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Review

An overview of the sustainability of emerging energy technologies in mitigating climate change

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ABSTRACT

The increasing reliance on fossil fuels has led to unprecedented levels of greenhouse gas emissions, environmental degradation, and public health risks. This paper explores renewable energy technologies and carbon capture methods as essential strategies for mitigating climate change and transitioning toward a low-carbon future. This paper evaluates the carbon emissions associated with various renewable sources, including solar, wind, hydropower, geothermal, and biomass, considering their full life cycles and regional variations. The paper also examines the role of carbon capture technologies, battery storage, smart grids, decentralized systems, and blockchain innovations in enhancing energy resilience and reducing emissions. While renewable energies significantly reduce carbon output compared to traditional fuels, the analysis highlights that no energy system is without environmental consequences. Policy support, technological advancements, and coordinated infrastructure improvements are identified as critical factors for successful large-scale adoption. Through integrated approaches that combine clean energy production, carbon management, and modernized energy systems, a sustainable and equitable energy transition is achievable.

1. Introduction

Carbon dioxide (CO_2) emissions are directly linked to the use and combustion of fossil fuels. The applications of petroleum, coal, and natural gas are convenient, reliable, and widely accepted worldwide. It is undeniable that the world is reliant upon these types of energies and fuels. The most attractive feature of these energies is the ability to be generated and used irrespective of the current state of the weather and its current availability. Petroleum can be accessed by drilling rigs twenty-four hours a day, seven days a week, throughout the year, and will last for approximately thirty years or more. Despite their popularity, nonrenewable energies are directly correlated to the increase of greenhouse gas emissions, destruction of the environment, and pollution of the air and land. Burning natural gas releases methane, which is 28% more harmful to the atmosphere than CO_2 [1]. The annual National Oceanic and Atmospheric Administration (NOAA) has a Global Monitoring Lab, and it collects data in over 80 different locations offshore to test the amount of greenhouse gases present in ambient air. The report indicates that the global average atmospheric CO_2 was 426.15 parts per million (ppm) in March 2025. This is the highest ppm recorded, with a two ppm increase for 12 consecutive years. Mauna Loa Observatory in Hawaii recorded 421 ppm, which closely supported the data collected by the NOAA (Figure 1) [2]. Continuing to overconsume nonrenewable energy sources without integrating sustainable energy will continue to exhaust supply sources, and greenhouse gas emissions will increase to unsustainable amounts, further affecting climate change and pollution. Pollution alone should be evidence that the globe's overconsumption of fossil fuels should be limited. According to the World Health Organization, nearly 99 percent of the world's population breathes unhealthy air. More than 13 million people die annually from preventable environmental causes, including air pollution [3]. The combustion of fossil fuels generates fine particulate matter and nitrogen dioxide. In 2018, it was reported that air pollution from fossil fuels caused upwards of $8 billion in health and economic losses [4]. The increase in energy demand from these types of fuels has also led to energy shortages from overconsumption and increased production, accounting for the release of nearly 75% of all greenhouse gas emissions and 90% of CO_2 and causing the most significant proponent of climate change and increase of the world temperature, and extreme weather conditions [5]. Figure 2 illustrates the correlation between CO_2 emissions and temperature increases, highlighting carbon emissions as one of the most significant contributors to climate change.

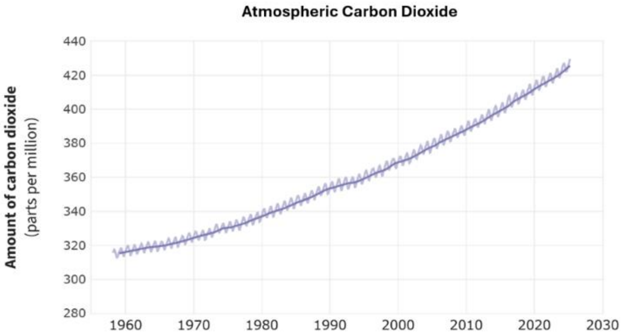

Figure 1. Results of the NOAA atmospheric CO_2 in ppm from 1960 to March 2025 [2]

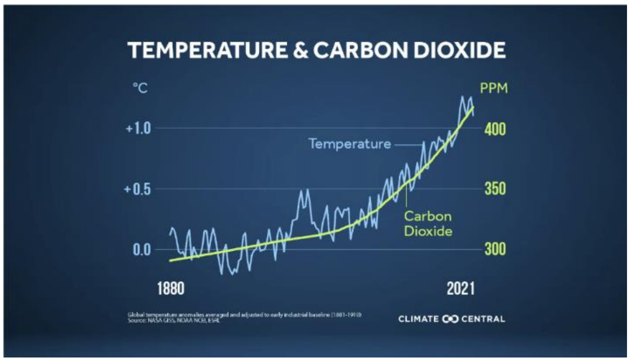

Figure 2. The correlation between CO_2 emissions and temperature increases

2. Renewable energy sources

Renewable energy sources are a cornerstone of climate change mitigation and decarbonization efforts. By 2030, renewables could provide 65% of the world's electricity supply. By 2050, they could decarbonize 90% of the electricity industry [6], significantly reducing carbon emissions and mitigating climate change. Future demands for sustainable energy are becoming increasingly popular. Their ability to generate renewable energy worldwide from 2000 to 2021 increased from 754 gigawatts to 3064 gigawatts [7], which shows substantial improvement in development.

2.1 Solar energy

Solar power is consistently among the most popular renewable energy sources and is one of the cheapest and most environmentally friendly. Solar heating methods include converting sunlight directly into usable energy using solar heating, building, and photovoltaic systems without emitting CO_2 during production. Global expansion and usage of solar power have increased significantly, with solar photovoltaic capacity reaching 843 gigawatts by 2021. This has nearly increased 21 times since 2010 [8]. Growth has been encouraged mostly due to supportive policies, technology improvements, and broad urban and industrial applications. From a climate change mitigation perspective, solar power offers significant results and advantages. Paris Agreement's 1.5°C and other organizations use solar energy as a key role in decarbonizing their global electricity sector and remaining under the target emission goals. The International Energy Agency (IEA) has projected that approximately 630 GW of solar PV capacity must be added annually by 2030 to achieve global net-zero goals by 2050. In countries like China, coal is a primary energy source, so carbon emissions are reduced through the integration of solar panel energy production. Despite how attractive zero emissions are during solar production, considering solar panel lifecycles reveals that carbon emissions are still present when considering this alternative energy. Although solar energy does not release carbon during operation, solar panels still possess carbon footprints during production, transportation, and disposal. Assessing the life cycle of photovoltaic (PV) panels shows that manufacturing includes intensive mining and energy use in fossil fuel-reliant energy production areas. For example, the lifecycle carbon footprint of large-scale PV systems in China is estimated at 60.13 g CO_2 per kilowatt-hour. The recycling stage adds another 5.81 g of CO_2 per kilowatt-hour. In comparison, European-manufactured panels emit significantly less, but still 42.3 g of CO_2 per kilowatt-hour during operation and only 1.0 g per kilowatt-hour during retirement because of cleaner energy usage. The emissions associated with Chinese panels are nearly double due to the fossil-intensive electricity used in their production (Figure 3) [9].

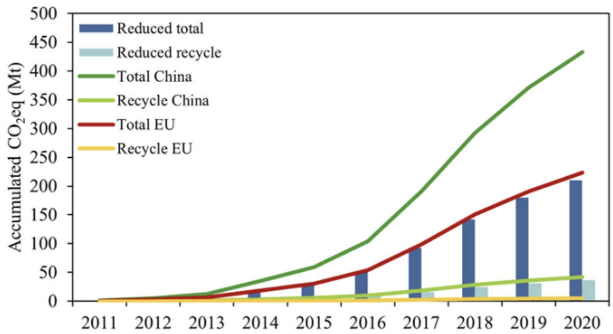

Figure 3. The national accumulated and reduced carbon emissions of the whole lifecycle and the recycling stage based on the present technology in China and advanced technology in Europe (EU), according to the accumulated PV panels installed in China during 2011–2020; Unit: million tons (Mt) [9]

Overall, the environmental impacts of solar energy vary by geography. Factors such as sunlight availability, panel efficiency, and the local energy mix during production influence the total emissions. For example, China's solar panel carbon footprint was significantly higher in the northwest during the early adoption years. Still, as installations expanded to the east, those regions became the leading carbon contributors due to increased distributed systems. Poor coordination of recycling facilities, long transportation distances, and light rejection (wasted solar power due to overgeneration) also reduce carbon efficiency [9]. The economics of solar energy have significantly improved, making it competitive with conventional power sources. Between 2010 and 2021, the global levelized cost of electricity for solar PV dropped 88%, from $0.417 to $0.048 per kilowatt hour. Increases originate from technological advancements, mass production, and decreasing hardware costs. Solar energy is often cheaper than fossil fuel-based energy, particularly when lifecycle environmental costs are considered. However, regional variations still exist. For instance, costs range from $0.041/kWh in China to $0.071/kWh in North America [8] due to differences in solar irradiance, land and labor costs, and policy support. China dominates global panel production and installation with 64%

of the crystalline silicon PV market, but it has also increased lifecycle emissions due to coal-based grids. Despite the negative impacts solar panels and their production have on the environment, they are still gaining popularity and reducing carbon emissions during energy production to assist in climate change mitigation, especially in urban areas where energy loss and cost during transmission are minimal. When heating and cooling solar panels are installed in a metropolitan area, there are even fewer environmentally associated issues since they are installed on roofs and in smaller, more maintainable quantities with minimal transmission losses [9].

2.2 Wind energy

Wind energy is one of the fastest-growing sources of renewable power worldwide, offering a sustainable alternative to fossil fuel-based electricity generation. By converting the kinetic energy of moving air into mechanical power through turbines, wind systems produce electricity without direct carbon emissions. Over recent decades, improvements in turbine technology and grid integration have significantly increased the efficiency and reliability of wind power. While wind energy contributes substantially to reducing greenhouse gas emissions, it is important to recognize that its full life cycle, from manufacturing and transportation to installation, maintenance, and disposal, does involve some carbon footprint. Understanding these environmental impacts is crucial for evaluating wind energy's true role in the transition to a low-carbon future. In Denmark, one of the global leaders in wind power adoption, wind energy accounted for 47% of gross electricity consumption as of 2019. This makes Denmark particularly insightful when considering the effects of wind energy on climate change mitigation. Analysis estimated that for every one megawatt-hour of wind energy produced, about 0.16 tons of CO_2 emissions are avoided [10]. Since this was a dynamic econometric study versus an engineering-based study, the marginal emission avoided (MEA) is lower. However, it reflects a more realistic relationship between wind energy and emissions in fundamental energy markets. It includes additional variables like electricity prices and emissions from biomass, reduces MEA to account for the equilibrium effect, and highlights that substitutions of wind for fossil fuel energy are not one-to-one due to changes in demand and pricing. This study also found that, beyond emission reduction, wind energy is measured by demand variables.

Another study located in Texas evaluates the emissions during lifetime cycles and takes into consideration different variables [11]. Carbon emissions associated with wind turbines primarily arise from processes such as raw material extraction, manufacturing, transportation, installation, maintenance, and decommissioning. The total amount of carbon emitted over a turbine's lifetime depends on factors like turbine size, manufacturing location, operational location, and lifespan. The detailed life cycle assessment study of a 1.3 MW Nordex N-60 wind turbine operating in the Panhandle of Texas found that over a 20-year operational lifespan, the turbine generated 467 TJ of electricity while producing approximately 1,870.52 metric tons (Mg) of CO_2. These result in a carbon emission intensity of about 14.45 gCO_2 per kilowatt-hour (kWh) of electricity generated. Manufacturing processes alone accounted for around 41% of the total emissions, while raw material extraction contributed approximately 38%, transportation 16%, construction 4%, and overhead operations about 1% [11]. The largest key factors were turbine size, manufacturing location, and operational lifetime. Wind energy is also notably resilient to the effects of climate change, allowing it to be a viable investment as the climate changes in the future. Climate models project only modest changes in wind power output even under severe global warming scenarios. For example, while temperature increases may slightly affect air density and turbine efficiency, the overall production remains largely stable, particularly in regions like Europe and North America. Costs associated with wind energy have been significantly reduced throughout the advancement of technology. Between 2010 and 2021, the global levelized cost of electricity for onshore wind fell by 68% from $0.089 to $0.028 per kilowatt hour [8]. This shows that wind energy is one of the cheapest sources available in recent years, especially in areas with high wind energy resources, with additional costs related to variability, storage, and backup generation. Flexible grid infrastructure is critical as demand for wind energy rises. Studies suggest that as wind energy availability increases, the demand for more energy overall could increase due to the low cost and further offset emission reductions [11]. Ultimately, although wind turbines have associated carbon emissions throughout their lifecycle, their emission intensity remains substantially lower, around 98% lower [10] than coal-based electricity generation. Understanding and minimizing the embedded carbon footprint becomes crucial for achieving low-carbon power generation as wind energy expands. Wind energy also offers a cheap and effective way to reduce global carbon emissions.

2.3 Hydroelectric power

Hydroelectric energy is among the largest and most advanced renewable energy sources globally. Hydropower has long been regarded as a clean and renewable source of electricity, contributing substantially to global efforts to mitigate climate change. However, recent research suggests that hydropower's carbon footprint may be far larger than previously assumed. Unlike fossil fuel plants, most emissions from hydroelectric reservoirs arise not from combustion, but from the biological decomposition of organic material submerged during the flooding of reservoirs [8, 12]. Global assessments of nearly 1,500 hydroelectric facilities found that the average carbon footprint of hydropower is about 273 kg of CO_2 eq per megawatt hour (MWh) of electricity produced. This footprint comprises 173 kg of CO_2 emissions and 2.95 kg of methane per MWh, based on the 100-year global warming potential [12]. Although these values are still lower than those associated with fossil fuel generation without carbon capture and storage, they are significantly higher than those for most other renewable energy sources. Several factors are key in determining how much carbon a hydropower project emits. Facilities that flood large land areas to produce relatively modest amounts of electricity tend to have the highest emissions, mainly because more submerged organic material decays over time. Geography also determines several variables, including locations that are tropical reservoirs, typically emitting more methane, as warm temperatures speed up decomposition. The age of a reservoir influences emissions as well; methane release often decreases over time, although CO_2 trends can vary. Additionally, new organic material carried into the reservoir by rivers continues to fuel greenhouse gas emissions over its lifetime. There is a wide variation between different projects. Some hydropower plants approach emission levels comparable to fossil fuel plants, primarily if they are located in vulnerable tropical environments or have large, flooded areas. On the positive side, certain reservoirs in the United States, India, and West

Africa show strong potential for capturing methane emissions and using the gas as a supplementary energy source. Hydropower remains one of the most cost-effective energy sources during operational lifecycles because of low operating and maintenance costs after initial investments in construction. However, these upfront capital costs during construction are significant, and the levelized costs of electricity increased from $0.039 in 2010 to $0.048 per kilowatt hour in 2021. This reflects a 24% increase in price within 11 years [8]. Future uncertainty and long-term investments influence the planning and operation of current and future hydroelectric facilities. A study of the Xiangjiaba hydropower plant in China reveals that climate change conditions could reduce average annual energy output by 30.7 TWh [13]. Additional variables compound the challenges of water reliance during droughts, extreme heat, and even floods, which are conditions fueled by climate change.

2.4 Geothermal energy

Geothermal energy is often seen as a clean and reliable source of renewable power because it does not rely on burning fuels. However, the amount of carbon emissions associated with geothermal energy can vary quite a bit depending on where and how it is used. Umar et al. [14] looked at the top seven geothermal energy-consuming countries and found that geothermal energy's impact on carbon emissions varies significantly. In countries like Italy, Mexico, and New Zealand, geothermal energy has reduced carbon emissions across various conditions. This shows that geothermal energy can be important for reducing a country's overall carbon footprint if monitored and maintained correctly. On the other hand, geothermal energy was linked to increased carbon emissions in places like India, the United States, Turkey, and the Philippines. In these cases, geothermal systems may have unintentionally added to climate change rather than mitigating it. One crucial factor to consider is the gases found within individual geothermal reservoirs. Some underground reservoirs naturally contain gases like CO_2, which are released when the geothermal heat is brought to the surface. Technology used at geothermal plants is another key factor. Older plants, or those without systems to capture and manage gases, can release more emissions than newer, advanced facilities. It also depends on the type of energy the geothermal power is being utilized for. The environmental benefits are considerable if geothermal energy replaces coal or oil-fired electricity, but not as beneficial as another type of energy if it is an alternative source. The study also found that geothermal energy consistently affects carbon emissions trends across all the countries studied. This shows that geothermal energy plays an ongoing and essential role in shaping a country's overall emissions profile. Even though geothermal energy generally emits far less carbon than fossil fuels, it is not completely emissions-free. To maximize its potential, countries must carefully manage where geothermal projects are built, invest in cleaner technologies, and update older infrastructure. With good planning, geothermal energy can continue to be an essential part of the shift to a low-carbon future. Implementation costs of geothermal locations are high due to expensive drilling to 4 to 6 kilometers below the Earth's crust and exploration for geothermal reservoirs. Lack of exploration and reservoir assessment tools also increases costs and operational risk, often leaving projects unsuccessful. For example, projects such as Australia's Cooper Basin enhanced geothermal systems plant were discontinued because of poor reservoir permeability and fluid circulation issues [15]. Technical difficulties and limitations combined with a lack of policy support often make geothermal projects less attractive and deter investors from more developed and widely accepted renewable energy sources like solar and wind. Today, as many as 32 countries use this to generate electricity, heating, and cooling in residential and commercial applications reliably and affordably. In 2023, the capacity to generate electricity using geothermal applications reached 16,318 MW. However, this was only about .34% of all electricity produced worldwide. The initial setup and equipment can be costly despite the low operational cost. It becomes even less attractive to purchase and utilize this type of energy since it lacks government support policies and subsidies compared to wind and solar power. Geothermal energy has favorable levelized energy costs, even though growth has been slower than other renewable energy sources [8]. Long-term cost attractiveness is seen once geothermal plants are installed and operating at capacity factors of 70% to 90%, which exceeds intermittent sources and improves the long-term cost-benefit balance.

2.5 Biomass and biofuels

Biomass is an organic material harvested from recently living or living organisms. This includes agricultural residues, forestry byproducts, and urban waste. Feedstock can be various forms of bioenergy, such as bioethanol, biodiesel, biogas, and electricity, that are converted from various processes (Figure 4). Combustion, gasification, pyrolysis, and anaerobic digestion are all types of conversion methods from materials that would be considered waste. Because the waste is used, it contributes to the circular lifecycle of CO_2, making it a renewable alternative to fossil fuels [8].

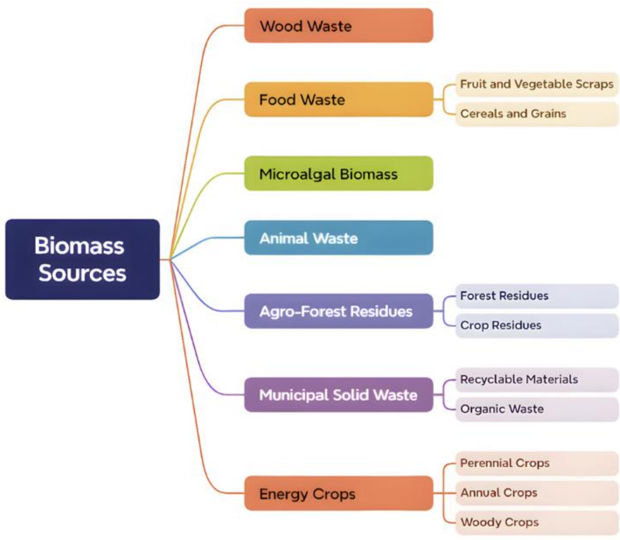

Figure 4. Common biomass sources [16]

Biomass is a significant contributing factor to mitigating climate change because the CO_2 produced during the combustion processes is absorbed and consumed by biomass during its growth cycle. This is considered a carbon-neutral process because of the consumption of the produced carbon. This carbon lifecycle is extremely short compared to the lifecycle of fossil fuel carbon, which is stored for millions of years and does not get consumed when released into the atmosphere. Because of its carbon lifecycle span, bioenergy could significantly decarbonize the globe, which is essential for reducing the global temperature by 1.5 degrees Celsius by

2050 [8]. Biomass could also solve other sustainability goals, such as promoting rural energy independence and reducing landfill waste. The environmental sustainability of biomass depends on the feedstock sourcing and production practices. If not correctly maintained, biomass cultivation and conversion would generate air pollution and additional greenhouse gas emissions. Particulate matter and nitrogen oxides will increase during combustion processes if they are not monitored or practiced correctly. Additionally, as demand for biofuel grows, so does the demand for land use. Increased land use demands may lead to deforestation, loss of biodiversity, and increased greenhouse gas emissions from harvesting methods. Other concerns are soil integrity due to over-harvesting crops, water depletion from irrigation, and runoff from fertilizers, which could contribute to eutrophication in nearby water sources and collections [15]. Climate change itself also threatens biomass's long-term effectiveness. Reference [8] highlights that rainfall pattern irregularities, increases in temperatures, and increased risk of droughts can adversely affect biomass and the processes associated with growth, harvesting, and conversion. Changes like these could alter the biochemical properties of feedstocks and disrupt lignocellulosic biorefineries by reducing biomass yields. A 1-degree Celsius increase in global temperatures indicates that maize yields decrease by 7.4% and wheat yields by 6%.

From an economic perspective, the cost of bioenergy has decreased, allowing it to be a competitive alternative to fossil fuels. Global levelized cost of electricity for bioenergy dropped from $0.078 per kilowatt hour in 2010 to $0.067 in 2021. Regional costs show that bioenergy is not consistent, though. Costs range from $0.057 in India to $0.097 in North America. Factors contributing to these cost variations include feedstock type and availability, conversion technology, transportation methods, and cost. For example, transportation in Switzerland for biomass can cost from 24 to 340 francs per ton for different biomass types and transportation methods. Unloading costs during this analysis accounted for approximately 65% of the total transportation costs. Harvesting equipment costs also have significant variances based on type, affecting the overall cost of considering biomass as a viable energy source. Studies from Kenya and Tanzania demonstrate that biomass used for cooking in improved biomass cookstoves lowers the life cycle costs per meal. Through this study, biomass proves to be an excellent choice for areas that are not as developed and reduces the cost of meals that need to be cooked or heated. However, government policies in such areas tend to put royalties or fees on resources like charcoal, which drives up costs and makes biofuel less attractive as a cheap alternative energy source. The lack of policies favoring biomass and biofuels hinders the rapid growth and desire to incorporate infrastructure supporting this fuel type. Biomass energy has promising potential to help support global climate change mitigation through carbon-balanced energy production. Considering environmental risks, ensuring sustainable land use, and addressing cost challenges in certain regions are key to the long-term success of implementing biomass and biofuels into everyday life. Through policy support and technology advancements, infrastructure upgrades could become more attainable and allow biomass to become a key component in lessening the effects of traditional fossil fuel emissions [16]. Table 1 presents the carbon dioxide emissions or emission trends for solar, wind, hydropower, and geothermal energy sources based on case studies in various regions. Values are reported either as specific emission intensities (gCO_2/kWh or $kgCO_2e$/MWh) or described qualitatively where numerical data was unavailable.

Table 1. Summary of Carbon Emissions Associated with Different Renewable Energy Sources Across Selected Countries

Type of Energy	Date and source	Country	Emissions	Notes
Fossil Fuel	March 2025 [2]	Worldwide	426.15 ppm of ambient air	
Solar	2024 [9]	China	5.81 g CO_2 eq/kWh (production) + 5.81 g CO_2eq/kWh (recycling)	3064 gigawatts 2021 worldwide [8] Higher due to coal-reliant grid manufacturing
Solar	2024 [9]	Europe	42.3 g CO_2 eq/kWh (production) + 1.0 g CO2eq/kWh (recycling)	lower emissions than China due to cleaner energy manufacturing and transportation
Wind	2019 [10]	Denmark	Avoids 0.16 tons CO_2/MWh	Marginal emission avoided (MEA) accounting for the market effects
Wind	2020 [11]	Texas, USA	14.45 gCO_2/kWh	1.3 MW Nordex N-60 turbine, 20-year lifespan
Hydropower	2016 [12]	Global Average	273 $kgCO_2e$/MWh	Based on 1,473 hydroelectric plants, includes CO_2 and methane
Geothermal	2024 [14]	India, USA, Turkey, Philippines	Reduces emissions	No specific grams/kWh given, but trend: decreases CO_2
Geothermal	2024 [14]	Italy, Mexico, New Zealand	Increases emissions	Due to geological and operational factors

Moreover, Table 2 summarizes the 2021 installed costs per kilowatt and the levelized costs of electricity per kilowatt-hour for various renewable energy technologies, along with their percentage change in LCOE from 2010 to 2021. Data highlight significant cost reductions for solar and wind technologies, while geothermal and hydropower exhibited modest increases over the same period [8]. Analysis of each type of alternative energy shows that no one kind of energy production is without environmental consequences or carbon footprint. However, they all have some competitive advantages over fossil fuels and tend to limit greenhouse gas emissions. Individually comparing each energy source to its previous years shows a decrease in cost as technology and understanding of their use advance. Popularity, as well as the capacity to support alternative energies, is increasing. Greenhouse gas emissions must be reduced with these technologies to aid climate change mitigation, but it is crucial to consider the processes in which these are harvested and harnessed.

Table 2. Installed costs and levelized costs of electricity (LCOE) for major renewable energy sources in 2021

Renewable Energy Source	Installed Cost (2021) ($/kW)	Levelized Cost of Electricity (LCOE) ($/kWh)	% Change in LCOE (2010–2021)
Solar Photovoltaics	857	0.048	−88%
Concentrated Solar Power	9091	0.114	−68%
Onshore Wind	1325	0.033	−68%
Offshore Wind	2858	0.075	−60%
Bioenergy	2353	0.067	−14%
Geothermal	3991	0.068	34%
Hydropower	2135	0.048	24%

3. Energy storage and grid integration

Grid integration is key to successfully utilizing all forms of energy produced. In addition to these challenges, most alternative energies are susceptible to environmental factors such as extreme weather and climate change. For energies produced by solar and wind, the challenge of inconsistent production occurs due to the limitations of the supply input. The grid system is designed to accommodate traditional fossil fuel-based power plants instead of renewable ones. Renewable systems are also typically located further away from the areas that need larger electricity inputs, requiring energy storage technologies like lithium-ion batteries for storage, upgraded smart grids to create a more flexible and efficient grid, and economic policy or regulation to prevent backlash from high-profit fossil fuel plants.

3.1 Battery storage and technologies

Batteries are essential for collecting and storing excess alternative energy for future use. For solar energy, battery storage can be utilized at night or on rainy days when the sun is not producing enough sunlight to keep a steady supply for consumers. For wind, it can store power for days when there is not enough wind. During floods and storms, hydroelectric power capacity increases, but capacity suffers during droughts and heat waves. Using batteries and other storage methods is a solution to extreme weather conditions and possible outages to help build grid resilience. As grid demand increases, the use and need for batteries also increase. Attractive qualities include backup power usage, black start services, and transition to decentralized systems, which are essential when considering sustainable energy integration [17].

Batteries, especially lithium-ion batteries (LIBs), are increasingly important in addressing climate change. As the world shifts toward renewable energy systems and electric transportation, the demand for LIBs has skyrocketed. Projections estimate that the global battery industry could see an annual growth rate of over 30% between 2022 and 2030, with the total market reaching more than $400 billion and a storage capacity of 4.7 terawatt-hours by the end of the decade [18]. While China will remain the dominant supplier, the fastest growth is projected in the U.S. and EU due to aggressive climate policies and supply chain localization. Meeting this demand will require the construction of up to 150 new battery plants and a shift toward more sustainable, circular production models (Figure 5) [19].

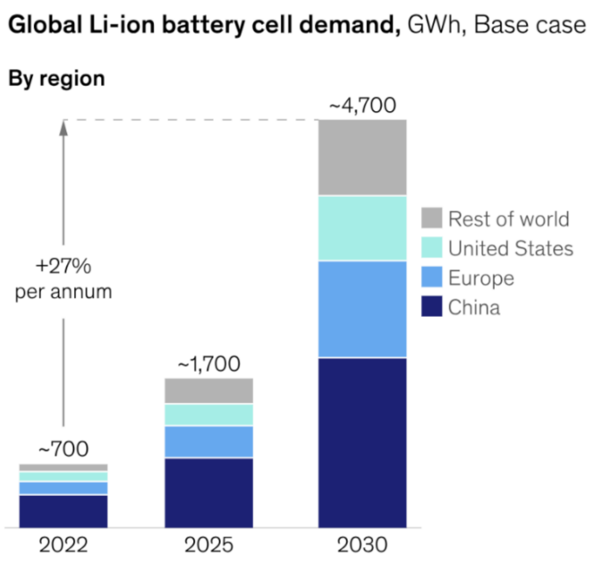

Figure 5. Projected global lithium-ion battery cell demand by region from 2022 to 2030 [19]

Batteries help mitigate climate change in a couple of significant ways. The first one is that they enable the electrification of transportation by powering electric vehicles (EVs), reducing the carbon emissions of gasoline and diesel engines, and the second one is that they serve a vital role in grid energy storage. As solar, wind, and other renewable energy sources become more common, the grid increasingly needs storage solutions to balance supply and demand. Used EV batteries are often repurposed for stationary storage applications and provide a cost-effective and sustainable way to support this transition [18]. However, the environmental impact of battery production and disposal remains a concern. Many traditional manufacturing processes rely on a linear model: extracting raw materials, building batteries, and discarding them at the end of life. This approach leads to heavy resource depletion and environmental damage. In response, the industry is moving toward a circular economy model, where the focus is on recycling critical materials such as lithium, cobalt, and nickel, reusing batteries when possible, and minimizing waste. Economically, circular strategies offer promising benefits. Recycling batteries uses far less energy compared to mining and manufacturing from raw materials, resulting in lower emissions and cost savings. Additionally, the emerging market for second-life batteries provides new economic opportunities while extending the useful life of valuable resources. Governments and regulatory bodies are also starting to support these changes. For example, the European Union's Circular Economy Action Plan (CEAP) sets clear guidelines for battery reuse, recycling targets, and lifecycle management. A recent microgrid framework [20] integrates photovoltaic panels, wind turbines, battery storage, and hydrogen-based technologies, including electrolyzers, hydrogen storage tanks, and fuel cells, into a grid-connected platform. At the core of the system is a rule-based energy management strategy enhanced by the Chimp Optimization Algorithm, which coordinates energy flow based on real-time grid pricing, seasonal resource availability, and changing demand conditions. Simulation results show that the model achieves a cost of energy as low as $0.272 per kilowatt-hour. This particular system is more efficient than other tested optimization methods, such as the Genetic Algorithm and Grey Wolf Optimizer. The system strategically balances short-term energy needs through battery storage while using hydrogen as a longer-term solution. This allows it to absorb excess solar and wind energy when production exceeds demand and dispatch it during periods of low generation, ensuring a continuous power supply and economic efficiency. This approach supports the principles of a circular economy, particularly in how it extends the usefulness of materials and reduces environmental impact. Recycling batteries requires far less energy than mining and manufacturing from raw resources, resulting in lower emissions and cost savings. Additionally, the growing market for second-life battery applications presents new economic opportunities and helps reduce waste. Regulatory efforts such as the European Union's Circular Economy Action Plan are reinforcing this shift by establishing clearer guidelines for battery reuse, recycling, and lifecycle management. The future of batteries in climate change mitigation is projected to be even more successful when implemented. Advances in recycling technologies like hydrometallurgy and direct cathode recycling are making materials easier to recover after their lifecycle use is completed.

At the same time, efforts are being made to power battery production with renewable energy, further lowering the industry's carbon footprint. As these innovations take hold, batteries are set to become a central pillar of global efforts to achieve net-zero emissions by 2050 [17].

3.2 Grid modernization and decentralized systems

Smart Grid utilizes two-way communication between consumers and suppliers to more accurately and closely monitor electricity usage. The new and advanced electrical grid versions will improve energy efficiency and reliability [17]. It acts as a helper during outages to help customers keep the power supply stable quickly and efficiently. Smart grids will be apt for accommodating multiple sources of electricity to connect. However, implementation, operational, and maintenance costs will likely be high. Entire infrastructures must be redesigned to accommodate the high increases in use of technology for sustainable energy integration (Figure 6) [21]. The cost and effectiveness of smart grids in the long term should be evaluated so they can be implemented appropriately.

Microgrids are an alternative approach to help minimize blackouts and utilize more energy production types. They are generally more flexible, allowing diverse energy resources to connect and create smooth transmission to every place delivered. Some renewable energy sources cannot power large systems, which can enhance the use of solar, wind, or other smaller electrical production. Microgrids also isolate faulty areas and assist each section in connecting to immediate power supplies. Integrating microgrids will improve the grid resilience of distribution centers and critical power loads during severe incidents. Greater amounts of energy can be supplied to larger regions by allowing closely located loads, allowing power sources to be utilized in closer locations, reducing transmission losses, and minimizing power flows in transmission and distribution circuits.

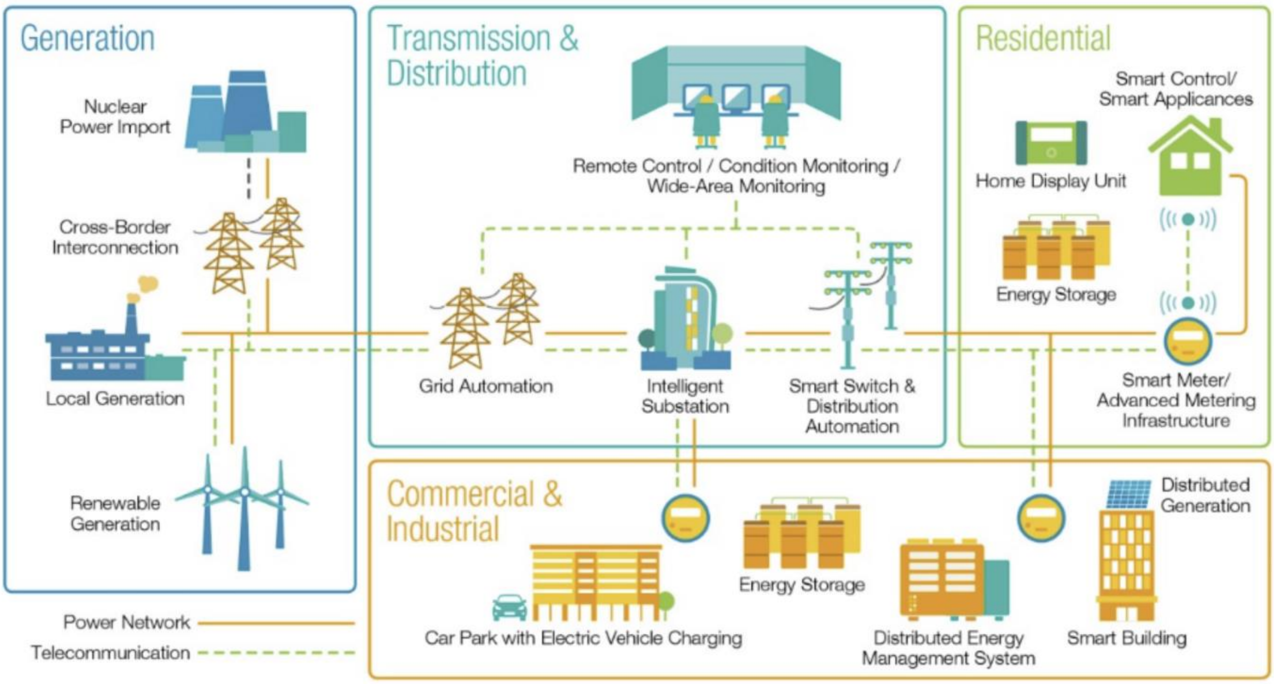

Figure 6. Functional layout of a smart grid system showing integrated communication between generation, distribution, and end-use sectors [22]

Ideally, microgrids operate autonomously without exchanging power with other microgrids or primary grids. Microgrids that fail will be able to connect to different types of grids to prevent further failures and ensure a continuous power supply to consumers during repairs, especially during emergencies such as extreme weather.

3.3 Blockchain technology

Blockchain technology is another resource for implementing sustainable energy into the grid. Blockchain technology operates through a decentralized ledger that records transactions permanently so they cannot be altered [23]. This enables transparency when monitoring transactions of energy production and consumption to all connections in a network. Leveraging blockchain technology during projects helps to allow peer-to-peer energy trading from producers and consumers. This allows for tracking each type of energy source connected to the network for how much energy was produced, where it was produced and consumed, and who consumed it, all while facilitating innovative financing models for renewable energy projects. This technology helps bridge the gap between having multiple alternative energy sources and decentralized networks. An example of how this type of technology works could be analyzed through solar panels owned by a single consumer. When the panels generate excess electricity, they can be distributed to neighboring consumers utilizing blockchain smart contracts. Neighbors can purchase additional electricity or energy produced, and the transaction will be recorded and stored in the transparent 'marketplace.' Blockchain technology will also be a helpful tool for eliminating energy waste and improving the overall efficiency and reliability of renewable energies.

Several countries, heavily populated states, cities including New York, California, and a few European countries, have facilitated startups for these energy trading networks. Other applications of blockchain that seem promising for sustainable energy applications are the use of renewable energy certification and tracking of the origin of the energy. Renewable energy certificates fund projects with this technology by enabling companies and individuals to purchase renewable energy credits. Despite enhanced sustainability in energy through blockchain technology, inefficient paperwork and high fees are levied. Using renewable energy consumption on open blockchain platforms can remove costs associated with its use and simplify the process as a whole [23].

4. Carbon capture

Carbon capture and storage are critical in storing and reducing anthropogenic greenhouse gas emissions and mitigating climate change. Carbon capture, utilization, and storage is abbreviated as CCUS. By capturing CO_2 emissions from sources such as coal-fired power plants, cement factories, steelworks, and refineries, carbon is intercepted before entering the atmosphere and transported in deep geological formations. Organizations such as the Intergovernmental Panel on Climate Change and the International Energy Agency predict that carbon emissions are projected to achieve net-zero emissions by 2050 through essential carbon capture technologies. For carbon capture to be obtainable and cost-effective in climate change mitigation, widespread adoption is necessary. Carbon capture can be a more attractive solution to greenhouse gas emissions than renewable energy sources due to land use efficiency. It reduces greenhouse gas emissions and completely removes their presence in the atmosphere. Table 3 summarizes major carbon capture technologies, briefly describing each method and outlining its primary use or application in reducing industrial, energy-sector, or atmospheric carbon dioxide emissions [24].

Table 3. Overview of carbon capture methods and their applications

Carbon Capture Method	Description	Use/Application
Post-Combustion Capture	Captures CO_2 from flue gases after fossil fuel combustion, often using amine-based solvents (e.g., Shell's Cansolv, BASF's aqueous amine process)	Used in existing power plants, especially coal-fired plants (e.g., Boundary Dam in Canada)
Pre-Combustion Capture	Converts fuel into a gas mixture of hydrogen and CO_2 before combustion; CO_2 is separated before burning	Used in Integrated Gasification Combined Cycle (IGCC) plants (e.g., Kemper County Project)
Oxyfuel Combustion	Burns fuel in pure oxygen instead of air, creating a flue gas of mostly CO_2 and water vapor, making CO_2 easier to capture	Used in specialized power plants designed for high-purity CO_2 capture
Industrial Carbon Capture	Captures CO_2 directly from industrial processes like hydrogen production, natural gas processing, and ethanol fermentation	Used in various industries to limit process emissions
Direct Air Capture (DAC)	Removes CO_2 directly from ambient air using chemical solutions or solid sorbents	Emerging technology aimed at atmospheric carbon removal; used for large-scale climate mitigation
Bioenergy with Carbon Capture and Storage (BECCS)	Captures CO_2 during the combustion of biomass for energy production	Provides "negative emissions" by removing carbon dioxide while generating energy

4.1 Carbon capture methods

Several carbon capture methods are being developed and used in several countries through several projects. Variations of methods are discussed. Additional variables compound the challenges of water reliance during droughts, extreme heat, and even floods, which are conditions fueled by climate change [24]. Post-combustion capture is a commonly used method that captures CO_2 from flue gases after burning fossil fuels. Amine-based solvent technologies like Shell's Cansolv and BASF's aqueous anime process are used to pull CO_2 from the exhaust of these fossil fuel-based plants. Successful implementation of large-scale post-combustion carbon capture has been in Canada at the SaskPower Boundary Dam facility since 2014. Another method used in the Kemper Country Project, the precombustion capture method, is used to convert fuel into gas before combustion, which produces hydrogen and CO_2 mixtures. CO_2 is then separated from hydrogen, and the hydrogen is used to produce further energy. This method uses the integrated gasification combined cycle within power plants. Oxyfuel combustion utilizes fuel that is burned by using only oxygen instead of air, resulting in a flue gas composed primarily of CO_2 and water vapor, allowing CO_2 to separate from the mixture easily. Another type of carbon capture is used during industrial processes to extract carbon from natural gas, hydrogen production, and ethanol fermentation. Emerging technologies like Direct Air Capture and Bioenergy Carbon Capture are removing CO_2 directly from the atmosphere, and when burning biomass for energy.

4.2 Carbon capture storage

After carbon is extracted using an existing method, it can be permanently stored in geological formations or depleted oil fields under the Earth's surface. Deep saline aquifers are seen as promising long-term storage solutions because of their large storage capacity and convenient locations near emission sources, minimizing the cost of transportation of these gases. Several projects worldwide have utilized long-term storage techniques and used monitoring, measurement, and verification systems like 4D seismic imaging and pressure sensors to verify the safety associated with their storage technologies. Although measures are taken to analyze the safety associated with carbon capture, it is still essential to identify risks related to carbon storage. The most significant risks are associated with geological storage and containment. Leakage of carbon gases could cause improper seals, corrosion of seals, or collapses of underground formations, allowing CO_2 to leak through small cracks. Carbon could migrate upwards from excessive injection pressure or activate faults. Earthquakes occurring independently of the effects of carbon storage could also impose the risk of altering formations in which the carbon is stored and allow leakage. Even though sites that have nearby earthquakes, just as Japanese carbon storage sites, have not experienced CO_2 leaks, it does not mean that the possibility is not a dangerous consideration. It is essential that proper maintenance and monitoring of CO_2-injected sites remain crucial. Governments like the United States Environmental Protection Agency have tried to regulate safety by enacting Class VI Rules for CO_2 storage and pressure control. Carbon Capture is an innovative solution to reduce large-scale industrial carbon emissions. Still, it must be enacted carefully by utilizing technology such as 4D seismic imaging, proper maintenance of equipment and sites, and monitoring of geological conditions through pressure management and well integrity. Global projects have shown that CO_2 can be effectively stored and contribute significantly to the climate with appropriate risk management, planning, and long-term monitoring (Figure 7).

5. Policy support

Renewable energy implementation relies heavily on policy support from local and national governments. A multinational longitudinal study covering 27 years and 138 countries confirmed that proactive and sustained government policies directly correlate with renewable energy growth and a corresponding decline in carbon emissions [24]. This relationship is especially evident in countries that tailor their policies to local infrastructure, economic structures, and energy needs. For example, in Pakistan, targeted stakeholder engagement and public-private transparency have fostered successful renewable energy integration projects. Other studies reinforce the importance of overcoming financial and policy barriers. In Saudi Arabia, nearly 70 percent of national energy consumption is tied to the residential sector. However, policy-related obstacles and cultural factors continue to hinder the deployment of renewables, despite clear potential for solar integration [8]. This highlights how regulatory frameworks, building codes, and financial incentives must evolve to enable energy-efficient technologies in emerging markets.

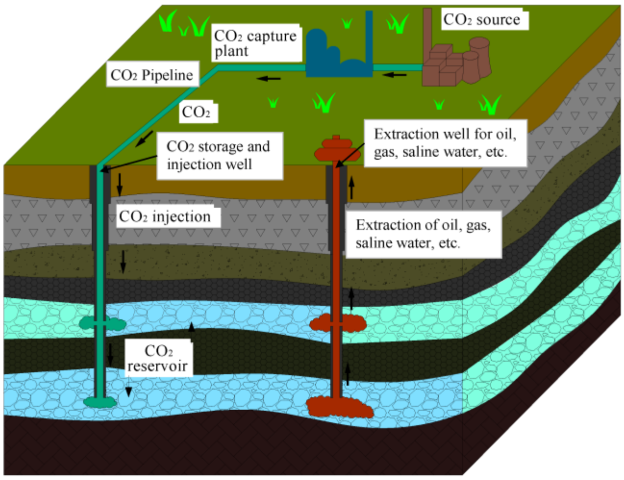

Figure 7. Basic concept visualization of carbon capture [25]

Other examples of policy in Europe are the European Union's Renewable Energy Directive (RED III), which mandates member states to increase the share of renewables in heating and cooling by 1.1 percentage points per year through 2030 [26]. When looking into the consequences of implementing such policies, it could be argued that the Directive's current energy accounting method inadvertently rewards inefficient heating systems. For instance, a wood fireplace with 50 percent efficiency receives more renewable "credit" under the RED than a high-efficiency heat pump. This misalignment weakens incentives for cleaner technologies. To address this, the authors propose a shift to an efficiency-based metric that credits useful energy output rather than input, better aligning policies with decarbonization goals. Meanwhile, other studies emphasize the importance of carbon pricing and green investment as essential policy levers across the EU. Countries like Germany, Sweden, and Spain have each committed tens of billions of euros toward renewable infrastructure, with Germany alone planning over EUR 1 trillion in green investments by 2050 [27]. These efforts are backed by frameworks such as the European Green Deal and national programs like Germany's "Energiewende," which prioritize the decarbonization of transport and building sectors through heat pump deployment, smart grids, and thermal retrofitting. Considering different nations and regions, a one-size-fits-all approach will not succeed and inadvertently cause more harm by creating inefficient development in the energy and heating sectors.

Another global policy, Net Zero Initiative [28] is a framework aimed at reducing greenhouse gas emissions to net zero by mid-century, meaning any remaining emissions are balanced by removals through technologies or natural processes. Its primary purpose is to limit global warming to 1.5°C which is a goal of the Paris Agreement. By setting clear long-term targets, the initiative drives countries and industries to transition away from fossil fuels and invest in renewable energy infrastructure. National commitments to net zero are often paired with policy tools such as subsidies for clean energy, carbon pricing, and emissions regulations. These efforts accelerate the deployment of solar, wind, and other low-carbon technologies, making net zero not just a climate goal but a catalyst for transforming the global energy system.

6. Projected future use of renewable energies

As the globe inevitably shifts towards renewable energy, fossil fuel reliance and carbon emissions decrease. Around 74% of the global energy share by 2050 will be produced by renewable energy sources, significantly higher than the 14% increase in 2018. Climate mitigation, reduction in carbon emissions, and the desire to reduce fossil fuel dependence drive the surge in the implementation and technology of renewable energy. Leading sources of this are projected to be wind and solar because of their affordability and ability to produce energy across diverse geographic locations. By the mid-century, about 90% of the electricity worldwide will be generated by renewable energy sources if policies and investments to accommodate infrastructure are implemented [8]. If this goal is successfully achieved, 90% of the electricity generation will be decarbonized. Contributions of this significance towards climate change mitigation will help limit global carbon emissions and prevent warming to 1.5 degrees Celsius above pre-industrial levels. Technological advancements, grid integration, and policy support in solar photovoltaic installations could increase twentyfold by 2050. Projections [29] from the International Energy Agency (IEA), the global energy mix is expected to undergo a significant transformation by 2050. The U.S. Government reports that projected carbon emissions are expected to decline up to 64% by 2040 [30]. While oil and natural gas are projected to remain dominant, comprising over 50 percent of total global energy consumption in ExxonMobil's forecast, the share of renewables such as wind, solar, hydro, and geothermal is anticipated to grow substantially, increasing more than fourfold to meet rising demand, particularly in developing economies [21]. In more climate-ambitious scenarios, such as the Intergovernmental Panel on Climate Change's (IPCC) "Likely Below 2°C" pathway, renewables are projected to represent up to 30 percent of the global mix by 2050, signaling a dramatic shift toward decarbonization (Figure 8).

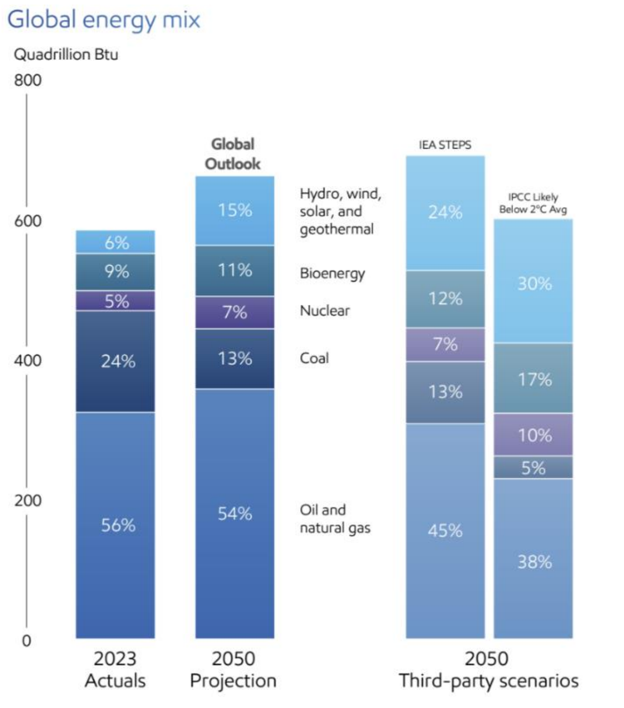

Figure 8. The projected global energy mix in 2023 versus 2050 by ExxonMobil presented in their executive summary. This includes Exxon's Global Outlook as well as the IEA and IPCC outlooks [29]

Despite economic limitations within specific countries, renewable energy is becoming increasingly cost-effective. This makes the increase in the integration of renewable energies look optimistic in the future. Awareness of the environmental harm caused by fossil fuels and carbon emissions also makes adopting renewable energy more attractive to developed and developing countries. Energy demand is projected to grow by 80% by 2050 because of the increasing population growth and industrialization. The implementation of renewable energy is expected to fill large portions of the growing demand for electricity in areas such as transportation, construction, and manufacturing. However, transitional and least-developed countries will struggle to overcome barriers such as high initial capital costs, technological disadvantages, and limited policy support, making achieving lower emissions even more difficult. Despite these barriers, these countries are still beginning to scale their investments into solar, wind, and biomass technologies and other renewable sources. As countries continue to implement supportive policies and invest in developing technologies, energy production will become dominated by renewables.

7. Conclusions

Climate change isn't just a far-off worry but something the globe already experiences through the environment around us and the health of communities. The heavy reliance on fossil fuels has caused severe damage, pushing carbon emissions to dangerous levels, fueling stronger storms, and making clean air and safe drinking water more challenging, and even affecting human health. Moving toward renewable energy isn't just about slowing down global warming. It is about protecting people's health, futures, and right to a livable planet. The technologies are already here: solar panels, wind farms, geothermal systems, and other new ways to store and share clean energy. The research shows that these solutions are becoming more affordable, smarter, and more beneficial for the planet than our current reliance on current fossil fuel technology and infrastructure. Innovations like smart grids, microgrids, and blockchain technology offer a more organized and reliable way to produce and control energy. Of course, no solution to combat climate change is perfect, and even renewable energies face specific challenges that must be carefully addressed. Despite the existing challenges and the cost of failing to reform current energy policies and infrastructure, they will far outweigh the benefits of implementing renewable energies and technology far outweigh the risks. Without strong leadership, innovative policies, and a genuine commitment to making the energy transition fair and accessible for all economic types, carbon emissions will continue to rise.

Ethical issue

The author is aware of and complies with best practices in publication ethics, specifically with regard to authorship (avoidance of guest authorship), dual submission, manipulation of figures, competing interests, and compliance with policies on research ethics. The author adheres to publication requirements that the submitted work is original and has not been published elsewhere.

Data availability statement

The manuscript contains all the data. However, more data will be available upon request from the author.

Conflict of interest

The author declares no potential conflict of interest.

References

[1] Nonrenewable Energy, https://education.nationalgeographic.org/resource/non-renewable-energy/.

[2] R. Lindsey, "Climate change: Atmospheric CO_2 ," NOAA Climate.gov, https://www.climate.gov/news-features/understanding-climate/climate-change-atmospheric-carbon-dioxide (accessed Apr. 24, 2025).

[3] "Climate Change," World Health Organization, https://www.who.int/news-room/fact-sheets/detail/climate-change-and-health/.

[4] "Renewable energy – powering a safer future," United Nations, https://www.un.org/en/climatechange/raising-ambition/renewable-energy#:~:text=In%202018%2C%20air%20pollution%20from,also%20air%20pollution%20and%20health. (accessed Apr. 26, 2025).

[5] Attanayake, K., Wickramage, I., Samarasinghe, U., Ranmini, Y., Ehalapitiya, S., Jayathilaka, R., & Yapa, S. (2024). Renewable energy as a solution to climate change: Insights from a comprehensive study across nations. PLoS ONE, 19(6 June). https://doi.org/10.1371/journal.pone.0299807

[6] "Peak CO2 & Heat-trapping emissions," Climate Central, https://www.climatecentral.org/climate-matters/peak-co2-heat-trapping-emissions (accessed May 1, 2025).

[7] "Renewable power generation costs in 2021," IRENA, https://www.irena.org/publications/2022/Jul/Renewable-Power-Generation-Costs-in-2021 (accessed Apr. 26, 2025).

[8] Osman, A. I., Chen, L., Yang, M., Msigwa, G., Farghali, M., Fawzy, S., Rooney, D. W., & Yap, P. S. (2023). Cost, environmental impact, and resilience of renewable energy under a changing climate: a review. Environmental Chemistry Letters, 21(2), 741–764. https://doi.org/10.1007/s10311-022-01532-8

[9] An, M., & Sun, X. (2024). Carbon footprints of solar panels in China provinces based on different production and waste treatment scenarios. Journal of Cleaner Production, 435. https://doi.org/10.1016/j.jclepro.2023.140453

[10] Carlini, F., Christensen, B. J., Datta Gupta, N., & Santucci de Magistris, P. (2023). Climate, wind energy, and CO2 emissions from energy production in Denmark. Energy Economics, 125. https://doi.org/10.1016/j.eneco.2023.106821

[11] Khoie, R., Bose, A., & Saltsman, J. (2021). A study of carbon emissions and energy consumption of wind power generation in the Panhandle of Texas. Clean Technologies and Environmental Policy, 23(2), 653–667. https://doi.org/10.1007/s10098-020-01994-w

[12] Scherer, L., & Pfister, S. (2016). Hydropower's biogenic carbon footprint. PLoS ONE, 11(9). https://doi.org/10.1371/journal.pone.0161947

[13] Guo, Q., & Hasani, R. (2024). Assessing the impact of water scarcity on thermoelectric and hydroelectric potential and electricity price under climate change: Implications for future energy management. Heliyon, 10(17). https://doi.org/10.1016/j.heliyon.2024.e36870

[14] Umar, M., Awosusi, A. A., Adegboye, O. R., & Ojekemi, O. S. (2024). Geothermal energy and carbon emissions nexus in leading geothermal-consuming nations: Evidence from nonparametric analysis. Energy and Environment, 35(5), 2726–2752. https://doi.org/10.1177/0958305X231153972

[15] Nkinyam, C. M., Ujah, C. O., Asadu, C. O., & Kallon, D. V. V. (2025). Exploring geothermal energy as a sustainable source of energy: A systemic review. In Unconventional Resources (Vol. 6). KeAi Communications Co. https://doi.org/10.1016/j.uncres.2025.100149

[16] Chowdhury, P., Mahi, N. A., Yeassin, R., Chowdhury, N. U. R., & Farrok, O. (2025). Biomass to biofuel: Impacts and mitigation of environmental, health, and socioeconomic challenges. Energy Conversion and Management: X, 25. https://doi.org/10.1016/j.ecmx.2025.100889

[17] Gonçalves, A. C. R., Costoya, X., Nieto, R., & Liberato, M. L. R. (2024). Extreme weather events on energy systems: a comprehensive review on impacts, mitigation, and adaptation measures. Sustainable Energy Research, 11(1). https://doi.org/10.1186/s40807-023-00097-6

[18] Bin, X., & Thakur, J. (2025). Circular economy metrics for batteries: Enhancing sustainability in energy storage systems. Sustainable Production and Consumption, 55, 470–485. https://doi.org/10.1016/j.spc.2025.02.014

[19] J. Fleischmann et al., "Battery 2030: Resilient, sustainable, and Circular," McKinsey & Company, https://www.mckinsey.com/industries/automotive-and-assembly/our-insights/battery-2030-resilient-sustainable-and-circular#/ (accessed May 17, 2025).

[20] Hamza, M. F., Modu, B., & Almutairi, S. Z. (2025). Integration of the Chimp Optimization Algorithm and Rule-Based Energy Management Strategy for Enhanced Microgrid Performance Considering Energy Trading Pattern. Electronics, 14(10), 2037. https://doi.org/10.3390/electronics14102037

[21] Gabriel, L. M. N., Adebisi, J. A., Ndjuluwa, L. N. P., & Chembe, D. K. (2025). Investigation of smart grid technologies deployment for energy reliability enhancement in electricity distribution networks. Franklin Open, 10. https://doi.org/10.1016/j.fraope.2025.100227

[22] T. Agarwal, "Smart Grid Technology working operation and applications," ElProCus, https://www.elprocus.com/overview-smart-grid-technology-operation-application-existing-power-system/ (accessed May 17, 2025).

[23] Lv, Y. (2023). Transitioning to sustainable energy: opportunities, challenges, and the potential of blockchain technology. Frontiers in Energy Research, 11. https://doi.org/10.3389/fenrg.2023.1258044

[24] Ma, J., Li, L., Wang, H., Du, Y., Ma, J., Zhang, X., & Wang, Z. (2022). Carbon Capture and Storage: History and the Road Ahead. In Engineering (Vol. 14, pp. 33–43).

Elsevier Ltd. https://doi.org/10.1016/j.eng.2021.11.024
[25] Li, J., Hou, Y., Wang, P., & Yang, B. (2019). A Review of carbon capture and storage project investment and operational decision-making based on bibliometrics. Energies, 12(1). https://doi.org/10.3390/en12010023
[26] Rosenow, J., Gibb, D., & Thomas, S. (2025). From Inefficient to Efficient Renewable Heating: A Critical Assessment of the EU Renewable Energy Directive. Sustainability, 17(9), 4164. https://doi.org/10.3390/su17094164
[27] Yakymchuk, A., & Rataj, M. A. (2025). Economic Analysis of Fossil CO2 Emissions: A European Perspective on Sustainable Development. Energies, 18(8). https://doi.org/10.3390/en18082106
[28] Net zero carbon events, https://www.netzerocarbonevents.org/initiative/ (accessed May 18, 2025).
[29] "Protect tomorrow. Today: ExxonMobil Sustainability," ExxonMobil, https://corporate.exxonmobil.com/sustainability-and-reports/sustainability (accessed May 17, 2025).
[30] "U.S. government publishes updated emissions projections," Energy.gov, https://www.energy.gov/policy/articles/us-government-publishes-updated-emissions-projections (accessed May 18, 2025).