BILINGUAL PUBLISHING GROUP

Journal of Environmental & Earth Sciences
https://journals.bilpubgroup.com/index.php/jees

REVIEW

Carbon-Neutral Pathways: Evaluating Renewable Technologies and Negative Emission Solutions

***Ming Zhong* [1,2]*, Jingjing Yu* [1]*, Qingyu Hong* [3*]**

[1] *Jiangxi Vocational College of Environmental Engineering, Ganzhou 341000, China*
[2] *Jiangxi University of Finance and Economics, Nanchang 330013, China*
[3] *Tea Research Institute, Chinese Academy of Agricultural Sciences, Hangzhou 310008, China*

ABSTRACT

The global transition to carbon neutrality is an urgent and multifaceted challenge that requires the deployment of renewable energy technologies and negative emission solutions (NETs) to reduce greenhouse gas emissions across all sectors. This is a review article that looks at the contemporary environment of renewable technologies, such as solar, wind, biomass, hydropower, and geothermal, and how they might help to decarbonize the power sector and their combination with NETs. The paper also looks at the prospects of carbon capture, utilization, and storage, afforestation and reforestation, soil carbon sequestration, ocean-based, and enhanced weathering as some of the methods of offsetting the residual emissions. The article also outlines the economic, policy, and social factors required to have these solutions scaled up, such as the need to have good policy frameworks, invest in innovation, and the need to have the people on board. Lastly, it also gives the future perspective of having a carbon-neutral global economy, and it highlights that technology must be enhanced, more cooperation between countries must be established, and a holistic, open-ended way of attaining carbon neutrality.

Keywords: Carbon Neutrality; Renewable Energy; Negative Emissions Technologies; Carbon Capture and Storage; Climate Policy

*CORRESPONDING AUTHOR:
Qingyu Hong, Tea Research Institute, Chinese Academy of Agricultural Sciences, Hangzhou 310008, China; Email: hongqingyu@dazhangshan.com

ARTICLE INFO
Received: 15 December 2025 | Revised: 5 February 2026 | Accepted: 10 February 2026 | Published Online: 11 February 2026
DOI: https://doi.org/10.30564/jees.v8i2.12881

CITATION
Zhong, M., Yu, J., Hong, Q., 2026. Carbon-Neutral Pathways: Evaluating Renewable Technologies and Negative Emission Solutions. Journal of Environmental & Earth Sciences. 8(2): 183–201. DOI: https://doi.org/10.30564/jees.v8i2.12881

1. Introduction

Climate change reduction is now a focus in the global agenda, and to achieve a carbon-neutral society, it is important to reduce CO_2 emissions to zero by the middle of the century to prevent the worst effects of warming, such as extreme weather, sea-level rise, and loss of biodiversity. The speed of reducing emissions, as well as processes of eliminating the already existing CO_2 in the air, will be required to achieve the goal of carbon neutrality. Negative emission technologies and renewable energy technologies are thus critical, which provide alternative avenues for decarbonizing the energy systems and rebalancing the carbon cycle on the planet[1,2].

Climate change reduction is now a focus in the global agenda, and to achieve a carbon-neutral society, it is important to reduce CO_2 emissions to zero by the middle of the century to prevent the worst effects of warming, such as extreme weather, sea-level rise, and loss of biodiversity. The speed of reducing emissions, as well as processes of eliminating the already existing CO_2 in the air, will be required to achieve the goal of carbon neutrality. Negative emission technologies and renewable energy technologies are thus critical, which provide alternative avenues for decarbonizing the energy systems and rebalancing the carbon cycle on the planet[3]. Net-zero emissions are those emissions that are balanced by removals in the form of mitigation and carbon removals in the form of capture, storage, and sequestration. The seriousness of this shift is indicated by climate surveys that suggest that it is necessary to restrict warming to 1.5 °C, and that a significant transformation is necessary in energy, industry, agriculture, and transport[4,5].

Renewable energy, such as solar, wind, hydro, geothermal, and bioenergy, offers alternatives to energy that are low in carbon to fossil fuels, which are the major contributors to global emissions. Although it is advancing fast, it has challenges like intermittency, storage, grid integration, and grid infrastructure, which can constrain the deployment, and renewables will not be able to produce full carbon neutrality, particularly in hard-to-abate industries. NETs are useful in bridging this gap by eliminating CO_2 in the air or sequestration of the same at the points of emission to balance the remaining emissions after mitigation. Among the main methods are carbon capture and storage, afforestation and reforestation, soil carbon sequestration, ocean-based, and enhanced weathering. They both have high potential, but technical, economic, and environmental limitations require improvement to scale[6–8].

The literature review explores the new developments in major renewable alternatives, especially solar and wind, that have rapidly advanced and become more cost-effective, and the place of hydropower, geothermal, and bioenergy in the overall low-carbon transition. It also assesses the best NETs, such as carbon capture, utilization, and storage, and direct air capture, and nature-based solutions, which can produce co-benefits, such as biodiversity support and restoration of an ecosystem. New solutions that include soil, ocean-based sequestration, and increased weathering are also being explored as options to cover the residual emissions[9–12].

Lastly, the review addresses the main issue of scaling up and integrating such technologies, with a focus on the role of policy, markets, and public acceptability. International cooperation, economic incentives, and government control will play a significant role in large-scale implementation. Opportunity to integrate renewables and NETs as synergistic systems, enhancing performance and cost reduction, is also looked at during the review[13,14]. On the whole, carbon neutrality is something that will need to be achieved with the help of coordinated technological innovation, favourable policy, and the involvement of society. Renewables and NETs should be employed but in a manner that is cost-effective, acceptable, and sustainable. However, this review gives a more recent evaluation of the progress, constraints, and future perspectives and reveals the necessity to do further research and international cooperation to ensure a net-zero future[1,15].

2. Carbon-Neutral Pathways: A Conceptual Framework

One of the most important goals of the global struggle against climate change is achieving carbon neutrality, also known as net-zero emissions. It requires a fundamental transformation in how societies generate and use energy, manage natural resources, and pursue environmental sustainability. Carbon-neutral pathways are part of efforts to keep global warming within safer limits, as called for by international agreements such as the Paris Agreement. This section provides an overview of carbon neutrality, explains why such pathways are necessary, and outlines the different ways carbon neutrality can be achieved[16,17].

2.1. Carbon-Neutrality Definition: A Holistic Approach

Carbon neutrality is a balance of carbon dioxide emitted into the atmosphere and carbon dioxide removed or nullified, such that there is no rise in atmospheric CO_2. It is not just a matter of decreasing the amount of greenhouse gases emitted, but the leftover emissions are also captured or offset by means of carbon capture or verified credits to reach a net-zero level. Since conditions and sources of emissions vary with time, the only way of ensuring this balance is through long-term effort.

This aim is backed by two key strategies of cutting emissions and eliminating carbon. Reduction of emissions lays emphasis on the closest path towards net neutrality, like changing to renewable energy sources, including solar, wind, and hydropower. The enhancement of energy usage in the industry, buildings, and transport also reduces the need for carbon-intensive power. Decarbonization can also be realized in other sectors with the help of technology, including heavy industry, agriculture, and aviation, and green hydrogen, electric vehicles, and climate-smart farming are among the solutions. Together with good regulation and changes in consumer behavior, such measures are fundamental in realizing massive reductions[15,18,19].

However, there will be carbon dioxide emissions even with the vigorous mitigation measures, particularly in hard-to-abate sectors of the economy like cement and steel production, and in aviation. The negative-emission (carbon removal) technologies come in handy in such instances. These solutions eliminate the CO_2 in the air and put it in long-term storage. These are nature-based (afforestation, reforestation, and soil carbon sequestration) and engineered (carbon capture and storage, and direct air capture with storage) ones. Carbon removal supplements the emission cuts and aids economies to be carbon-neutral by managing residual emissions in hard-to-abate sectors[20,21].

Carbon neutrality cannot be achieved without cutting emissions or eliminating carbon, since it should be a holistic approach. The successful transition relies on solutions based on the challenges and technological capabilities of various sectors and regions. In order to achieve net zero, innovation, improved policy, and individual and organizational behavior change will be necessary to achieve the global climate targets. One of the avenues that can be used in curbing climate change is carbon neutrality. Through intensive emissions reductions and viable carbon elimination, societies have a chance to enter into a more resilient and sustainable future and decrease climate impacts in the long run.

2.2. The Critical Role of Carbon-Neutral Pathways for Climate Goals

The need to realize carbon neutrality is an urgent problem. Climate science has always emphasized the major importance of lowering the level of CO_2 in the air so that the most dangerous effects of global warming can be reduced. The Intergovernmental Panel on Climate Change has set forth a clear objective, which is to keep global warming at 1.5 °C above pre-industrial levels by the year 2,100 in order to prevent the worst effects of climate change. To accomplish this, the emissions of greenhouse gases on the planet must be lowered to a net zero by 2050 or sooner, with the major reduction taking place during the decade[22].

The carbon-neutral pathways are important in the international initiative to combat climate change. Failure to reach carbon neutrality would result in the global temperature exceeding levels at which ecosystem and human systems might experience irreversible and possibly disastrous change. Some of the effects that are already felt are increased and severe heat waves, a rise in sea level, severe droughts, and food and water disruption. There is also a need for carbon-neutral pathways in order to stabilize the carbon dioxide levels in the atmosphere. This stabilization not only assists in keeping a check on climate change, but it also helps restore the balance in the carbon cycle, which has been tipped by centuries of human activity. The carbon cycle explains the natural circulation of carbon in the atmosphere, ocean, soil, and living organisms. The activities of human beings, in particular, the burning of fossil fuels and deforestation, have raised CO_2 levels, enhanced the greenhouse effect, and boosted climate change. To reverse the trend, there is a need to move away from activities that are carbon-intensive to those that have less carbon emissions and those that capture and sequester carbon[23].

The Paris Agreement aims are closely in line with the road to carbon neutrality. Article 2 of the Agreement requests the restriction of the global average rise of temperature to clearly less than 20 °C from the temperature before the industrialization era, and aims at trying to reduce it to 15 °C. Article 4 also highlights the necessity of establishing a balance between the removals and the greenhouse gas emissions in the second half of the current century. To attain these ambitious purposes, it will be necessary to scale up low-carbon technologies quickly and strategically make large-scale carbon removal projects. Carbon-neutral pathways can be developed to help stabilize the climate for future generations. Moreover, carbon neutrality has wider benefits, such as the purification of the air and the decrease in health effects caused by pollution, as well as more innovative clean technologies, which potentially can lead to the development of the economy and the creation of jobs. Carbon neutrality will allow countries and regions to improve energy security through less reliance on foreign fossil fuel consumption and encourage renewable energy markets to develop. Moreover, carbon-neutral pathways facilitate conservation of biodiversity and restoration of ecosystems, particularly when accompanied by nature-based solutions, including reforestation and sustainable soil management[24–26].

2.3. Pathways to Achieving Carbon-Neutrality

Carbon neutrality is not easy; it involves concerted effort not only on the technological, social, economic, and political fronts but also on all of them. The goal of having a carbon-neutral world is ambitious, and the road towards it will require significant shifts in industries, with the help of innovation and radical transformations of the system. Due to the interdependence of such challenges, advancements have to be placed on many fronts at once to achieve global carbon-neutrality goals.

The energy sector often receives attention in the process of decarbonization as this sector contributes a significant portion of carbon dioxide emissions, especially during electricity generation, transportation, and heating. The principal aim of reducing emissions in this sector is the replacement of fossil fuels with renewable energy (solar, wind, geothermal, and hydropower). Nevertheless, due to the fact that most renewable sources cannot be sustained, the development of energy storage and the upkeep of electricity grids are also necessary. Storage technologies, such as batteries and pumped-hydro storage, are useful in stabilizing supply and allow more areas of significant energy use to be electrified, such as transport and heating. The decision to electrify these industries is imperative to limit the use of fossil fuels, and the energy shift has to be both comprehensive and clean in its results[27–30].

The hardest sectors to decarbonize are cement, steel, and chemicals, as the production process is extremely carbon-heavy. These industries will need significant technological development for carbon neutrality, such as hydrogen-based steelmaking, carbon capture, utilization, and storage, and electrification of industrial heat. With the magnitude and intricacy of heavy industry, the achievement of net zero is probably contingent on both emissions cuts and carbon elimination. Bioenergy models, including carbon capture and storage, and direct air capture, would contribute to the elimination of residual emissions, as well as the decarbonization of core industrial processes.

Farming is also a significant contributor of greenhouse gases, especially methane and nitrous oxide. The emission mitigation in this sector will involve changes to more sustainable operations, including precision agriculture, tilling less, better management of manure and fertilizer, and agroforestry. There is also a high potential for carbon sequestration in soils and forests by land-use strategies, such as reforestation, afforestation, and better land management. These measures can also improve ecosystem services and biodiversity, and can be used to match conservation objectives with emissions mitigation as well as eliminate carbon[31,32].

Some of the most difficult sectors to decarbonize include cement, steel, chemicals, and agriculture due to their emissions, which are energy-consuming and, in most instances, the chemistry of production. The future will be based on a suite of solutions: hydrogen-based steel-making, electrified industrial heat, and carbon capture, utilization, and storage of processes that are hard to avoid. Since there will probably be some leftover emissions, carbon capture solutions like bioenergy with carbon capture and storage and direct air capture can be used to offset the leftover emissions in addition to deep cuts in the industrial processes.

Agriculture also must be targeted to mitigate, as it becomes one of the largest emitters of methane and nitrous oxide. Precision agriculture, better maintenance of fertilizers and manures, less tilling, and agroforestry are more sustainable practices that enable the reduction of emissions.

Complementary land-use activities such as reforestation, afforestation, and improved land management can enhance carbon sequestration in soils and forests, and supply co-benefits in terms of the provision of better ecosystem services and the safeguarding of biodiversity[33,34].

The combination of these pathways must be planned and coordinated across sectors. The expansion of renewable energy, energy storage, carbon capture, and low-carbon industrial production requires cross-sectoral alignment in terms of policies and investments. To implement large-scale clean energy solutions, smart grids, enhanced energy efficiency, and sustained innovation of the low-carbon technologies will be necessary. Governments need to foster innovation and enhance global cooperation and establish predictable and enabling regulatory and market environments to hasten the shift to a carbon-neutral, net-zero economy.

Finally, carbon neutrality requires a relational strategy that is regional, sectoral, and technological in nature, which involves profound emissions cuts and carbon capture and removals. This will take long-term commitment to the policies, long-term innovation, and cooperation between the governments, industry, and communities to succeed. Since it is a systemic change of the global economy, it is also reliant on the behavioral and social acceptance changes and technological advancement. Carbon-neutral pathways present the most plausible way forward to a strong and sustainable future through a coordinated effort and involvement of the broad stakeholders[35–37].

3. Renewable Technologies for Carbon Neutrality

Further technological development of renewable energy sources is a significant part of what will achieve carbon neutrality. These systems will be able to provide electricity and fuels with significantly lower greenhouse gas emissions since they will utilize resources like sunlight, wind, biomass, water, and geothermal heat. Renewables consequently feature at the heart of the decarbonization of energy systems, although scaling the renewables also presents difficulties, particularly the variability of production, the need to have low-cost storage facilities, and significant grid and other infrastructure upgrades[15]. **Table 1** highlights the global installed capacity of renewable technologies as of 2024, showing that while renewables are expanding rapidly, the integration of negative emission technologies still requires substantial scaling to meet global targets. The Key Regional Deployment column highlights major energy-use regions based on their renewable energy installations: North America (led by the U.S. and Canada, with strong wind and solar capacity), Europe (with leaders like Germany and Spain in wind and solar), Asia (dominated by China and India in solar and wind), Africa (featuring countries like South Africa and Morocco for solar and wind), and Latin America (with Brazil leading in bioenergy and expanding wind and solar). This categorization provides a clear view of regional contributions to global renewable energy deployment, showcasing both leadership and disparities in adoption. The section also gives an in-depth study of the most popular renewable technologies that have been deployed and how they would help in ensuring carbon neutrality. **Figure 1** illustrates the global energy mix in 2024, highlighting the contribution of renewable energy sources (solar, wind, hydropower, biomass, and geothermal) alongside fossil fuels (coal, oil, natural gas), and nuclear energy[38–41].

3.1. Solar Energy: The Dominant Renewable Power Source

Solar photovoltaic energy has emerged as one of the most popular sources of renewable electricity, and the use of solar energy has been rising in recent years. The PV systems directly convert sunlight into electricity by means of semiconductor cells. This rapid growth has been fueled by the falling cost, the ongoing technological advances, and enabling policies: the total installed solar PV around the world stands at approximately 1.86 TW as of the end of 2024, or approximately 452 additions in 2024 alone. The necessary evidence also includes the number of solar productions exceeding 2,000 TWh in 2024, which provides approximately 6.9% of the total world power generation and indicates its growing role in the electric grid[42–45].

Solar energy is scalable, which is a major strength of this type of energy. Solar PV can be implemented on a wide variety of scales, including small rooftop systems and homes and businesses, or on utility-scale solar farms, which makes it suitable for a wide range of locations and energy requirements. Prices have been reduced significantly, and prices of solar PV have been reduced by about 80% since 2010; therefore, it is currently one of the cheapest sources of electricity in most areas. The primary weakness of solar energy is that it is variable; it varies with the amount of sunlight as well as with time of day, season, and weather. The grid integration may become a problem with high penetration of solar energy solutions unless it is accompanied by sufficient flexibility, such as energy storage, demand control, and enhanced grid infrastructure. Utility-scale projects can also occupy extensive land, which is incompatible with their ability to use land or conserve it[46–48].

Table 1. Global Installed Capacity of Renewable Energy Technologies (2024).

Technology	Installed Capacity (GW)	Contribution to Global Electricity (%)	Annual Growth Rate (%)	Key Regional Deployment
Solar Photovoltaic (PV)	1,100	3.6	32	China, USA, India
Wind (Onshore)	850	5.8	9	Europe, China, USA
Biomass	140	1.0	2	USA, Brazil, Europe
Hydropower	1,300	16.5	1	China, Brazil, Canada
Geothermal	15	0.2	4	Iceland, Philippines, USA

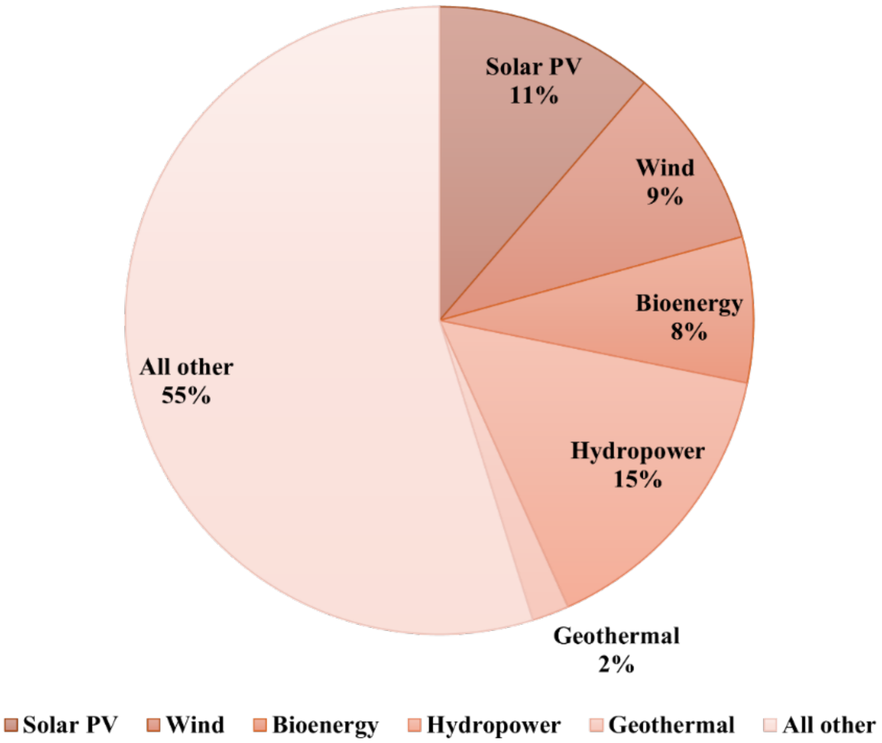

Figure 1. Global Energy Mix and Contribution of Renewables (2024).

3.2. Wind Energy: Powering the Future with Air

Global decarbonization has come to rely on wind energy. The energy present in the wind has been converted to electricity with the help of modern wind turbines, and their application has increased as the performance of the turbine has been enhanced, the cost has been reduced, and supporting policies have increased. The wind industry recorded its biggest boom of 117 GW in 2024, which served customers of approximately 1,136 GW globally. 8.1% of the world's electricity is provided by wind, which also reemphasizes the trend of increasing the mix of power sources[49–51].

There are significant benefits of wind energy. Onshore wind has become one of the cheapest sources of new electricity, and the levelized cost of energy has reduced by over 40% over the last decade. Offshore wind has its future as well: the more intense and stable the wind, the higher its output, and it is more typical in coastal areas, but the projects are still more capital-intensive and demand special foundations, ports, vessels, and grid connections, that is, they are more expensive than onshore wind. Key impediments are fluctuation in wind generation that varies by hour, season, and location, and may make balancing the grid a bigger percentage of the generation challenge. Onshore projects can also be inconsistent with land-use and conflict with agricultural or conservation objectives. Moreover, deployment can be slowed down by allowing and publicly accepting it, especially in areas of apprehension regarding the effects on the eye, noise, and contact with wild animals [52–54].

3.3. Biomass and Bioenergy: Harnessing Organic Matter

Organic materials like wood, agricultural residues, and organic waste are biomass sources of energy, which are used to generate electricity, heat, and transport fuels. As a source of power, biomass is burnt to generate heat to make steam and produce electricity, and liquid biofuels like ethanol and biodiesel can be used in place of the gasoline and diesel in a transportation system. As of 2023, the world's biopower potential was approximately 150 GW, providing biofuel to approximately 5–6% of the liquid transport fuel demand in 2023. One advantage of biomass is dispatchability: biomass plants can generate controllable power in contrast to solar and wind plants, which can be used to balance the grid. Though the advantages of climate features on sustainable sourcing and complete lifecycle emissions because of land-use change, the feedstock collection, gathering, and supplier chains are potential influences contributing to the net impacts [55,56].

Another crucial limitation with biomass energy is biomass. Bioenergy large-scale development will increase land use competition that may lead to food production loss or deforestation and other land-use alterations. In the case of feedstocks harvesting or management in an unsustainable manner, lifecycle greenhouse gas emissions may exceed the expected levels, which will reduce the benefits of climate. Also, not all biomass paths would provide as high net returns of energy as other renewables, like solar and wind. To deal with these concerns, high sustainability criteria, diligent selection of feedstock (e.g., residues and wastes where warranted and otherwise), and solid lifecycle accounting are needed. Nevertheless, bioenergy could still be a viable component of a low-carbon portfolio, particularly to serve those uses that are hard to electrify, such as some industrial processes and parts of the aviation and heavy transport [57].

3.4. Hydropower and Geothermal Energy: Stable and Reliable Sources

Some of the oldest and most appreciated renewable energy technologies are hydropower and geothermal energy, which offer dispatchable, low-carbon, and steady electricity. The hydropower, which has been in use for the past century, produces power by using the moving water, and the large system of dams and reservoirs remains a significant contributor to the renewable energy supply in the globe. By 2024, the total hydropower stations in the globe numbered approximately 1,283 GW and were able to provide approximately 14% of the global electricity that year [58,59].

3.5. Hydrogen: A Promising Future for Hard-to-Decarbonize Sectors

Green hydrogen production is an emerging source of decarbonization of industries that are hard to electrify, such as heavy industry, high-temperature heat, and long-distance transport. Hydrogen as the energy carrier can be stored and thereafter used in fuel cells to produce electricity, or be burned as a fuel, or it can be utilized as an industrial feedstock. The future energy demand and investment in green hydrogen are likely to increase sharply within the next several decades, and most of the long-term energy scenarios also predict that hydrogen may be able to provide a significant portion of the final energy demand of the world by the middle of this century. The main benefit is its capacity to take excess renewable energy and store it over longer periods of time during periods of high demand or low wind and solar energy. Direct electrification is frequently limited by high temperatures, so that hydrogen can also facilitate decarbonization in hard-to-abate sectors of low-carbon steelmaking, high-temperature industrial heating, and the generation of synthetic shipping and aviation fuels where high temperatures are common [60].

Hydrogen is no exception and is affected by severe obstacles, with the production cost being the biggest obstacle. Green hydrogen is costly in large part due to the fact that electrolyzers consume a great deal of renewable electricity, and power costs still present the biggest portion of the total price. Moreover, the infrastructure to be developed to produce, store, and transport hydrogen pipelines, storage facilities, compression or liquefaction systems, port and fueling networks is not yet a large-scale deployment, which is capital-intensive. Another limitation is that the efficiency of the conversion of electricity into hydrogen and back to usable energy requires a lot of losses. Despite such obstacles, hydrogen has good prospects as a versatile, low-carbon energy carrier, especially in reducing emissions from hard-to-abate industrial processes and over long-haul transport. However, at the end, there will be no one-stop solution that will bring net zero. The energy system of the future, in the form of a resilient, low-emissions energy system, will be based on a portfolio: solar and wind will supply the bulk of electricity production, and the dispatchable low-carbon components of the energy system will include hydropower, geothermal, and sustainably sourced biomass, and hydrogen will have a specific role where direct electrification is not viable. Geothermal energy involves the use of the internal heat of the earth to produce electricity, and in a few instances, it can be used for heating. Its major strength is that it has a consistent baseload, as production does not rely on weather. The world's capacity for geothermal is approximately 17 GW, and a slight growth is persisting in the geothermal resource abundance of the world, like the United States, Iceland, and the Philippines. The two technologies are not only low operating technologies but also relatively low operating costs with build-up limitations. Hydropower projects may pose immense environmental and social effects, such as loss of habitat, disturbance of the river ecosystem, and displacement of communities, especially large-scale projects. Geothermal utilization is geographically constrained and can be expensive to initiate and drill in terms of startup capital and the associated drilling risk. Nevertheless, hydropower and geothermal are still valuable contributors to firm electricity and contribute to the uncertainty of solar and wind[61,62].

4. Negative Emission Technologies

Although renewable energy technologies are vital towards decreasing carbon emissions at the point of generation, they might not be enough to achieve complete carbon neutrality, particularly in high-carbon industries or areas of heavy production, e.g., heavy industry, agriculture, and long-distance transport. This is vital to the NETs. These technologies absorb CO_2 in the air or take it at the levels of emission, which will not lead to global warming. The NETs provide additional solutions to emissions reductions, which can be implemented to achieve the removal of CO_2 from the atmosphere once the emissions are minimized. In this part, the author discusses the most promising NETs, such as carbon capture, utilization, and storage, afforestation and reforestation, soil carbon sequestration, ocean-based solutions, and enhanced weathering, and explains their potential and obstacles to achieving carbon neutrality[15,63]. **Table 2** provides an overview of different NETs, highlighting their operational principles, potential carbon removal capacity, technological maturity, and main challenges.

Table 2. Overview of Main Negative Emission Technologies (NETs).

NET Technology	Operational Principle	Carbon Removal Potential (tons of CO_2 per Year)	Current Technological Maturity	Key Challenges
Carbon Capture and Storage (CCUS)	Captures CO_2 from industrial processes and stores it underground	~7.6 Gt globally by 2050	Advanced (limited deployment)	High cost, storage risks, infrastructure needs
Afforestation & Reforestation	Planting and restoring forests to absorb CO_2 through photosynthesis	~4–5 Gt globally per year	Widely used (implementation underway)	Land competition, biodiversity concerns
Soil Carbon Sequestration	Enhances carbon storage in soils through agricultural practices	~3.6 Gt globally per year	Emerging (limited pilot projects)	Measurement uncertainty, long-term stability
Direct Air Capture (DAC)	Uses chemical processes to capture CO_2 directly from the air	~10 Gt by 2050	Early-stage (expensive)	High energy cost, scalability issues
Ocean-based Solutions	Enhances natural processes like ocean fertilization or blue carbon ecosystems	~1.2–2.4 Gt globally annually	Experimental (research ongoing)	Environmental risks, uncertainty in impact

4.1. Carbon Capture, Utilization, and Storage

One of the most sophisticated negative emissions technologies and the most researched is carbon capture, utilization, and storage. It involves capturing CO_2 emissions throughout the industrial operation or even in the atmosphere and then transporting them to storage facilities where they are injected into geological formations, where they will be stored for a long period. In other uses, captured CO_2 is also used in industrial applications, including improved recovery of oil, or the transformation of the CO_2 into useful products such as chemicals or fuels.

More than 30 large-scale facilities of CCUS have been operational globally so far, capturing millions of t CO_2/yr. Such plants cannot be in any other places other than industrial areas where the production of CO_2 is a major contributor, like cement, steel, and chemical manufacturing centers. The IEA estimates that the world will need about 7.6 Gt of CO_2 to be taken every year in order to achieve the global climate targets by 2050. This estimate highlights the urgent necessity of CCUS implementation on a significantly larger scale. One of the greatest benefits that will be of great importance to the CCUS is the capacity of the technology to cut down on the emissions of heavy industries such as cement, steel, and chemicals. These sectors contribute significantly to the emission of CO_2, and decarbonizing the industries is extremely difficult. CCUs offer a possible solution to this issue, which would allow cutting the emissions that are hard to reduce in other ways. Also, it is possible to retrofit CCUS to the old fossil fuel-fired power plants and industrial facilities to provide a viable way of decreasing the emissions of old infrastructure, as renewable energy sources will grow [64,65].

Nevertheless, there are a number of obstacles to the wide-ranging implementation of CCUS. Capturing, transportation, and storage of CO_2 have a high cost, which is one of the main concerns. The high energy consumption of the existing approaches precludes the economic viability of large-scale CCUS implementation as a major challenge. In addition, the cost of removing CO_2 is still higher than the other methods of reducing emissions. The other difficulty is that CO_2 has a low storage volume. Although geological storage is considered secure, there is still a concern about how these storage sites can be monitored over the long run and the chances of leakage. Moreover, regardless of the bright prospects of CCUS, its applications are limited at present. To achieve a significant effect on global carbon neutrality, CCUS will have to be widely adopted, which will take a lot of investment, plus solid policy development [66–68]. These technical and economic challenges are the key to the successful implementation of CCUS. It will be important to address these barriers to unlock its full potential and global endeavors to achieve net-zero emissions.

4.2. Afforestation and Reforestation

Afforestation and reforestation are natural processes that involve planting trees and the restoration of forests to absorb atmospheric CO_2 through the process of photosynthesis. Forests are carbon sinks, which take in greater amounts of CO_2 than they give out, and have the capability to store carbon in living biomass and soil over longer periods, in decades or centuries. Such approaches are some of the most affordable and universal strategies for negative emissions in place at the moment. There are about 289 Gt of carbon in forests around the world today. According to the estimates of the United Nations Food and Agriculture Organization (FAO), it is estimated that with the help of afforestation and reforestation, 4–5 Gt of CO_2 can be sequestered every year. Such endeavors are backed by other initiatives in the world, including the Bonn Challenge, which targeted to put back 350 million ha of degraded lands by 2030, which could possibly enable the sequestration of hundreds of millions of tons of CO_2 annually. Afforestation and reforestation have several benefits. They are also comparatively cheap in contrast to other types of negative emissions technologies, particularly when using degraded lands, which can be restored. Besides carbon sequestration, these practices come with a number of co-benefits such as biodiversity conservation, water cycle regulation, soil protection, and air quality. Large-scale carbon sequestration has a high potential, especially in the tropical areas where deforestation has been a significant concern, and hence they form an important element of worldwide actions to reduce climate change [69].

These approaches have a number of challenges in spite of their strengths. The extensive afforestation and reforestation programs need vast land space, and that may conflict with agricultural practices and urbanization. Access to appropriate land, especially in congested areas, is a major limitation. Moreover, the system of monocultures or non-native species, which are introduced into carbon sequestration projects, may harm local ecosystems and biodiversity. Forests are also susceptible to risks, including wildfires, pests, and disease, releasing stored carbon back into the atmosphere in this manner, which may compromise the efficacy of such strategies on a long-term basis.

Afforestation and reforestation remain critical strategies for improving the natural carbon sinks of the earth in spite of the limitations that they encounter. They will continue to play an important part in the global climate change control programs, particularly when joined by other measures of carbon reduction and environmental rehabilitation[70].

4.3. Soil Carbon Sequestration

Soil carbon sequestration is a term that has been used to refer to the application of agricultural and land management strategies that seek to enhance the level of carbon fixed in soils. No-till farming, cover crop farming, agroforestry, and rotational grazing are all practices that not only increase the ability of soil to absorb carbon in the atmosphere but also increase its ability to retain it. The soils can hold more carbon than the forests, therefore making them one of the most important devices in reducing climate change. Soil carbon sequestration has great potential. It has been estimated that by 2030, soil management practices will be a significant contribution to global carbon removal, with projections that the management of soils might be able to sequester up to 3.6 Gt CO_2/yr. This puts into perspective the importance of soil carbon storage to deal with the ever-increasing climate change problem[71].

Carbon sequestration in soils has many benefits, especially the universal nature of the practice. These practices can be applied in agricultural lands all over the world, thus making it a cheap and scalable approach to carbon removal. In addition to carbon storage, management practices on soil enhance soil fertility, increase water retention, and minimize erosion, which has a direct positive effect on agricultural productivity. Moreover, such practices have the potential to boost crop yields, as well as make the crops more resistant to climate change, giving the farmers a major reason to use them.

Despite the advantages, there are a number of challenges that restrict the widespread application of soil carbon sequestration. Soil carbon storage is a hard measure and verification, and even current techniques may not capture the amount of carbon sequestered. There are also land-use dilemmas, especially in instances where such agroforestry practices necessitate a major alteration in land use, which can be contrary to other agricultural or development agendas. Also, carbon stored in soils is not very stable in the long term. One can release it into the atmosphere by either tilling, deforestation, or land degradation, which compromises the long-term sequestration of carbon. Managing soil carbon sequestration is a potential, cost-effective, and scalable solution to curbing atmospheric $CO_{2,}$ although several challenges have been encountered. Combined with sustainable agricultural methods, it provides a good way of increasing carbon capture activities on a global scale[72].

4.4. Ocean-Based Negative Emissions

Oceans are also great carbon absorbers, where they can take enormous quantities of CO_2 from the atmosphere. Ocean-based negative emissions. One way to supplement this natural process is through ocean fertilization, blue carbon ecosystems, and algae-based carbon sequestration. These methods consider stimulating the development of marine creatures that trap and save carbon or the physical elimination of CO_2 in water. The blue carbon ecosystems are also referred to as coastal and marine ecosystems, and they are important in the process as they are able to capture carbon in the sediments. The sea grasses, mangroves, and salt marshes, such as those, are estimated to trap 1.2–2.4 Gt CO_2/yr. Recovery of such ecosystems would contribute greatly to this capacity, and thus they are good for large-scale carbon sequestration.

Ocean-based sequestration has the potential to be huge, considering the fact that oceans occupy over 70% of the Earth. These ecosystems provide a major potential for large-scale carbon capture. Another type of environmental benefit, including the conservation of biodiversity, coastal protection, and water filtration, is also provided by restoring and enhancing blue carbon ecosystems. Moreover, solutions located at the sea are relatively cheap relative to other negative emissions technologies, and implementation is possible in the coastal areas of the world, and hence very scalable. Despite such impressive benefits, there are a number of challenges to ocean-based solutions. The process of ocean fertilization, which consists of the introduction of nutrients to accelerate the growth of plankton, is a very controversial one. Its environmental impact remains unpredictable, and the threats that it has on marine life have yet to be fully comprehended. Moreover, determining and confirming the efficiency of ocean-based carbon sequestration is complicated because of the complications involved in ocean ecosystems and because carbon storage in the sea is hard to track. There is also an issue of ethics and governance, particularly concerning the possible effects on marine life and the livelihood of the local communities [73,74].

Carbon removal solutions that involve the ocean have great potential, but should be considered with a lot of care, both in terms of environmental and ethical aspects. Achieving the potential of these means will be critical in dealing with the complexities and risks that they entail in fighting climate change.

4.5. Enhanced Weathering

Enhanced weathering is a geoengineering approach used to speed up the natural phenomenon known as mineral weathering, which removes CO_2 from the atmosphere. It is done by sprinkling crushed minerals like basalt on vast stretches of land, and then a reaction between the finished mineral and the CO_2 forms stable carbonates. This method, though still in the experimental phase, has the potential to be used on a large scale to remove carbon. Enhanced weathering is the concept that is under research and pilot projects to test. Early research has shown that when applied at a large scale, this technology would be able to capture up to 5 Gt of CO_2 in a single year by 2050. This ability throws light on its potential as an instrument for reducing climate change, but there is still a lot to be discovered regarding its practical application.

Long-term carbon storage can be considered as one of the most important benefits of enhanced weathering. The process will entrap carbon over millennia through the conversion of CO_2 to solid minerals, and thus offers a stable sequestration over time. Moreover, the materials to be used in the process of promoting weathering are relatively common and vast, and they can be potentially used in many areas around the world. This availability would help in the mass adoption of this technology in various geographical locations. Nevertheless, there are a number of issues that restrict the usage of enhanced weathering. Grinding of minerals to fine powder and applying it to large areas of land consumes a lot of energy and resources, and thus could be an expensive and energy-consuming process. Additionally, the mining and processing of minerals on a large scale may have adverse environmental effects, such as disturbance of the ecosystem and water issues. The effectiveness of the increased weathering in the long term is dubious, and additional research is necessary in order to clearly comprehend the possible effects and threats [75,76].

The improved weathering is the new solution to the elimination of CO_2, yet its feasibility and scalability should be explored. The issues with its energy requirements, environmental consequences, and long-term efficiency will be a key concern in deciding whether it can contribute to large-scale carbon removal plans around the globe.

4.6. Conclusion: Integrating NETs into Carbon Neutrality Pathways

Negative emission technologies offer critical elements in the process of reaching carbon neutrality as a complementary measure to the reduction of emissions by renewable energy and energy efficiency. Although all of the NETs present a considerable potential to eliminate CO_2 from the atmosphere, most of them have difficulties regarding the cost, scaling, and ecological effects. In order to successfully overcome these issues, a multi-faceted strategy of combining various NETs, as well as policy support, research, and technological innovation, will be required. The combination of NETs with renewable energy technologies, carbon markets, and global climate policies will also be very critical in ensuring that the objectives of carbon neutrality are achieved. As they continue to invest and develop, NETs can have significant roles in combating climate change, as they will provide solutions to compensate for emissions from other sectors that are hard to decarbonize in other ways [77].

5. Integration, Policy, Economics, and Future Outlook

A carbon-neutral international economy will involve incorporating renewable energy technologies, negative emission technologies, and policy frameworks that support it so that the process of decarbonization is sustainable, affordable, and equitable. Carbon neutrality is not a technical problem but a complex phenomenon that includes economic aspects, social acceptance, and regulations. As illustrated in **Table**

3, the cost comparison of carbon-neutral technologies emphasizes the varying costs of renewable energy and carbon removal technologies. In this section, the author investigates the combination of renewable technologies and NETs, their synergies, challenges, and ways of increasing the scale of these solutions. It further talks about the policy landscape, the economics of carbon-neutral pathways, and the future of the decarbonized sustainable world[78,79].

Table 3. Cost Comparisons of Carbon Neutral Technologies.

Technology	LCOE or Cost of CO_2 Removal (USD per ton CO_2eq)	Capital Investment (USD per MW)	Operating Cost (USD per MWh)	Technological Stage
Solar PV	\$30–\$50	\$800,000–\$1,200,000	\$20–\$30	Mature (low cost)
Onshore Wind	\$20–\$40	\$1,000,000–\$1,500,000	\$25–\$35	Mature (low cost)
Biomass with CCS (BECCS)	\$60–\$120	\$1,500,000–\$2,000,000	\$50–\$80	Emerging (high cost)
Direct Air Capture (DAC)	\$100–\$600	\$1,000,000–\$2,000,000	\$400–\$600	Early-stage (very high cost)
Ocean Fertilization	\$20–\$50	N/A	N/A	Experimental (low cost, high risk)

5.1. Integration of Renewable Technologies and Negative Emission Solutions

Renewable energy technologies and NETs should be brought together to achieve a state of carbon neutrality. Although renewable sources of energy, such as solar, wind, and hydropower sources, will be crucial in decarbonizing the power sector, the NETs will be essential in dealing with the remaining emissions that cannot be reduced by the renewable energy sources. As an example, the industries, including heavy industry (steel, cement, chemicals), aviation, and agriculture, are hard to decarbonize fully with the help of renewable energy technologies. This means that carbon capture, utilization, and storage, afforestation and reforestation, soil carbon sequestration, and ocean-based solutions are some of the strategies that should be used to counteract these sectors[1,80].

Hybrid systems can be considered as one of the most promising methods of integrating renewable energy and NETs. As an example, direct air capture systems can be powered by renewable electricity produced using solar or wind to capture CO_2 in the atmosphere. In the same fashion, bioenergy with carbon capture and storage is biomass energy production that incorporates carbon capture technologies, making it possible to produce renewable energy and, at the same time, eliminate CO_2. These technologies should be integrated successfully and well, giving a lot of consideration to the flows of energies, compatibility of the infrastructure, and the technological feasibility. Intermittency issues could be resolved with a combination of renewable energy and NETs, as excess electricity produced by renewable energy in high production periods can be utilized to energize carbon removal systems, and the CO_2 can be captured and stored to be sequestered over a long period[81].

Although these synergies can be a possibility, a number of challenges still exist in the integration of renewable energy and NETs. To start with, both systems are costly in terms of their infrastructure, such as energy storage, grid modifications, and transportation and storage systems for the captured CO_2. Second, the regulatory frameworks should be made to accommodate the mass adoption of these technologies. In addition, the adoption of various technologies could involve significant initial expenditure, and the returns are not guaranteed in the short term, which poses risks to both the investors and the policymakers.

5.2. Policy and Economic Considerations

The use of policy frameworks and economic incentives is important in accelerating the implementation of renewable technologies and NETs. The governmental support, both regulatory and financial, is necessary to innovate, cut down on expenses, and increase the scale of implementation. Carbon neutrality will necessitate a holistic combination of policies in most countries, including carbon pricing, renewable technologies subsidies, and specific incentives for carbon removal activities[2,82]. The main policy measures and economic implications of various carbon-neutral technologies are summarized in **Table 4**, highlighting the importance of policy support in enabling the widespread adoption of renewable technologies and NETs.

Table 4. Policy and Economic Impacts of Carbon-Neutral Pathways.

Technology/ Policy Area	Key Policy Measures	Economic Impact	Social Implications	Time Frame for Implementation
Renewable Energy Subsidies	Tax incentives, feed-in tariffs, and renewable portfolio standards	Lower electricity costs, job creation, and reduced fossil fuel dependence	Energy equity, job creation, and rural development	Short-term (5–10 years)
Carbon Pricing/ Carbon Taxes	Carbon taxes, cap-and-trade systems, carbon credits	Encourages emissions reduction, revenue generation for climate investments	Potential costs for consumers, social equity concerns	Medium-term (10–15 years)
BECCS and CCUS Investment	Research and development subsidies, carbon credits	High initial costs, long-term climate mitigation	Potential displacement of local industries, job creation in tech sectors	Long-term (15–30 years)
Green Hydrogen and Storage	Support for hydrogen infrastructure, subsidies for clean tech	Creation of new industries, energy security, and export potential	Job creation in clean industries, potential energy price increase	Long-term (10–20 years)

Carbon pricing policies, including carbon tax or emissions trading system (ETS), are some of the best policy tools that can be used to encourage emission cuts. With the carbon price, governments can establish market incentives to make industries cut their carbon footprint and use cleaner technologies. Carbon pricing is also a way to give a monetary boost to the development of carbon capture and storage technologies that are critical to achieving net-zero emissions in hard-to-decarbonize industries. Along with carbon pricing, subsidies and tax incentives on renewable energy projects have also been critical in bringing down the cost of solar and wind energy, as well as other renewable energy technologies. Renewable energy has become the cheapest new source of electricity in most parts of the world, and decades of government support have achieved this. Nevertheless, with the cost of renewable energy going down, governments have to make sure that aid is focused on the areas that need it the most, one of which is emerging technologies, energy storage, and grid infrastructure.

The carbon-neutral transition has complicated economic implications. On the one hand, the massive implementation of renewable technologies and NETs opens great prospects for economic growth and job creation, as well as innovation. The renewable energy industry has already provided millions of jobs to people in different parts of the world, and additional investments in clean technologies might result in the establishment of more green jobs. Moreover, switching to a low-carbon economy can contribute to preventing reliance on energy imports and improving energy security, and reducing the general cost of energy production in the long run[83,84].

Nevertheless, the transition is dangerous and problematic as well. Economic shocks may occur in some industries and regions that are highly dependent on fossil fuels, and employees in such industries might also need retraining and facilitation to get new jobs in the clean energy industry. To alleviate such effects, governments need to formulate policies that will cover the social aspects of the transition, such as retraining the population, diversifying their economies regionally, and assisting the affected communities.

5.3. Social Acceptance and Public Engagement

Technological and economic factors will not be the only determinants of the successful implementation of renewable technologies and NETs, which will also require societal involvement and acceptance. Increasing renewable energy projects and carbon removal efforts need to be created with a strong concern for their social and environmental effects. Opposition to large-scale renewable energy projects like wind farms or solar installations by the public may slow down or stop the development, particularly where the local people are not fully involved in the development. The aspect of social acceptance is critical, especially for some NETs, which include big afforestation or reforestation pits or carbon capture plants. These projects can be very demanding in terms of land use and thus can conflict with agricultural, conservation, or urban development requirements. Furthermore, there are certain NETs, including ocean fertilization or direct air capture, that are questioned on the level of possible impact on the environment and their ethical aspects. To gain the overall acceptance of these technologies in society, public trust and open communication are mandatory[85].

The policymakers have to focus on community involvement to encourage people to engage and accept the policies, as well as ensure that the local stakeholders are properly consulted and that the advantages and disadvantages of the renewable energy and carbon removal technologies are clearly and transparently presented. Moreover, the incentives that will encourage individuals and communities to implement low-carbon solutions, including residential solar installations or electric cars, should be developed to make the process of carbon neutrality more rapid.

5.4. Future Outlook: Scaling Up and Technological Innovation

Continued technological innovation and the expansion of current solutions will define the future of carbon neutrality. Although important advances have been achieved in making renewable energy technologies less expensive, more innovation would be necessary in order to achieve these high targets of carbon neutrality proposed by the Paris Agreement. The following technologies: energy storage, smart grids, carbon capture technologies, and green hydrogen production will be instrumental in providing a solution to the existing constraints and promoting the implementation of renewable technologies and NETs at large. Specifically, the invention of new high-power storage systems, including next-generation batteries and long-duration storage systems, will play a critical role in mitigating the intermittency of solar and wind power. Such technologies are going to contribute to the fact that renewable energy can be stored and dispatched when demanded, and the efficient addition of variable energy sources to the grid[15].

On the same note, carbon capture and storage technologies, such as direct air capture and bioenergy with carbon capture and storage, will play a critical role in eliminating CO_2 in the atmosphere and producing a net-zero environment. The development of new materials, more effective capture methods, and cheaper storage options will contribute to the reduction in the price of these technologies, as well as the increased availability and scalability of these technologies. The further perspectives of the carbon-neutral routes also require further cooperation between the governments, the private sector, and the research institutions. International cooperation in knowledge exchange, creation of global standards, and harmonization of policy frameworks will be critical in aiding the rapid pace of the goal of transitioning to a low-carbon economy. Implementation of clean technologies on an international level will entail huge financial investments, public-private ventures, and the creation of international markets for carbon credits, renewable energy certificates, and other incentives.

Carbon neutrality is a multi-dimensional and multi-layered process that needs to include renewable technology, negative emission technology, facilitating policy, and economic structures. Although the shift towards a carbon-neutral economy may be seen as a challenging task, it is also an opportunity to innovate, develop economically, and protect the environment with huge possibilities. It will be the key to the achievement of the global climate goals and the establishment of a sustainable and low-carbon future for the entire world population with the help of the effective integration of renewable energy and NETs that are facilitated by effective policies, involvement of the population, and technological innovations. The future of carbon neutrality will rely on further cooperation among all industries and the desire to create a strong and resilient economy of clean energy[86–88].

6. Conclusion

Carbon neutrality is a course that needs to be implemented immediately in every segment of society. Carbon neutrality is not only a technical issue but a multifaceted process of mass implementation of renewable technologies, creating negative emission technologies, and creating a strong system of policies. As discussed in this review, renewable energy technologies, including solar, wind, bio-energy, hydropower, and geothermal, are the key to a low-carbon future, with solutions that are sustainable and scalable in terms of power energy generation. Simultaneously, negative emission technologies are needed to take care of residual emissions that cannot be completely removed with the help of renewable energy, especially in the hard-to-decarbonize industries, such as heavy industry, agriculture, and long-distance transportation. Although the opportunities of renewable technologies and NETs are enormous, the successful experience of introducing them into current systems has to overcome considerable difficulties. The periodic nature of renewable energy sources, the necessity of large-scale storage of energy, and the creation of carbon-capturing and removal infrastructure are essential challenges to be overcome. In addition to that, the financial, social, and political aspects of the transition cannot be neglected. Aggressive, futuristic policies will be necessary to propel the large-scale adoption of renewables and NETs through strong policies and subsidies on clean technologies and international collaboration in the form of carbon pricing. Besides, the need to engage the populace and make the use of these technologies socially acceptable will be essential to the successful adoption of these technologies. Technological innovation will remain central as we move into the future. This will allow the smooth adoption of renewable energy and carbon capture, and hydrogen generation into the global energy systems with advancement in energy storage, carbon capture, and hydrogen production. Moreover, the further decrease in the price of renewable technologies and the growth of carbon-neutral solutions will become more affordable and accessible, and will speed up the process of the transition to a sustainable global economy.

Conclusively, governments, industries, and communities around the world would have to work in unison in order to achieve the carbon neutrality path. Through the maximum utilization of renewable technologies and NETs, combined with both proper policy frameworks and international cooperation, we will be able to map the path toward our carbon-neutral future. The transition is not only a requirement in the reduction of the effects of climate change but also in the provision of a sustainable, resilient, and successful world for future generations. It is time to get down to business and find the solutions.

Funding

This work received no external funding.

Institutional Review Board Statement

Not applicable.

Informed Consent Statement

Not applicable.

Data Availability Statement

No new data were created or generated in this study. As this is a review, it is based on data and information from previously published sources, which are cited in the reference list.

Conflicts of Interest

The authors declare no conflict of interest.

References

[1] Chen, L., Msigwa, G., Yang, M., et al., 2022. Strategies to Achieve a Carbon Neutral Society: A Review. Environmental Chemistry Letters. 20(4), 2277–2310. DOI: https://doi.org/10.1007/s10311-022-01435-8

[2] Williams, J.H., Jones, R.A., Haley, B., et al., 2021. Carbon-Neutral Pathways for the United States. AGU Advances. 2(1), e2020AV000284. DOI: https://doi.org/10.1029/2020AV000284

[3] Sharma, S., Khurana, M.K., 2024. An Approach to Carbon Neutrality Addressing Obstacles and Remedies in the Framework of Climate Change. In: de Pablos, P.O. (Ed.). Building Climate Neutral Economies through Digital Business and Green Skills. IGI Global: Hershey, PA, USA. pp. 37–66.

[4] Chen, J.M., 2021. Carbon Neutrality: Toward a Sustainable Future. The Innovation. 2(3), 100127. DOI: https://doi.org/10.1016/j.xinn.2021.100127

[5] Laine, J., Heinonen, J., Junnila, S., 2020. Pathways to Carbon-Neutral Cities Prior to a National Policy. Sustainability. 12(6), 2445. DOI: https://doi.org/10.3390/su12062445

[6] Buettner, S.M., Wang, D., 2022. An Approach to Reducing the Greenhouse Gas Footprint in the Manufacturing Industry: Determinants for an Economic Assessment of Industrial Decarbonisation Measures. Institut für Energieeffizienz in der Produktion: Stuttgart, Germany. Available from: http://nbn-resolving.de/urn:nbn:de:bsz:93-opus-ds-126348

[7] Patt, A.G., 2015. Transforming Energy: Solving Climate Change with Technology Policy. Cambridge University Press: New York, NY, USA.

[8] Puthalpet, J.R., 2024. Carbon Capture-Utilization and Storage: Climate Change Mitigation. BSP Books: Jaipur, India.

[9] Zou, C., Xiong, B., Xue, H., et al., 2021. The Role of New Energy in Carbon Neutral. Petroleum Exploration and Development. 48(2), 480–491. DOI: https://doi.org/10.1016/S1876-3804(21)60039-3

[10] Ng, W., Low, C., Putra, Z., et al., 2020. Ranking Negative Emissions Technologies under Uncertainty. Heliyon. 6(12), e05730. DOI: https://doi.org/10.1016/j.heliyon.2020.e05730

[11] Yang, S., Yang, D., Shi, W., et al., 2023. Global Evaluation of Carbon Neutrality and Peak Carbon Dioxide Emissions: Current Challenges and Future Outlook. Environmental Science and Pollution Research. 30(34), 81725–81744. DOI: https://doi.org/10.1007/s11356-022-19753-9

[12] Zeng, N., Jiang, K., Han, P., et al., 2022. The Chinese Carbon-Neutral Goal: Challenges and Prospects. Advances in Atmospheric Sciences. 39(8), 1229–1238. DOI: https://doi.org/10.1007/s00376-021-1093-8

[13] Aziz, S., Ahmed, I., Khan, K., et al., 2024. Emerging Trends and Approaches for Designing Net-Zero Low-Carbon Integrated Energy Networks: A Review of Current Practices. Arabian Journal for Science and Engineering. 49(5), 6163–6185. DOI: https://doi.org/10.1007/s13369-023-08380-8

[14] Feng, H., 2022. The Impact of Renewable Energy on Carbon Neutrality for the Sustainable Environment: Role of Green Finance and Technology Innovations. Frontiers in Environmental Science. 10, 924857. DOI: https://doi.org/10.3389/fenvs.2022.924857

[15] Wang, F., Harindintwali, J.D., Yuan, Z., et al., 2021. Technologies and Perspectives for Achieving Carbon Neutrality. The Innovation. 2(4), 100180. DOI: https://doi.org/10.1016/j.xinn.2021.100180

[16] Al Khaffaf, I., Tamimi, A., Ahmed, V., 2024. Pathways to Carbon Neutrality: A Review of Strategies and Technologies across Sectors. Energies. 17(23), 6129. DOI: https://doi.org/10.3390/en17236129

[17] Mathur, M., Awasthi, S., 2016. Carbon Neutral Village/Cluster: A Conceptual Framework for Envisioning. Current Science. 110(7), 1208–1215. DOI: https://doi.org/10.18520/cs/v110/i7/1208-1215

[18] He, B., Yuan, X., Qian, S., et al., 2023. Carbon Neutrality: A Review. Journal of Computing and Information Science in Engineering. 23(6), 060809. DOI: https://doi.org/10.1115/1.4062693

[19] Tan, Q., Li, X., Liang, Y., 2023. Risks, Challenges and Strategies of Power Systems against the Background of Carbon Neutrality. Clean Energy. 7(4), 767–782. DOI: https://doi.org/10.1093/ce/zkad037

[20] Daehn, K., Basuhi, R., Gregory, J., et al., 2022. Innovations to Decarbonize Materials Industries. Nature Reviews Materials. 7(4), 275–294. DOI: https://doi.org/10.1038/s41578-021-00376-y

[21] Habert, G., Miller, S.A., John, V.M., et al., 2020. Environmental Impacts and Decarbonization Strategies in the Cement and Concrete Industries. Nature Reviews Earth & Environment. 1(11), 559–573. DOI: https://doi.org/10.1038/s43017-020-0093-3

[22] Allen, M.R., de Coninck, H., Dube, O.P., et al., 2019. Technical Summary. In: Masson-Delmotte, V., Zhai, P., Pörtner, H.-O., et al. (Eds.). Global Warming of 1.5 °C: An IPCC Special Report on the Impacts of Global Warming of 1.5 °C above Pre-Industrial Levels and Related Global Greenhouse Gas Emission Pathways, in the Context of Strengthening the Global Response to the Threat of Climate Change, Sustainable Development, and Efforts to Eradicate Poverty. Intergovernmental Panel on Climate Change (IPCC): Geneva, Switzerland. Available from: https://www.ipcc.ch/site/assets/uploads/sites/2/2019/05/SR15_TS_High_Res.pdf

[23] Warren, R., Andrews, O., Brown, S., et al., 2022. Quantifying Risks Avoided by Limiting Global Warming to 1.5 or 2 °C above Pre-Industrial Levels. Climatic Change. 172(3), 39. DOI: https://doi.org/10.1007/s10584-022-03378-9

[24] Ekardt, F., Wieding, J., Zorn, A., 2018. Paris Agreement, Precautionary Principle and Human Rights: Zero Emissions in Two Decades? Sustainability. 10(8), 2812. DOI: https://doi.org/10.3390/su10082812

[25] Rogelj, J., den Elzen, M., Höhne, N., et al., 2016. Paris Agreement Climate Proposals Need a Boost to Keep Warming Well below 2 °C. Nature. 534(7609), 631–639. DOI: https://doi.org/10.1038/nature18307

[26] Seneviratne, S.I., Rogelj, J., Séférian, R., et al., 2018. The Many Possible Climates from the Paris Agreement's Aim of 1.5 °C Warming. Nature. 558(7708), 41–49. DOI: https://doi.org/10.1038/s41586-018-0181-4

[27] Rockström, J., Gaffney, O., Rogelj, J., et al., 2017. A Roadmap for Rapid Decarbonization. Science. 355(6331), 1269–1271. DOI: https://doi.org/10.1126/science.aah3443

[28] Thiel, G.P., Stark, A.K., 2021. To Decarbonize Industry, We Must Decarbonize Heat. Joule. 5(3), 531–550. DOI: https://doi.org/10.1016/j.joule.2020.12.007

[29] Tian, X., An, C., Chen, Z., 2023. The Role of Clean Energy in Achieving Decarbonization of Electricity Generation, Transportation, and Heating Sectors by 2050: A Meta-Analysis Review. Renewable and Sustainable Energy Reviews. 182, 113404. DOI: https://doi.org/10.1016/j.rser.2023.113404

[30] Zou, C., Xue, H., Xiong, B., et al., 2021. Connotation, Innovation and Vision of "Carbon Neutrality". Natural Gas Industry B. 8(5), 523–537. DOI: https://doi.org/10.1016/j.ngib.2021.08.009

[31] Almena-Ruiz, A., Sparks, J., Thornley, P., et al., 2021. Opportunities and Challenges for Bioenergy with Carbon Capture and Storage (BECCS) Systems Supporting Net-Zero Emission Targets. Available from: https://publications.aston.ac.uk/id/eprint/43231/1/BECCS_Briefing_note_final_clean.pdf (cited 14 December 2025).

[32] Filonchyk, M., Peterson, M.P., Zhang, L., et al., 2024. Greenhouse Gas Emissions and Global Climate Change: Examining the Influence of CO_2, CH_4, and N_2O. Science of the Total Environment. 935, 173359. DOI: https://doi.org/10.1016/j.scitotenv.2024.173359

[33] Ishaq, H., Crawford, C., 2025. Negative Emission Technologies: A Way Forward? RSC Sustainability. 3(9), 3652–3680. DOI: https://doi.org/10.1039/D5SU00132A

[34] Yao, L., Tan, S., Xu, Z., 2023. Towards Carbon

Neutrality: What Has Been Done and What Needs to Be Done for Carbon Emission Reduction? Environmental Science and Pollution Research. 30(8), 20570–20589. DOI: https://doi.org/10.1007/s11356-022-23594-3

[35] Lund, H., Mathiesen, B.V., 2012. The Role of Carbon Capture and Storage in a Future Sustainable Energy System. Energy. 44(1), 469–476. DOI: https://doi.org/10.1016/j.energy.2012.06.001

[36] Sayed, E.T., Olabi, A.G., Alami, A.H., et al., 2023. Renewable Energy and Energy Storage Systems. Energies. 16(3), 1415. DOI: https://doi.org/10.3390/en16031415

[37] Viebahn, P., Nitsch, J., Fischedick, M., et al., 2007. Comparison of Carbon Capture and Storage with Renewable Energy Technologies Regarding Structural, Economic, and Ecological Aspects in Germany. International Journal of Greenhouse Gas Control. 1(1), 121–133. DOI: https://doi.org/10.1016/S1750-5836(07)00024-2

[38] Ashraf, A., Sagheer, M., 2025. Renewable Energy Capacity and Technological Innovations: A Review of Global Trends and Future Directions. Environmental Progress & Sustainable Energy. 44(6), e70071. DOI: https://doi.org/10.1002/ep.70071

[39] Izunwa, M.O., Michael, O.D., Ovwoshokpite, O.D., et al., 2025. Climate Change and Energy Transition in the Global Economy: A Legal Examination of the Shift from Oil Dependency in Nigeria to a Diversified Energy Mix. African Journal of Law and Human Rights. 9(2). Available from: https://journals.ezenwaohaetorc.org/index.php/AJLHR/article/view/3415/0

[40] Lopez, A., Zuckerman, G.R., Pinchuk, P., et al., 2025. Renewable Energy Technical Potential and Supply Curves for the Contiguous United States: 2024 Edition. National Renewable Energy Laboratory: Golden, CO, USA.

[41] Valavanidis, A., 2024. Global Electricity Generation from Renewable Sources. Available from: https://www.researchgate.net/publication/378078144_Global_Electricity_Generation_from_Renewable_Sources_Renewables_are_expected_to_account_for_almost_half_of_the_world's_electricity_generation_by_2026 (cited 14 December 2025).

[42] Hasanuzzaman, M., Zubir, U.S., Ilham, N.I., et al., 2017. Global Electricity Demand, Generation, Grid System, and Renewable Energy Policies: A Review. Wiley Interdisciplinary Reviews: Energy and Environment. 6(3), e222. DOI: https://doi.org/10.1002/wene.222

[43] Jacobson, M.Z., Delucchi, M.A., Bazouin, G., et al., 2015. 100% Clean and Renewable Wind, Water, and Sunlight (WWS) All-Sector Energy Roadmaps for the 50 United States. Energy & Environmental Science. 8(7), 2093–2117. DOI: https://doi.org/10.1039/C5EE01283J

[44] Nazar, A., Anwer, N., 2025. Global Penetration and Recent Developments in Semiconductor Devices for Solar Harvesting: A Review. In: Kuchhal, P., Kumar, D., Pachauri, R.K. (Eds.). Revolutionizing Solar Energy Harvesting: Advanced Semiconductor Devices and Technology with Artificial Intelligence and Machine Learning Integration. CRC Press: Boca Raton, FL, USA. pp. 63–92. DOI: https://doi.org/10.1201/9781003515784-3

[45] Pavlović, T., Milosavljević, D., Radonjić, I., et al., 2013. Possibility of Electricity Generation Using PV Solar Plants in Serbia. Renewable and Sustainable Energy Reviews. 20, 201–218. DOI: https://doi.org/10.1016/j.rser.2012.12.003

[46] Hayat, M.B., Ali, D., Monyake, K.C., et al., 2019. Solar Energy—A Look into Power Generation, Challenges, and a Solar-Powered Future. International Journal of Energy Research. 43(3), 1049–1067. DOI: https://doi.org/10.1002/er.4252

[47] Ramakrishna, Y., 2024. Future Innovations in Photovoltaic Technology: Shaping Solar Energy. Indian Journal of Renewable Energy. 1(3), 17–20.

[48] Solangi, K., Islam, M., Saidur, R., et al., 2011. A Review on Global Solar Energy Policy. Renewable and Sustainable Energy Reviews. 15(4), 2149–2163. DOI: https://doi.org/10.1016/j.rser.2011.01.007

[49] Aswal, D., Chandra, A., 2024. Key Drivers for Achieving India's 100 GW Nuclear Power Ambition. Current Science. 127(4), 393.

[50] Nassar, Y., Khaleel, M., 2024. Sustainable Development and the Surge in Electricity Demand across Emerging Economies. International Journal of Electrical Engineering and Sustainability. 2(1), 51–60.

[51] Vinay, M.L., 2025. Realizing Rooftop Photovoltaics for China's Carbon Neutrality Goals. Nature Reviews Electrical Engineering. 2, 519. DOI: https://doi.org/10.1038/s44287-025-00176-6

[52] Fernández-Arias, P., Antón-Sancho, Á., Lampropoulos, G., et al., 2024. On Green Hydrogen Generation Technologies: A Bibliometric Review. Applied Sciences. 14(6), 2524. DOI: https://doi.org/10.3390/app14062524

[53] Jung, C., Schindler, D., 2025. Global Future Onshore Wind Energy Droughts Intensify under Climate Change. Journal of Cleaner Production. 523, 146391. DOI: https://doi.org/10.1016/j.jclepro.2025.146391

[54] Palm, S.A., 2025. Managing Renewable Energy Production across the African-European Continents [Master's Thesis]. Royal Institute of Technology (KTH): Stockholm, Sweden. Available from: https://kth.diva-portal.org/smash/record.jsf?pid=diva2%3A1949027&dswid=-8112

[55] Motola, V., Rejtharova, J., Scarlat, N., et al., 2023. Clean Energy Technology Observatory: Advanced

Biofuels in the European Union—2024 Status Report on Technology Development, Trends, Value Chains and Markets. Publications Office of the European Union: Luxembourg, Luxembourg. Available from: https://publications.jrc.ec.europa.eu/repository/handle/JRC139335

[56] Song, M., Wang, S., 2025. Biomass Power Generation. In: Feng, Y., Li, Q., Song, M., et al. (Eds.). Overview of China's Non-Fossil Fuel Power Generation. Springer: Singapore. pp. 271–310.

[57] Field, C.B., Campbell, J.E., Lobell, D.B., 2008. Biomass Energy: The Scale of the Potential Resource. Trends in Ecology & Evolution. 23(2), 65–72. DOI: https://doi.org/10.1016/j.tree.2007.12.001

[58] Gutiérrez-Negrín, L.C., 2024. Evolution of Worldwide Geothermal Power 2020–2023. Geothermal Energy. 12(1), 14. DOI: https://doi.org/10.1186/s40517-024-00294-w

[59] Yüksel, I., 2010. Hydropower for Sustainable Water and Energy Development. Renewable and Sustainable Energy Reviews. 14(1), 462–469. DOI: https://doi.org/10.1016/j.rser.2009.07.025

[60] Vechkinzova, E., Steblyakova, L.P., Roslyakova, N., et al., 2022. Prospects for the Development of Hydrogen Energy: Overview of Global Trends and the Russian Market State. Energies. 15(22), 8503. DOI: https://doi.org/10.3390/en15228503

[61] Ammar, M., Oyewale, B.O., Elseragy, A., et al., 2025. A Global Review of Blue and Green Hydrogen Fuel Production Technologies, Trends and Future Outlook to 2050. Fuels. 6(4), 88. DOI: https://doi.org/10.3390/fuels6040088

[62] Benbouzid, M., Bouhachlaf, L., Labjar, N., et al., 2025. Global Journey of Green Hydrogen: Opportunities and Challenges. In: Labjar, N., EL Hajjaji, S., Verma, C., et al. (Eds.). Green Hydrogen. Scrivener Publishing LLC: Beverly, MA, USA. pp. 337–371.

[63] National Academies of Sciences, Engineering, and Medicine, 2019. Negative Emissions Technologies and Reliable Sequestration: A Research Agenda 2019. The National Academies Press: Washington, DC, USA. DOI: https://doi.org/10.17226/25259

[64] Dziejarski, B., Krzyżyńska, R., Andersson, K., 2023. Current Status of Carbon Capture, Utilization, and Storage Technologies in the Global Economy: A Survey of Technical Assessment. Fuel. 342, 127776. DOI: https://doi.org/10.1016/j.fuel.2023.127776

[65] International Renewable Energy Agency, 2019. Global Energy Transformation: A Roadmap to 2050. International Renewable Energy Agency: Abu Dhabi, United Arab Emirates. Available from: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2019/Apr/IRENA_Global_Energy_Transformation_2019.pdf

[66] Cavanagh, A.J., Lockwood, T., 2025. Carbon Capture & Storage 2030: As the Market Takes Shape, Can Europe's CO_2 Storage Projects Meet Growing Demand? International Journal of Greenhouse Gas Control. 148, 104505. DOI: https://doi.org/10.1016/j.ijggc.2025.104505

[67] Parisi, P., Arca, S., Ciulla, M., et al., 2024. Toward 2050: Critical Analysis of Energy and Economic Requirements of Carbon Capture and Storage in Post-Combustion Capture. In Proceedings of the SPE Europe Energy Conference and Exhibition, Turin, Italy, 26–28 June 2024. DOI: https://doi.org/10.2118/220020-MS

[68] Storrs, K.D.P., Lyhne, I., Drustrup, R., 2023. A Comprehensive Framework for Feasibility of CCUS Deployment: A Meta-Review of Literature on Factors Impacting CCUS Deployment. International Journal of Greenhouse Gas Control. 125, 103878. DOI: https://doi.org/10.1016/j.ijggc.2023.103878

[69] Chan, S., Pauw, P., 2014. A Global Framework for Climate Action (GFCA): Orchestrating Non-State and Subnational Initiatives for More Effective Global Climate Governance. Available from: https://www.idos-research.de/uploads/media/DP_34.2014.pdf (cited 14 December 2025).

[70] Sedjo, R.A., Solomon, A.M., 2016. Climate and Forests. In: Rosenberg, N.J., Easterling, W.E., Crosson, P.R., et al. (Eds.). Greenhouse Warming. Routledge: London, UK. pp. 105–118.

[71] He, K., Huo, H., Zhang, Q., et al., 2005. Oil Consumption and CO_2 Emissions in China's Road Transport: Current Status, Future Trends, and Policy Implications. Energy Policy. 33(12), 1499–1507. DOI: https://doi.org/10.1016/j.enpol.2004.01.007

[72] Srivastava, P., Kumar, A., Behera, S.K., et al., 2012. Soil Carbon Sequestration: An Innovative Strategy for Reducing Atmospheric Carbon Dioxide Concentration. Biodiversity and Conservation. 21(5), 1343–1358. DOI: https://doi.org/10.1007/s10531-012-0229-3

[73] De Pryck, K., Boettcher, M., 2024. The Rise, Fall and Rebirth of Ocean Carbon Sequestration as a Climate "Solution". Global Environmental Change. 85, 102820. DOI: https://doi.org/10.1016/j.gloenvcha.2024.102820

[74] Quintana-Alcantara, C.E., 2014. Carbon Sequestration in Tidal Salt Marshes and Mangrove Ecosystems [Master's Thesis]. University of San Francisco: San Francisco, CA, USA. Available from: https://repository.usfca.edu/cgi/viewcontent.cgi?article=1016&context=capstone

[75] Hartmann, J., West, A.J., Renforth, P., et al., 2013. Enhanced Chemical Weathering as a Geoengineering Strategy to Reduce Atmospheric Carbon Dioxide, Supply Nutrients, and Mitigate Ocean Acidification. Reviews of Geophysics. 51(2), 113–149. DOI:

https://doi.org/10.1002/rog.20004

[76] Kelemen, P., Benson, S.M., Pilorgé, H., et al., 2019. An Overview of the Status and Challenges of CO_2 Storage in Minerals and Geological Formations. Frontiers in Climate. 1, 9. DOI: https://doi.org/10.3389/fclim.2019.00009

[77] Prabhakar, S., Bandyopadhyay, S., 2023. Optimum Integration of Negative Emission Technologies for Carbon-Constrained Energy Sector Planning. Journal of Cleaner Production. 411, 137302. DOI: https://doi.org/10.1016/j.jclepro.2023.137302

[78] Ehlig-Economides, C., de Guzman, N., 2020. Cost Comparison between Carbon Neutral Fuel and Alternative Low Carbon Energy Options. In Proceedings of the SPE Annual Technical Conference and Exhibition, Online, 27–29 October 2020. DOI: https://doi.org/10.2118/201613-MS

[79] Wang, Z., Sun, Y., Kong, H., et al., 2025. An In-Depth Review of Key Technologies and Pathways to Carbon Neutrality: Classification and Assessment of Decarbonization Technologies. Carbon Neutrality. 4(1), 15. DOI: https://doi.org/10.1007/s43979-025-00116-x

[80] Poullikkas, A., Kourtis, G., Hadjipaschalis, I., 2013. A Review of Net Metering Mechanism for Electricity Renewable Energy Sources. International Journal of Energy and Environment. 4(6), 975–1002.

[81] Yu, Z., Kamran, H.W., Amin, A., et al., 2023. Sustainable Synergy via Clean Energy Technologies and Efficiency Dynamics. Renewable and Sustainable Energy Reviews. 187, 113744. DOI: https://doi.org/10.1016/j.rser.2023.113744

[82] Lehmann, P., Söderholm, P., 2018. Can Technology-Specific Deployment Policies Be Cost-Effective? The Case of Renewable Energy Support Schemes. Environmental and Resource Economics. 71(2), 475–505. DOI: https://doi.org/10.1007/s10640-017-0169-9

[83] Asibor, J.O., Clough, P.T., Nabavi, S.A., et al., 2022. A Country-Level Assessment of the Deployment Potential of Greenhouse Gas Removal Technologies. Journal of Environmental Management. 323, 116211. DOI: https://doi.org/10.1016/j.jenvman.2022.116211

[84] Narassimhan, E., Gallagher, K.S., Koester, S., et al., 2018. Carbon Pricing in Practice: A Review of Existing Emissions Trading Systems. Climate Policy. 18(8), 967–991. DOI: https://doi.org/10.1080/14693062.2018.1467827

[85] Huijts, N.M.A., Molin, E.J.E., Steg, L., 2012. Psychological Factors Influencing Sustainable Energy Technology Acceptance: A Review-Based Comprehensive Framework. Renewable and Sustainable Energy Reviews. 16(1), 525–531. DOI: https://doi.org/10.1016/j.rser.2011.08.018

[86] Alizadeh, S.M., Khalili, Y., Ahmadi, M., 2024. Comprehensive Review of Carbon Capture and Storage Integration in Hydrogen Production: Opportunities, Challenges, and Future Perspectives. Energies. 17(21), 5330. DOI: https://doi.org/10.3390/en17215330

[87] Gabrielli, P., Gazzani, M., Mazzotti, M., 2020. The Role of Carbon Capture and Utilization, Carbon Capture and Storage, and Biomass to Enable a Net-Zero-CO_2 Emissions Chemical Industry. Industrial & Engineering Chemistry Research. 59(15), 7033–7045. DOI: https://doi.org/10.1021/acs.iecr.9b06579

[88] Shu, D.Y., Deutz, S., Winter, B.A., et al., 2023. The Role of Carbon Capture and Storage to Achieve Net-Zero Energy Systems: Trade-Offs between Economics and the Environment. Renewable and Sustainable Energy Reviews. 178, 113246. DOI: https://doi.org/10.1016/j.rser.2023.113246