hydrogen fuel cells can provide backup power for homes, industries, and businesses. They are cleaner and quieter than diesel-powered generators and can be used as off-grid power sources in remote locations not connected to the electrical grid. This includes remote communication towers, oil and gas drilling operations, and remote mining sites. Due to their lightweight and high-energy-density properties, hydrogen fuel cells are also suitable for aerospace applications, including fueling space probes, satellites, and aircraft. They can even be used for portable power needs in activities such as camping and hiking (US Energy Information Administration, 2023).

2.4.2. Hydrogen Fuel Cells for Transportation

The primary use of hydrogen fuel cells is to provide a cleaner and more efficient alternative to internal combustion engines (ICEs) in vehicles. Fuel cells convert the chemical energy of hydrogen and oxygen into electrical energy, with water being the only byproduct, making them more efficient and cleaner than fossil fuel-powered ICEs. Hydrogen fuel cells can be up to three times more efficient than gasoline engines, allowing vehicles to travel further on the same amount of fuel (Stanford et al., 2012).

Due to hydrogen's high energy density, hydrogen fuel cells can store a large amount of energy in a relatively small space, resulting in a longer driving range than battery-powered electric vehicles. Additionally, hydrogen fuel cells can be quickly refueled, similar to gasoline vehicles, making them practical for long-distance travel and reducing range anxiety for drivers (Wang et al., 2022).

The main challenges facing hydrogen fuel cells include the lack of infrastructure and the high cost of hydrogen production. However, as technology progresses and adoption increases, the scale of production and development of infrastructure will reduce costs, making hydrogen fuel cells a more attractive option. Furthermore, advancements in renewable energy production will lower the cost of green hydrogen, enhancing its viability (International Energy Agency, 2021).

Hydrogen fuel cells offer several advantages over conventional gasoline engines and battery-powered electric vehicles, including efficiency, high-energy density, and lower environmental impact. As the technology improves and costs decrease, hydrogen fuel cells are expected to play a crucial role in powering various sectors and driving the transition to a more sustainable future (Stanford et al., 2012).

Table 5 Comprehensive Overview of Hydrogen Energy

Aspect	Details	Advantages	Challenges	References
Hydrogen Production	Produced using renewable energy sources (green hydrogen) or fossil fuels.	Cleaner and greener energy source, no harmful greenhouse gases when used.	High production costs, particularly for green hydrogen.	Fan et al., 2021
Electrochemical Process	Combines hydrogen with oxygen to produce electrical energy, with water as the only byproduct.	Environmentally friendly, no greenhouse gas emissions.	Efficiency improvements needed for broader viability.	Fan et al., 2021
Hydrogen Power Applications	Used in powering vehicles, energy storage, backup power for homes and industries, and off-grid sources.	High energy density, versatile applications, potential to reduce greenhouse gas emissions.	Lack of infrastructure, initial investment costs.	Wang et al., 2022; International Energy Agency, 2021
Transportation Applications	Provides a cleaner, more efficient alternative to internal combustion engines (ICEs).	Up to three times more efficient than gasoline engines, quick refueling, longer driving range.	Infrastructure development and cost of hydrogen production.	Stanford et al., 2012; Wang et al., 2022
Aerospace and Portable Power	Suitable for aerospace applications and portable power needs like camping and hiking.	Lightweight, high-energy density, clean and quiet operation.	Technical and cost barriers.	US Energy Information Administration, 2023
Environmental Impact	Significantly reduces greenhouse gas emissions.	Cleaner and quieter than diesel generators, supports sustainability goals.	Production cost and infrastructure requirements.	International Energy Agency, 2021
Future Prospects	Expected to play a crucial role in various sectors as technology improves and costs decrease.	Transition to a sustainable future, widespread adoption in multiple industries.	Technological advancements and scaling up production.	Stanford et al., 2012

Table 5 provides a comprehensive overview of hydrogen energy, focusing on its production processes, applications, advantages, and challenges. Hydrogen fuel cells are emerging as a cleaner and more sustainable alternative to conventional energy sources, particularly in the transportation sector. This table summarizes key aspects of hydrogen energy, including its environmental benefits, diverse applications, and the technological advancements that are driving its adoption.

2.5. Carbon and Methane Capture, Storage, and Sequestration (CCS)

The world is already reeling from the effects of climate change, evidenced by severe weather conditions, droughts, and ocean acidification. To mitigate these impacts, it is crucial to reduce the concentration of greenhouse gases (GHGs) like carbon and methane in the atmosphere. Carbon and methane capturing processes play a significant role in this effort.

Carbon capture technologies can be divided into three categories: pre-combustion capture, post-combustion capture, and oxy-fuel combustion (International Energy Agency, 2021).

2.5.1. Carbon Capture Technologies

Pre-combustion technologies capture carbon dioxide before combustion by converting fossil fuel into a mixture of hydrogen and carbon dioxide. The hydrogen is then used as fuel, while the carbon dioxide is captured and stored. Post-combustion technologies capture carbon dioxide directly from the exhaust gas released by the combustion of fossil fuels. This method, commonly used in existing power plants, involves using filters to capture carbon from exhaust gases. The main drawback of post-combustion capture is the significant energy required for the separation process, increasing costs (Global CCS Institute, 2022).

Oxy-fuel technology, the most efficient of the three, involves burning fossil fuels in pure oxygen instead of air, producing water vapor and carbon dioxide. The vapor is separated by condensation, and the pure carbon dioxide is captured and stored. Although efficient, this technology is still experimental and not widely used (Global CCS Institute, 2022).

Sustainable processes such as Bioenergy with Carbon Capture and Storage (BECCS) and Direct Air Capture (DAC) are also being developed. BECCS uses biomass to generate electricity, offsetting carbon emissions. DAC captures carbon directly from the air using filters and solvents. Another sustainable technology is carbon mineralization, which uses minerals like magnesium and calcium to react with carbon dioxide, forming stable carbonates. This process occurs naturally but is being accelerated by scientists (Global CCS Institute, 2022).

2.5.2. Methane Capture Technologies

The main sources of methane (CH₄) emissions are landfills, agricultural processes, and natural gas production. Methane capture technologies can be classified into two categories: biological and chemical. In biological technologies, microbes are used in landfills with high organic waste content to break down methane into carbon dioxide and water or convert it into biogas, which can be used as fuel. The carbon dioxide produced in this process can also be stored and used in various combustion processes. The broken-down organic matter resulting from this method is environmentally friendly and decomposes easily. Electrosynthesis is also employed to convert carbon dioxide and methane into various liquid fuels or chemicals (United States Environmental Protection Agency, 2023).

2.5.3. Landfill Gas (LFG) Treatment Process

The process of treating landfill gas (LFG) involves three stages. Primary treatment removes moisture as the gas passes through a knockout pot, filter, and blower. Secondary treatment involves using an aftercooler or additional moisture removal as necessary, followed by siloxane/sulfur removal and compression as needed. After removing impurities in the secondary treatment stage, the LFG can be used to generate electricity or as a medium-Btu fuel for arts and crafts or boilers. Advanced treatment removes additional impurities (CO₂, N₂, O₂, and VOCs) and compresses the LFG into a high-Btu gas that can be used for vehicle fuel or injected into a gas pipeline. Waste/tail gas is sent to a flare or thermal oxidizer (United States Environmental Protection Agency, 2023).

Chemical or physical methane capture technologies capture methane and convert it into a more stable and less reactive form for storage. Adsorption is used to capture methane using solid materials, such as zeolite clay, which has been found to significantly reduce the cost of the methane capturing process (MIT News, 2021). Membrane separation separates methane from other gases based on differences in molecular size. Cryogenic separation freezes the gas mixture to a temperature where methane condenses into a liquid and is separated from the mixture (MIT News, 2021).

Table 6 Overview of Carbon and Methane Capture, Storage, and Sequestration (CCS) Technologies

Aspect	Details	Advantages	Challenges	References
Carbon Capture Technologies	Involves pre-combustion, post-combustion, and oxy-fuel combustion methods to capture CO ₂ .	Reduces CO ₂ emissions, supports climate change mitigation efforts.	High energy requirements and costs, especially in post-combustion capture.	International Energy Agency, 2021; Global CCS Institute, 2022

Pre-Combustion Capture	Captures CO ₂ before combustion by converting fossil fuel into hydrogen and CO ₂ .	Enables hydrogen use as fuel, efficient CO ₂ capture.	Initial high costs, requires advanced infrastructure.	Global CCS Institute, 2022
Post-Combustion Capture	Captures CO ₂ directly from exhaust gases using filters.	Can be retrofitted to existing power plants.	Significant energy required for CO ₂ separation, increasing operational costs.	Global CCS Institute, 2022
Oxy-Fuel Combustion	Burns fossil fuels in pure oxygen, producing water vapor and CO ₂ .	High efficiency, pure CO ₂ capture.	Experimental stage, not widely used.	Global CCS Institute, 2022
Sustainable Carbon Capture Methods	Includes BECCS, DAC, and carbon mineralization.	Offsets carbon emissions, captures CO ₂ from the air, accelerates natural processes.	High initial investment, technological development required.	Global CCS Institute, 2022
Methane Capture Technologies	Includes biological and chemical methods to capture and convert methane.	Reduces CH ₄ emissions, produces biogas and useful byproducts.	Technological complexity, cost of implementation.	United States Environmental Protection Agency, 2023; MIT News, 2021
Biological Methane Capture	Uses microbes in landfills to break down methane into CO ₂ and water or convert it into biogas.	Environmentally friendly, decomposes organic matter, produces biogas.	Requires high organic waste content, management of microbes.	United States Environmental Protection Agency, 2023
Chemical Methane Capture	Uses adsorption, membrane separation, and cryogenic separation to capture methane.	Efficient methane capture, reduces cost using materials like zeolite clay.	Requires advanced technology and infrastructure, cost of development.	MIT News, 2021
Landfill Gas (LFG) Treatment Process	Involves primary, secondary, and advanced treatment stages to purify landfill gas.	Converts LFG into usable energy forms, reduces landfill emissions.	Complexity of treatment process, costs of advanced treatment and compression.	United States Environmental Protection Agency, 2023

Table 6 provides a comprehensive overview of Carbon and Methane Capture, Storage, and Sequestration (CCS) technologies. These technologies are essential for mitigating the impacts of climate change by reducing the concentration of greenhouse gases, such as carbon dioxide (CO₂) and methane (CH₄), in the atmosphere. The table summarizes various methods of capturing these gases, their applications, advantages, and challenges, highlighting the significant role these technologies play in addressing global environmental concerns.

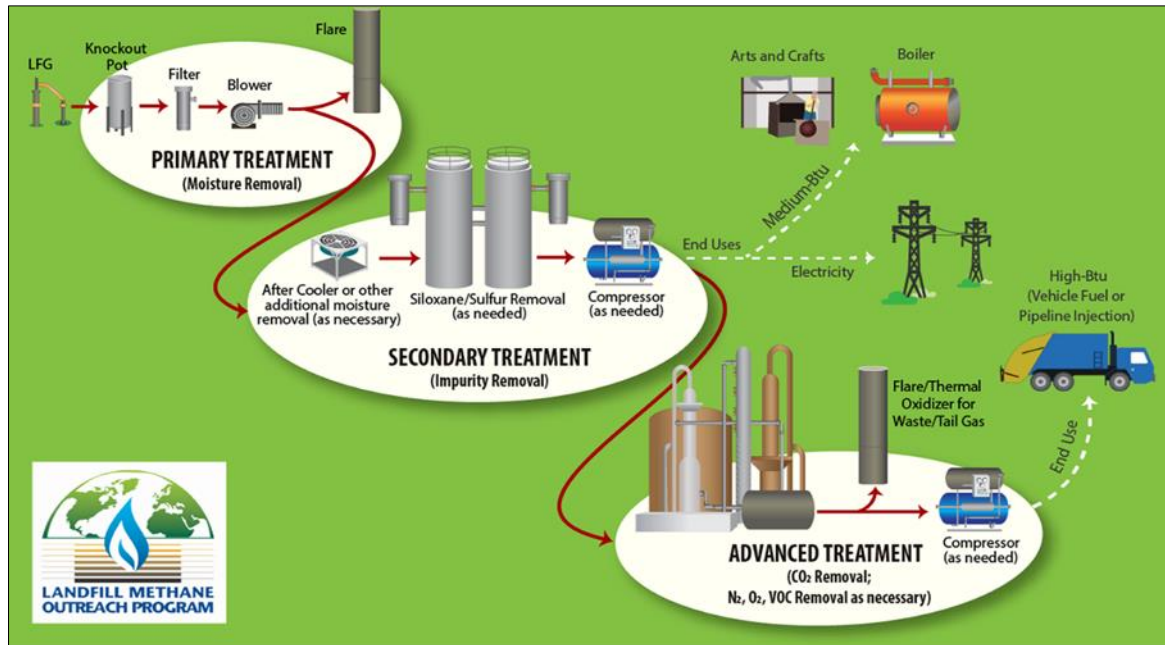


Figure 11 Land fill Gas treatment. (United States Environmental Protection Agency, 2023)

Figure 11 illustrates the comprehensive process of treating landfill gas (LFG) through a series of stages: primary treatment, secondary treatment, and advanced treatment. The primary treatment stage involves moisture removal, using components such as a knockout pot, filter, and blower. The secondary treatment focuses on impurity removal, including siloxane and sulfur removal, with compressors as needed. This treated gas can then be used for various end uses, such as electricity generation and medium-Btu fuel for arts and crafts or boilers. The advanced treatment stage further removes carbon dioxide, nitrogen, oxygen, and volatile organic compounds (VOCs), producing high-Btu gas suitable for vehicle fuel or pipeline injection. This diagram highlights the Landfill Methane Outreach Program's efforts to capture and utilize landfill gas effectively, thereby reducing greenhouse gas emissions and providing a sustainable energy source.

3. The intersection of renewable energy and sustainable development

In today's world, the quest for sustainable development is driven by the imperative to safeguard our planet and ensure a better future for generations to come. Renewable energy sources play a transformative role in achieving sustainable development by addressing the pressing challenges of climate change and environmental degradation. Integrating renewable energy into our energy systems is critical for advancing sustainable development goals (SDGs) as envisioned by the United Nations (UN, 2023).

3.1. Renewable Energy and Climate Change Mitigation

Renewable energy sources such as wind, solar, and hydropower are crucial for mitigating climate change and fostering sustainable development. Solar power, for instance, harnesses energy from the sun without emitting greenhouse gases or depleting finite resources. Its scalability and versatility make it adaptable to diverse environments and energy needs (Global Wind Energy Council, 2021). Similarly, wind energy generates electricity without the emissions associated with fossil fuels, providing a clean and abundant energy source that also creates job opportunities in local communities (Global Wind Energy Council, 2021).

3.2. Economic and Social Dimensions of Renewable Energy

Sustainable development encompasses economic and social dimensions, with renewable energy sources significantly impacting both. Investments in renewable infrastructure stimulate economic growth, create jobs, drive innovation, and support local economies. Transitioning to renewable energy can revitalize struggling industries and support a just transition for workers in fossil fuel-dependent regions. Moreover, renewable energy democratizes energy access, offering significant social benefits, particularly in remote or underserved areas where off-grid solar installations provide clean electricity and enhance educational and economic opportunities (Renewable Energy Focus, 2022).

3.3. Enhancing Energy Security and Independence

Renewable energy sources also enhance energy security and independence. Traditional energy sources, especially fossil fuels, are subject to geopolitical tensions and price volatility. Renewable energy sources such as geothermal and hydropower, which are domestically available, provide a stable energy supply and reduce reliance on finite resources (International Energy Agency, 2021).

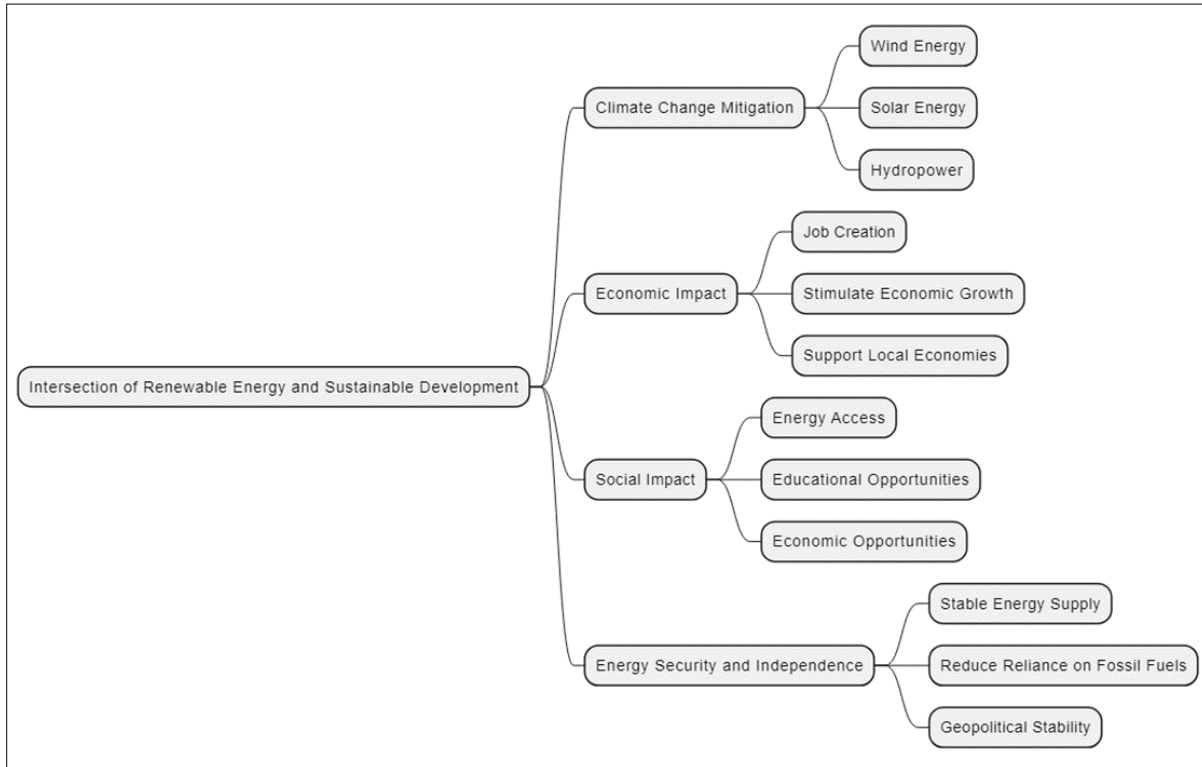


Figure 12 The Intersection of Renewable Energy and Sustainable Development

Figure 12 illustrates the intersection of renewable energy and sustainable development. It highlights the critical role renewable energy sources play in mitigating climate change, fostering economic growth, enhancing social impact, and ensuring energy security and independence. Key aspects such as wind, solar, and hydropower are shown to contribute to climate change mitigation, while the economic benefits include job creation and stimulating local economies. The social impact encompasses improved energy access and educational opportunities, and the energy security section underscores the stability and geopolitical benefits of reducing reliance on fossil fuels. This diagram provides a comprehensive overview of how renewable energy advances sustainable development goals.

Recommendations

To accelerate the global transition to renewable energy and achieve sustainable development goals, several key actions are recommended. First, there should be a significant investment in research and development to enhance the efficiency and cost-effectiveness of renewable energy technologies such as wind, solar, geothermal, and hydrogen. This includes promoting the development of advanced materials, smart technologies, and innovative designs to improve the performance and durability of renewable energy systems.

Policy support must be strengthened by implementing incentives for the adoption of renewable energy, such as subsidies, tax credits, and grants. Regulatory frameworks should be established to facilitate the integration of renewable energy into national grids and support the development of necessary infrastructure. Enhancing energy storage solutions is crucial to addressing the intermittent nature of renewable energy sources. Investments should focus on developing advanced energy storage technologies, promoting the use of batteries, supercapacitors, and other storage solutions to ensure a stable and reliable energy supply.

International collaboration and knowledge sharing are essential to accelerate the global transition to renewable energy. Joint initiatives and projects leveraging the strengths and resources of multiple countries can significantly advance

renewable energy technologies. Public awareness and education campaigns should be launched to highlight the benefits of renewable energy and the importance of sustainable development. Renewable energy education should be integrated into school curricula, and training programs should be provided for professionals in the energy sector.

Supporting local economic development through renewable energy projects is vital. Such projects can create jobs and stimulate economic growth in local communities. Small and medium-sized enterprises (SMEs) involved in the renewable energy sector should receive financial incentives and technical assistance. To overcome market and information barriers, mechanisms should be developed to address market failures and provide accurate information on the costs, benefits, and feasibility of renewable energy technologies. Platforms for sharing best practices and case studies should be created to guide the adoption of renewable energy solutions.

Access to financing for renewable energy projects, particularly in developing countries, must be increased through international funds, private investments, and public-private partnerships. Innovative financial instruments such as green bonds and climate funds can mobilize resources for renewable energy investments. Encouraging sustainable practices in the design, construction, and operation of renewable energy projects is essential. The use of life cycle assessments should be promoted to minimize the environmental impact of renewable energy technologies.

Finally, establishing monitoring and evaluation frameworks to track the progress of renewable energy initiatives and assess their impact on sustainable development is necessary. Data and analytics should be used to inform policy decisions and adjust strategies as needed to achieve desired outcomes.

4. Conclusion

Renewable energy is fundamental to achieving the Sustainable Development Goals (SDGs), particularly SDG-7, which aims for universal access to affordable, reliable, sustainable, and modern energy. This paper underscores the transformative impact of renewable energy sources such as solar, wind, geothermal, and hydrogen in addressing climate change, enhancing energy security, and promoting economic and social development.

Renewable energy sources are pivotal in reducing greenhouse gas emissions and mitigating climate change. Advancements in technology and policy development are critical to overcoming challenges such as market failures and the need for essential raw materials. Investments in renewable infrastructure stimulate economic growth, create jobs, and support local economies, while also democratizing energy access and enhancing energy security by reducing reliance on finite fossil fuels.

In conclusion, the transition to renewable energy is not only essential for combating climate change but also for fostering sustainable development. Coordinated global efforts, technological innovations, and supportive policies are necessary to realize the potential of renewable energy and ensure a clean, prosperous future for all.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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