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Review

Carbon Footprint Reduction and Climate Change Mitigation: A Review of the Approaches, Technologies, and Implementation Challenges

Nikolay V. Lobus [1,*], Maria A. Knyazeva [2], Anna F. Popova [2] and Maxim S. Kulikovskiy [1]

[1] Timiryazev Institute of Plant Physiology, Russian Academy of Sciences, 35 Botanicheskaya St., 127276 Moscow, Russia
[2] Murmansk Arctic University, 16 Kapitana Egorova St., 183038 Murmansk, Russia
* Correspondence: lobus.nikolay@gmail.com

Abstract: Since the Industrial Revolution, human economic activity and the global development of society in general have been heavily dependent on the exploitation of natural resources. The use of fossil fuels, deforestation, the drainage of wetlands, the transformation of coastal marine ecosystems, unsustainable land use, and many other unbalanced processes of human activity have led to an increase both in the anthropogenic emissions of climate-active gases and in their concentration in the atmosphere. It is believed that over the past ~150 years these phenomena have contributed to an increase in the global average temperature in the near-surface layer of the atmosphere by ~1 °C. Currently, the most pressing tasks facing states and scientific and civil societies are to reduce anthropogenic CO_2 emissions and to limit the global air temperature increase. In this regard, there is an urgent need to change existing production systems in order to reduce greenhouse gas emissions and to sequester them. In this review, we consider up-to-date scientific approaches and innovative technologies, which may help in developing roadmaps to reduce the emissions of climate-active gases, control rising temperatures, decarbonize economies, and promote the sustainable development of society in general.

Keywords: renewable energy sources; carbon sequestration; carbon sink; CCUS technologies; green carbon; blue carbon

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1. Introduction

Large amounts of greenhouse (climate-active) gases are released into the atmosphere as global industrialization and the overexploitation of non-renewable energy sources develop. This results in a global temperature increase and causes a number of issues related to environmental degradation [1,2]. According to numerous studies, the global average concentration of carbon dioxide (CO_2) in the atmosphere has increased significantly from ~285 to ~420 ppm from the pre-industrial period (~1850) to the present [3]. It is now believed that anthropogenic increases in CO_2 concentrations have contributed to an increase in the global average temperature by 0.97–1.21 °C in the near-surface atmosphere layer over this period [4]. In addition, researchers predict that global greenhouse gas emissions will increase by ~50% by 2050, mainly due to the continued combustion of fossil hydrocarbons [5]. Concentrations of greenhouse gases in the air, global ground level, and ocean surface temperatures, will continue to rise without effective measures or technologies to reduce and/or control CO_2 emissions. Anthropogenic activities associated with the release of climate-active gases have already caused significant social, economic, and environmental damage to habitats, including the extinction of some plant and animal species, a loss of biodiversity, droughts, floods, forest fires, the acidification of land and ocean surface waters, the melting of glaciers on poles, and sea level rise [6–8].

In response to the global rise in atmospheric greenhouse gas concentrations and air temperature, 197 parties of the United Nations Framework Convention on Climate Change unanimously adopted post-2020 global climate action plans on December 12, 2015 at the Paris Conference, the so-called Paris Agreement [9,10]. In this document, each country agreed to limit the increase in global temperature to less than 2 °C and to take measures to limit it to less than 1.5 °C [11]. In February 2021, 124 countries around the world have declared their intention to become carbon neutral and achieve net-zero carbon emissions by 2050 or 2060. A complete phase-out of fossil fuels, the main source of anthropogenic CO_2, is unlikely in the next decade. However, there is no doubt that the given decarbonization trend will continue and that more and more players in the global energy market will be included in this process [12]. In order to achieve the goals of the Paris Agreement and to support sustainable development, it is necessary both to reduce CO_2 emissions and to remove CO_2 from the atmosphere, so that zero or negative carbon emissions, through various social, economic, environmental and technological measures, can be achieved [13].

The reduction of CO_2 emissions cannot be achieved through the implementing of only one measure. Instead, multiple strategies to reduce carbon emissions are required that must work synergistically [14,15]. However, emissions reduction itself is not always possible or practical in all sectors of human economic activity. Therefore, it is also important to pay attention to the development of both biotechnologies for CO_2 sequestration from gas mixtures formed because of human economic activities and technologies for capturing and removing the CO_2 already released into the atmosphere. It is necessary to actively develop and promote approaches to carbon removal and sequestration in terrestrial and marine ecosystems to achieve zero carbon emissions and to pursue sustainable development [16–19].

2. Renewable Energy Sources and Carbon-Free Energy Carriers with Regards to Global Energy Transition

Experts say that it is critical to reduce carbon emissions from fossil fuels while investing in carbon sequestration technologies both in terrestrial and marine ecosystems in order to achieve carbon neutrality and to ensure sustainable human development. According to the International Energy Agency [20], the extraction and development of new fossil fuels such as oil, natural gas, and coal should have ceased as early as 2021 to achieve carbon neutrality by 2050. In this regard, investment in the research and deployment of carbon-free renewable energy sources is key to bridging the gap between the conventional rhetoric of net-zero CO_2 emissions and our current reality [21,22].

The renewable energy approach to emission reduction and industrial development is scientifically sound and is based on years of research and data analysis [23]. The optimal use of these resources is the basis for sustainable development: they reduce our impact on the environment, produce a minimum amount of secondary waste, and meet the current and future socio-economic needs of society [22,24]. In contrast to conditional energy sources, renewable ones are replenished naturally and will not run out. These include hydropower, solar and wind energy, bioenergy, geothermal energy, and ocean energy, as well as nuclear and hydrogen fuel [25].

It should be noted that over the past ~15 years there have been significant changes in the global structure of power generation [26]. The share of renewable energy sources meeting the global energy demand has increased from 14% in the 2000s [27] to 40% in 2022 [28]. Currently, renewable energy's capacity is more than 3300 GW (Figure 1). The world has added almost 295 GW of renewables to power generation, largely due to the growth of solar and wind power. Over the past 10 years, their total capacity has shown a record increase from 441 GW to 1952 GW. At the end of 2022, solar and wind power accounted for ~55% of the total renewable energy capacity [28].

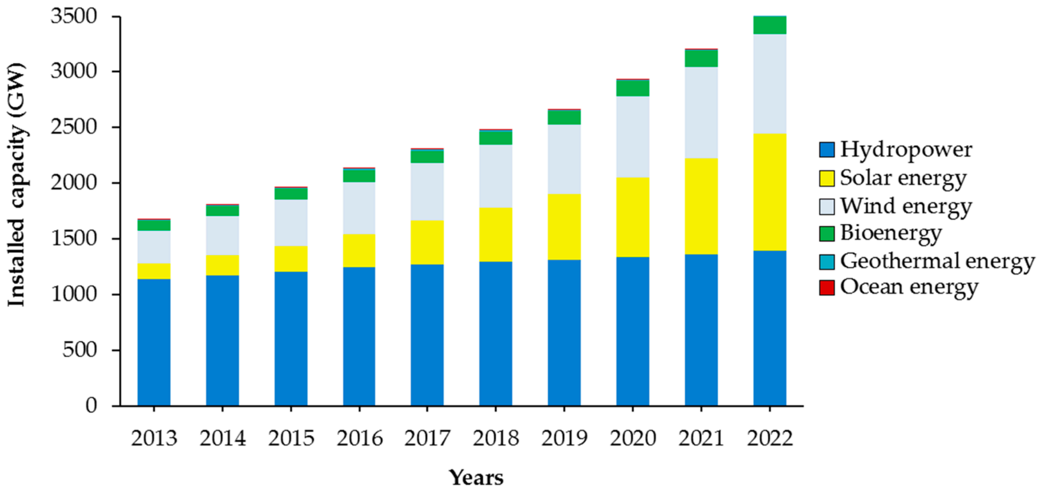

Figure 1. Dynamics of changes in the capacity of renewable energy sources in the world [28].

Second, renewable energy may improve the availability of energy resources in sparsely populated and remote areas. This helps reduce the energy gap between different social groups, increasing social equity, and promoting sustainable development. In addition, the use of renewable energy sources reduces the risk of disasters and man-made accidents associated with the production, transportation, and use of fossil fuels [29,30]. Third, investing in renewable energy boosts economic growth and new jobs. For example, the renewable energy sector provides more than 11 million jobs worldwide, according to a report from the International Renewable Energy Agency (IRENA). This decreases unemployment and increases the living standards of the population [26,31,32].

2.1. Hydropower

Hydropower is one of the most common forms of renewable energy, in which the energy of flowing or falling water is used to produce electricity. This method of energy generation has a long history, so the technologies are technologically mature and are actively used worldwide [33]. The benefits of hydropower are significant. Firstly, it is a clean and environmentally friendly source of energy. Hydropower is expected to play an important role in the deep decarbonization of the energy sector. It should be noted that the capacity of hydropower has not changed much over the past 10 years. According to the IRENA, its capacity increased from 1137 GW in 2013 to 1363 GW in 2022. Nevertheless, the share of hydropower in the composition of renewable energy's capacity decreased from 67% to 40%, respectively [28]. This happened due to a significant increase in the share of solar and wind energy (Figure 1).

However, at present, the idea that hydropower is a completely carbon-free alternative to hydrocarbon energy, on a par with solar and wind, is controversial [34]. Secondly, hydropower is highly efficient. Hydraulic structures, such as hydroelectric power stations and small hydropower, are capable of converting the kinetic energy of a water flow into electrical energy with high efficiency. Thanks to this, hydropower is one of the most efficient ways to produce electricity of all renewable resources [35]. In addition, hydropower has the ability to store energy. With compulsory reservoirs or dams, hydroelectric power plants may store energy during periods of low demand and use it during periods of peak demand. This is important to ensure the stability of the electrical grid and energy supply in case of surges in demand [36]. The operation of reservoirs created during the construction of hydroelectric power plants is important and they are actively used not only for generating electricity, but also for solving other socio-economic problems; for example, to combat floods and drought, as a supply of technical and drinking water, for the irrigation of agricultural land, navigation, breeding, and the extraction of biological resources [37].

Hydroelectric power generation does not produce greenhouse gases and is therefore generally referred to as a green energy source. However, hydropower has some limitations as well, and its dependence on the availability of water resources is one of them. The development and construction of hydropower structures requires the presence of large rivers and the creation of reservoirs, which limits their use geographically and their available resources [38]. Large hydropower projects may also cause social and environmental problems. For example, the construction of dams may displace people and change river ecosystems. The need to maintain ecological balance and minimize negative environmental consequences is becoming increasingly relevant when planning and operating hydropower projects [39].

Generally, hydropower plays an important role in the global energy climate by providing stable and environmentally friendly electricity production. However, despite its many benefits, hydropower is also limited by geographic, social, and environmental factors. Understanding these limitations when continuing with the development of new technologies will help to further advance and optimize this important form of renewable energy.

2.2. Solar Energy

Solar energy, as a versatile resource, can be harnessed and converted into various usable forms. One common method is the conversion of solar energy into heat or electricity. Solar thermal systems use sunlight to generate heat, which can be used for heating water or spaces. On the other hand, photovoltaic (PV) systems convert solar energy directly into electricity using photovoltaic cells. Furthermore, solar energy can also be transformed into solar fuels. One prominent example is the process of photosynthesis, where plants and certain microorganisms convert solar energy into chemical energy [40].

Direct solar energy is one of the most significant sources of renewable energy, playing an important role in the worldwide transition to sustainable energy systems. The benefits of using direct solar energy to generate electricity are obvious. First of all, it is an innovative and inexhaustible source based on the use of clean and safe solar energy [15,41]. Solar PV technology has gained wide popularity in the last few years in large-scale power generation, making it a key factor in the power sector around the globe. According to the IRENA, the cumulative global PV installed capacity increased from 714 GW in 2020 to 1047 GW in 2022, revealing a ~46.5% relative growth (Figure 1) [28]. The process of generating electricity from solar radiation does not produce greenhouse gas emissions or other pollutants, ensuring its minimal impact on the environment and protecting human health. The invention of photovoltaic cells using inorganic semiconductors, which convert light energy directly into electrical energy, was the technological basis for the development of solar energy use [42]. The current commercial efficiencies of PV modules are in the range of 5% to 23% depending on the manufacturer, materials, technology type, location, and manufacturing techniques. The low efficiency values underline the need for further improvements to ensure the improved competitiveness of PV technology [43,44].

Solar PV cells can be categorized into three main types, which are commonly known as the first, second, and third generations of solar PV, determined by their technologies and market entry time [45]. The majority of modern solar photovoltaic systems fall under the first generation, utilizing silicon as their semiconductor material. These cells are renowned for their efficiency and durability, making them valuable for residential and commercial applications [40,46]. However, the disadvantage of these technologies is their high cost [44]. The second generation of solar PV cells refers to thin-film solar cells constructed from thin layers of a polycrystalline semiconducting material. These cells are cost-effective and relatively easy to manufacture due to their lower material requirements. They are also known for their flexibility, lightweight nature, and suitability for portable applications. Thin-film solar cells are commonly used in buildings and small PV systems [47]. Their widespread use is limited by their shorter lifetime and/or the use of highly toxic components [46]. Presently, solar PV technologies have made significant advancements, and various types of third-generation solar PV cells are being developed. Nevertheless, these technologies are still primarily in the research and development phase, and their commercial availability is limited [4]. It should be noted that solar photovoltaic cells have been developed whose efficiency reaches 40%. However, their use is limited due to their very high cost and the need to combine them with solar energy tracking systems and cooling devices to achieve high efficiency [48]. A new generation of solar cells may complement traditional systems and serve as an alternative to photovoltaic technologies in many specific industries, since they provide electricity generation, reduce CO_2 emissions effectively, and achieve carbon neutrality targets easily [1].

However, direct solar energy also has some limitations. Firstly, it depends on the availability of solar radiation. This means that electricity production may be inconsistent, ineffective during periods of cloudy weather or nighttime. This issue may be solved by development and the use of efficient energy storage systems [47]. Secondly, the deployment of solar power plants requires significant investment and infrastructure. Installing solar panels, inverters, and energy storage batteries requires specialized technical expertise and may be expensive [49]. Thirdly, the availability of the resources and materials used in the production of solar panels may be limited. For example, rare metals such as cadmium or tellurium are key components in the production of some types of high-efficiency solar cells. Depletion of their supplies could affect the cost, availability, and profitability of these PV systems [50]. Despite this, the development and promotion of direct solar energy technologies continues. Photovoltaic technologies have achieved commercial acceptance, technological maturity, and look forward a leading role in the current energy transition to combat the adverse environmental issues posed by fossil fuel-based power generation [28,45].

2.3. Wind Energy

Wind occurs due to horizontal gradients of atmospheric pressure, which, in turn, are the result of the uneven heating of the Earth's surface by the sun. Wind is a common atmospheric phenomenon and is present everywhere on our planet. However, different wind speeds and numbers of windy days are observed in different regions. Grasslands, deserts, coasts, and islands are rich in wind resources [51]. The use of wind energy is another way to mitigate the effects of climate change. It is based on converting the kinetic energy of moving air into electrical energy using wind generators, which rotate under the wind's influence. Wind energy has a number of advantages that make it an attractive alternative for the energy sector [52]. The current worldwide installed capacity of wind energy has reached ~900 GW, creating significant interest from public and private investment companies in the further development of this sector [28]. Furthermore, over the past ~15 years the cost of wind turbines has decreased by almost 1/3 since 2008–2010. It is anticipated that wind power has the potential to supply 30% of the world's electricity production by 2030, thereby generating 2.4 million job opportunities and decreasing annual CO_2 emissions by over 3.3 billion tons [28,53]. The successes and future prospects in the development of wind energy determine its current identification as one of the most competitive alternative energy sources for the energy transition being carried out by many countries around the world. Wind energy technologies are seen as one of the key tools for achieving carbon neutrality [32,54].

However, despite all the advantages of using wind energy, its development faces some challenges. Noise pollution is one of the main problems that arise when generating electricity from wind power due to the operation of mechanisms and the air's movement through turbine blades [55]. Low-frequency parts of the noise from wind turbines may be felt over long distances and affect nearby residential areas. They may create unpleasant sound vibrations and cause discomfort to people living near the wind farm [56]. High-frequency parts of the noise from wind turbines are usually not audible over long distances, however, they may be perceived as a nuisance by people in close proximity to the turbine. Noise pollution from wind turbines is thus important to consider when developing and operating wind energy projects. Therefore, a more efficient use of wind resources is needed, minimizing their negative impact on the environment and ensuring comfortable living for people near wind power plants [57]. Another concern with using wind energy is the adverse impacts that wind turbines may have on birds due to collisions or habitat destruction, especially if they are located on migration routes or nesting areas [58,59]. It is also necessary to take into account the unstable nature of wind speed, causing certain issues when integrating wind energy into the electrical grid [60]. Meteorological conditions (wind direction, air temperature, pressure, and humidity) affect wind energy production as well [61]. Therefore, estimates of at least future wind speeds are required to integrate wind energy into the electrical grid. This significantly increases the costs of the design and construction of wind power plants, and requires investing in the development of reliable algorithms for predicting the changes in certain environmental parameters [62].

2.4. Bioenergy

The biomass of living organisms, usually plants, is a renewable source of energy. Its application is based on its ability to be used as a solid, liquid, or gaseous fuel for a wide range of applications, including biofuel for transport, power generation, house heating, and cooking [63]. Biomass makes up 70% of all renewable energy sources, and its use provides ~14% of the annual global energy consumed [64].

Today, bioenergy resources are usually divided into two categories. The first, traditional bioenergy, is the main source of energy for more than a third of the world's population. Historically, it has been associated with the combustion of plant materials, wood, and agricultural and livestock waste. Traditional bioenergy poses a major challenge to sustainable development because it is deeply rooted in the daily lives of poor people in developing countries and provides them with vital energy services such as cooking and heating. The need to replace the traditional combustion of plant biomass by small households with cleaner and harmless energy sources higher up the "energy ladder" is long overdue. However, experts admit that this is quite a complex task, since it will require major changes in the technology and infrastructure for supplying the population with fuel, energy and social policies, and may even affect the cultural customs and foundations of populations [65]. The second category is modern bioenergy. It represents the development of technologies for using the biomass of living organisms to produce fuel products with a high added value [66,67]. Various technological processes are used to convert biomass into energy, including thermochemical, chemical, and biochemical conversion methods. Through deep technological processing, biofuel and biogas are produced. Bioethanol and biodiesel are the most common types of biofuels used currently in private, public, and commercial transport. The lignocellulosic extraction cake (biochar), derived from agricultural and forestry waste, is the most common raw material for the production of technical bioethanol and biobutanol [68]. Food-grade bioethanol is typically produced from crops such as corn, sugar cane, or wheat, while biodiesel is derived from vegetable oils or animal fats. The resulting biofuel may be blended with or replace traditional fossil fuels, which reduces overall greenhouse gas emissions [69,70]. Biogas is produced by the anaerobic digestion of organic waste such as sewage, agricultural waste, or food waste. The main component of biogas is methane, which is a valuable source of renewable energy. Biogas may be used for house heating, farming, electricity generation, or as a fuel gas for vehicles [71,72].

Since the 2000s, there has been an urgent need to find alternative resources to replace fossil fuels. Initially, humankind focused on producing biodiesel from crops such as soybean, canola, jatropha, karanja, mahua, palm, and castor oil, which were further classified as first- and second-generation biofuels. However, production from these crops has several limitations, including the need for land for cultivation, irrigation, and their dependence on weather, as well as labor-intensive and time-consuming processes. The entire production process, from cultivation to final biofuel production, is also more expensive than mining fossil fuels [73]. Biofuels may be classified into four generations. First-generation biofuels are produced from edible crops. Second-generation biofuels are produced from a variety of feedstocks, ranging from lignocellulose to municipal solid waste. Third-generation biofuels are currently associated with algal biomass [73]. Technologies for the production of fourth-generation biofuels are currently being actively developed. Their essence lies in the combination of the second- and third-generation approaches with the simultaneous genetic modification of plant objects, which are targeted by metabolic engineering [74]. Next-generation bioenergy, combined with other renewable energy sources, is an important component of a mixed energy portfolio that helps in reducing our emissions of CO_2 and other climate-active gases. The third- and fourth-generation raw materials are a potential sustainable source for future biofuel production and intensive green energy development. However, further detailed studies are necessary to improve the energy efficiency, competitiveness, and profitability of next-generation technologies, as well as to ensure the sustainability of biomass production and use [64].

The electricity generation from most renewable energy sources is intermittent. This is one of the significant factors that prevents the widespread use of alternative energy resources. Developing energy storage technologies is considered to be of the same importance as that of developing energy production technologies for reducing CO_2 emissions and achieving carbon neutrality. These approaches complement each other, so their practical implementation cannot be considered separately when solving the problems of the global energy transition and the final banning of the use of fossil fuels [26,75].

2.5. Geothermal Energy

Geothermal energy is a renewable energy source based on the use of heat stored inside the Earth. Geothermal energy is obtained from hot underground reservoirs or geothermal wells that contain heated water or steam [76,77]. This type of energy does not contain carbon, so its use produces virtually no anthropogenic emissions of greenhouse gases or other pollutants, which helps in reducing our negative impact on both the climate and the environment. This is consistent with combatting climate change and achieving sustainable development goals through global energy transition [78]. Compared to other renewable, carbon-free sources of energy such as solar and wind energy, geothermal energy has a number of advantages. It is characterized by high efficiency and high stability: it does not depend on the season or weather conditions [79]. The efficiency of its use is ~5.2 times higher than that of solar photovoltaic energy and ~3.5 times higher than that of wind energy. Attention must be paid to the safety of geothermal energy and its relatively low operating costs. At present, it is actively used for electricity production, house heating, and hot water supply [80]. Over the past 5 years, geothermal energy production has averaged 13–15 GW per year [28]. The world's total installed capacity is forecasted to be ~19–19.5 GW in the year 2025. Moreover, according to the World Energy Council, the estimated rate of annual compound growth of the geothermal industry from 2015 to 2060 will be around 5.4%, 4.6%, or 3.4%, respectively, under one of three optimistic, basic, or pessimistic scenarios [81].

Although geothermal energy has many benefits, its widespread use has some limitations. Geothermal energy requires hot underground reservoirs or geothermal wells. This means that only some regions have suitable geological conditions for the use of geothermal energy. In some areas, the ability to utilize heat from underground reservoirs may be limited. Some reservoirs may not contain enough hot water or their temperature may not be high enough to be used effectively [76]. Geothermal systems may be expensive to build and operate, especially if deep wells have to be drilled. The costs of drilling wells and installing equipment may be significant, affecting the economic feasibility of the project. Geothermal installations may have an impact on local ecosystems and water resources. The overheating or depletion of underground water reserves may lead to changes in the ecological balance and the availability of water for other purposes. All these limitations do not mean that geothermal energy has no future. It is important to consider these limitations and to develop strategies to eliminate or mitigate them for the successful implementation of geothermal energy projects [77,82].

Overall, geothermal energy represents a significant energy source that combines stability, environmental friendliness, and a wide range of applications. As technology advances and its economic feasibility improves, geothermal energy may have an increasing impact on sustainable energy development and the reduction of anthropogenic CO_2 emissions. In 2018–2022, the global use of geothermal energy reduced annual CO_2 emissions by approximately 300 million tons per year [1].

2.6. Ocean Energy

The use of ocean energy is one of the most promising areas for development in terms of renewable energy technologies [83]. Oceans cover more than 70% of the Earth's surface and have enormous potential for energy production. There are generally five different forms of energy provided by the ocean: tidal energy, wave energy, ocean current energy, thermal energy, and osmotic energy [84]. Tidal energy is one of the most common ways to harness ocean energy, extracting it from the tidal movements resulting from the gravitational interaction of seawater with the Moon or Sun. Tide energy includes the potential energy associated with water levels and the kinetic energy of the tidal current. Tidal energy installations are built at the border between the sea and land, so the use of tidal energy makes it possible to generate electricity both during high and low tides. The potential of tidal energy is estimated at approximately 1200 TW per year, which is a relatively low share of all ocean energy, since there are only a limited number of places where tidal energy may be collected [85,86]. Tidal barrages, used to harvest the potential energy of tides, are technologically mature. However, at present, tidal energy currently accounts for the largest share of the use of ocean energy [87].

Wave energy is the kinetic and potential energy of water waves, which are widespread in the ocean. This mainly comes from the wind, which transfers some of its kinetic energy to the water at the ocean's surface. Worldwide, the wave energy potential is ~29,500 TW per year [32]. Wave energy is considered to be an underappreciated source of renewable energy. Wave energy harvesting technology is less mature than tidal energy technology; currently, a large number of prototypes are being tested for commercialization [88]. Improving energy storage technologies in the future may help in reducing greenhouse gas emissions and achieving carbon neutrality in electricity production [89].

The energy of ocean currents is stored in large circulations of seawater around the world. This is the kinetic energy of the water flow; the supply of this source is very stable, with slight fluctuations [90]. Another example of ocean energy use is thermal energy, which occurs through the heating of the surface water layer due to solar radiation, so that there is a strong difference in this parameter between the surface and deep-water layers of the water. Such temperature differences may be used to generate electricity, mainly based on thermal cycles, and the technology is called Ocean Thermal Energy Conversion. This form of energy is mainly found in tropical regions due to the large difference in temperatures required to increase efficiency. The potential of this form of energy is estimated at 44,000 TW per year [91]. Osmotic energy, also called salinity gradient energy, is the energy that exists between water masses characterized by different salt concentrations. The seawater's salinity is not uniform on a global scale. For example, the salinity gradient forms in estuaries where fresh water meets a salt water mass. The use of such energy depends on highly efficient membranes that are resistant to seawater [92].

However, despite all the potential and benefits of ocean energy harnessing, there are some challenges associated with these technologies. Their economic competitiveness and technological reliability in harsh ocean environments are still the main ones. Tidal and wave energy harvesting technologies are at the commercialization stage. Technologies for harvesting the ocean's current energy, thermal energy, and osmotic energy are still at the research stage at universities and research institutes. Overall, ocean energy represents an innovative and promising approach to renewable energy production. If properly developed and deployed, these technologies may play an important role in diversifying energy sources and reducing our dependence on fossil fuels during the global energy transition. [1,14]. However, it must be recognized that there is currently a huge gap between expectations and reality. According to the IRENA, the power generation at ocean and marine stations is only 0.5 GW per year and has not undergone significant changes in the past 10 years [28].

2.7. Nuclear Energy

Nuclear power is an important constituent of the global energy transition. Its use provides ~40% of the generation of carbon-free electricity with a low content of climate-active gases and prevents ~1.7 Gt of CO_2 emissions being released into the atmosphere globally per annum. Nuclear power is a strategic approach to ensuring national energy security, reducing our dependence on fossil hydrocarbons, and achieving carbon neutrality targets [1].

Today, nuclear energy is generated mainly through nuclear fission, and nuclear fusion technology is at the stage of scientific development and laboratory research. It should be noted that the future development of nuclear fission energy in the long term is uncertain for several reasons: rising costs, problems with the disposal of radioactive spent fuel, and nuclear plant safety. The active development and research of IV-generation nuclear reactors aims to improve their safety, reliability, physical protection, and profitability [1].

However, considering the entire life cycle of nuclear power, including fuel extraction, its enrichment and spent nuclear waste management are extremely demanded. It goes without saying that the total emissions associated with each stage of the process cycle should be minimized to achieve carbon neutrality. This includes implementing efficient and sustainable mining methods, optimizing fuel technologies, and developing advanced waste management strategies. In addition, nuclear power should be considered a complementary element in a diverse energy portfolio that also includes renewable energy sources such as solar and wind power. The combination of these low-carbon and carbon-free energy sources may provide a reliable and balanced electricity supply while reducing greenhouse gas emissions [93].

It is critical to continue research and development to improve the safety, efficiency, and sustainability of nuclear power to harness the potential of nuclear energy to achieve carbon neutrality in full. This includes advances in nuclear reactor technology, research into improved fuel cycles to minimize waste, and strengthened nuclear safeguards and safety measures. Ultimately, nuclear power's role in achieving carbon neutrality depends on responsible and sustainable practices throughout the nuclear fuel cycle and on a well-planned and comprehensive energy strategy that considers a range of low-carbon options [15,94,95].

2.8. Hydrogen Energy

Historically, hydrogen (H_2) has been a technologically necessary raw material for the chemical industry and, currently, its global consumption is >90 Mt per year. Until now, H_2 has been produced almost entirely from fossil fuels, consuming about 6% of the world's natural gas and 2% of the world's coal, and has had a high carbon footprint. This is so-called "gray hydrogen", the production of which results in emissions of about 850–900 Mt CO_2 per year [96,97]. H_2 production from more environmentally friendly sources has been an area of intensive research for the last few years. Progress in the field of energy contributes to the development of innovative technologies that make it possible to use H_2 not only as a raw material, but also as a promising H_2 fuel [98].

It should be noted that hydrogen energy is based on the use of H_2 as an energy carrier. That is, initially the energy must be spent on the production of H_2, which will then be converted back into energy [99]. H_2 production using renewable or carbon-free energy sources has a high likelihood of both technological and economic viability in the near future. This is so-called "green hydrogen". This ensures the development of a low-carbon and carbon-free economy that minimizes anthropogenic impact on the climate. The hydrogen economy enjoys the most political support as a large-scale energy storage solution to maximize the deployment of renewable energy sources and decarbonize energy-intensive industries [100]. The definition of "green hydrogen" is now widely understood as H_2 produced from water electrolysis powered by renewable energy sources. However, other carbon-low energy sources could power electrolysis and produce hydrogen with no CO_2 emissions, e.g., nuclear energy. “Blue” and “turquoise” hydrogen can also be created. In the first option, H_2 is produced by the steam reforming of CH_4, including CO_2 capture and use technologies (see below). In the second option, H_2 is produced from the pyrolysis of CH_4 and solid CO_2 storage (see below) [97].

The created H_2 fuel cells are increasingly used in the automotive and energy industries. This is an electrochemical process converting the chemical energy of H_2 into electrical energy. The developed H_2 burners may be used to produce thermal energy in various technological processes, including in industry, heating, and power supply [101]. The main advantage of H_2 is its absence of CO_2 emissions when used as an energy carrier, since the combustion of H_2 fuel produces water, which can again enter the closed H_2 production cycle [102]. In the medium term, we should expect a manifold increase in demand for H_2 as a fundamentally new energy carrier, and specifically for “carbon-free” hydrogen. Green hydrogen is expected to become the most popular production method and economically competitive with natural gas prices by 2050 [97,100].

However, currently, the use of H_2 energy is related to certain difficulties and challenges. The cost of H_2 production is determined by the energy costs of its production, storage, and transportation. When using H_2 gas as a fuel, the main problem is the availability of H_2 in nature and the need to scale up the inexpensive, environmentally friendly methods of its production [103]. Technologies for hydrogen gas storing and transporting are also challenging, as H_2 requires high pressures or low temperatures to ensure its compactness and safety. It is important to note that the integration of technologies for its production that use renewable energy sources, such as solar or wind energy, is important for the development of green hydrogen. It is absolutely necessary to develop the appropriate infrastructure to effectively use hydrogen energy, which requires significant investment and coordination between different stakeholders [99].

Overall, the use of hydrogen energy may play an important role in reducing our dependence on fossil hydrocarbons and reducing harmful emissions into the atmosphere. However, for its full potential to be realized, further research and development into the storage, distribution, and economic feasibility of using hydrogen in various sectors of the economy must continue. A long-term commitment to the fundamental understanding and development of new technology and infrastructure strategies is strongly required [104].

3. Physicochemical Methods for the Capturing, Separating, Storing, and Using of Anthropogenic CO_2

The capture-and-storage technologies (CCS) and capture-and-use technologies (CCU) of carbon (in the form of CO_2) are key techniques for reducing anthropogenic greenhouse gas emissions and combating climate change [105]. The International Energy Agency (IEA) predicts that reducing emissions cannot be achieved by improving the efficiency of renewable energy use and adjusting the energy mix alone. Without CCS and CCU, the total cost of reducing carbon dioxide emissions will increase by 70% by 2050 [105,106]. The use of CCS and CCU impacts directly on the cost of energy generated and the rate of economic viability (cost to benefit) of such technologies. As the world continues to rely heavily on fossil energy sources, the need for an efficient method of carbon capture, storage, and/or use is critical to achieving carbon neutrality [107].

3.1. CO_2 Capture Technologies

CO_2 capture is the basis of the CCS technology concept, which was first developed in 1977. Depending on the configuration of fossil fuel power plants, the partial pressure of CO_2, and the pressure of the gas stream, there are three approaches by which CO_2 may be captured and sequestered. They are classified as pre-combustion, post-combustion, and oxy-combustion carbon capture technologies [105].

Technologies for separating CO_2 from flue gases, generated by the large-scale combustion of fossil fuels, include physical absorption, chemical absorption, membrane separation, etc. [108].

Due to the large volume of flue gases and their low concentrations of CO_2, the chemical absorption method is the most suitable technology for separating and capturing CO_2 from other combustion gases [105]. This method has certain advantages: the process is easy to control and there is no need to strongly modify the power generation system. However, the current focus in gas separation and CO_2 capture after combustion is on the searching for effective absorbers and optimizing the process to reduce energy costs [109]. A low CO_2 concentration in the resulting flue gas mixture is the main reason for a high energy consumption when separating gases after fuel combustion [105]. Typically, the CO_2 concentration in the exhaust gas of coal-fired power plants is 10−15%, and that of natural gas-fired power plants is even lower (<3−5%), while the volume of these exhaust gases is large. Technologically low concentrations of CO_2 in flue gases predetermine the high final costs of the generated energy [1].

The method used to separate CO_2 before combustion is called pre-combustion. This technology is a promising method for reducing our carbon footprint [110]. During the reforming process, fuel is pre-gasified into synthesis gas (mainly composed of H_2 and CO). Then, CO in the syngas is converted into CO_2 and hydrogen and, afterward, CO_2 is separated from the H_2. Since CO_2 separation occurs before the fuel combustion process, and the fuel gas is not diluted, the CO_2 concentration in the synthesis gas is more than 30% [111]. According to calculations, capturing 90% of CO_2 before combustion reduces the net energy efficiency of the energy production process much less than capturing CO_2 after combustion [112]. However, the further development of advanced technologies for coal gasification and gas turbines running on hydrogen-enriched gas is necessary for fuel pre-combustion [105].

Carbon dioxide capture in the oxy-combustion process is based on technologies for burning fossil fuels in pure O_2, in which nitrogen-free flue gases containing only CO_2 and H_2O are formed. The condensation of flue gases contributes to the production of pure CO_2 (concentration of ~95%) and NO_x gas impurities. The bottleneck in this method is the need to increase the energy efficiency of the fuel combustion system in pure oxygen through the development of advanced and inexpensive technologies for obtaining O_2 from the atmosphere [1,111].

3.2. CO_2 Extraction Technologies

The development of technologies for separating carbon dioxide from the flue/fuel gas stream before its transportation is one of the cutting-edge tasks associated with the implementation of a program to reduce anthropogenic CO_2 emissions into the atmosphere. Advanced CO_2 recovery techniques have already been developed yet, although technologies such as wet scrubbers, dry regenerable sorbents, membranes, cryogenics, pressure–temperature swing adsorption, and other up-to-date approaches have been proposed. Table 1 provides a comparison of various CO_2 extraction technologies [113].

Table 1. Comparison of technologies for separating CO_2 from the flue gas stream.

Technologies	Advantages	Flaws	Source
Absorption	• High absorption efficiency (>90%) • Sorbents may be regenerated by heating and/or depressurization • Most developed CO_2 separation process	• The absorption efficiency depends on the CO_2 concentration in the flue gases • A significant amount of heat is required to regenerate the absorbent • It is necessary to understand the environmental impacts associated with sorbent degradation	[114]

Table 1. *Cont.*

Technologies	Advantages	Flaws	Source
Adsorption	• The process is reversible and the absorbent may be recycled • High adsorption efficiency (>85%) is achievable	• Requires a high-temperature adsorbent • CO_2 desorption requires a lot of energy	[115]
Chemical loop combustion	• CO_2 is the main combustion product that does not mix with N_2, thereby avoiding energy-intensive air separation	• The process is still in development and there is no experience in its large-scale operation	[116]
Membrane separation	• The process has been adopted for the separation of other gases • High separation efficiency is achievable (>80%)	• Operational problems include low flows and clogging	[114]
Cryogenic distillation	• Mature technology • Used for many years in industry for CO_2 recovery	• Only suitable for very high CO_2 concentrations in flue gases (>90% by volume) • Should be carried out at very low temperatures • The process is very energy intensive	[117]

3.3. CO_2 Transportation and Storage Technologies

After CO_2 is separated from the remaining components of the flue gas, it must be transported to a storage location or to facilities for its further use. Whatever the final fate of CO_2, a reliable, safe, and cost-effective transport system is a key feature of any CCS or CCU project. Depending on the volumes involved, a variety of vehicles may be used, from tank trucks to offshore vessels and pipelines. Pipelines are considered the most viable method for transporting large volumes of CO_2 over long distances overland. For commercial-scale CCS projects, it is necessary to develop an extensive network of these pipelines [118,119]. In order to optimize the mass/volume ratio, CO_2 is transported as a dense phase in either a liquid or a supercritical state. This requires maintaining certain temperature and pressure conditions. These technologies are quite mature and are actively used in various types of carbon dioxide transportation. However, impurities in the gases and water vapor in CO_2 capture pose a serious problem, since their presence may change the boundaries of the range of pressures and temperatures providing a stable single-phase state to pure carbon oxide [113]. Once captured, the high-CO_2 stream may be transported for long-term storage or industrial reuse to produce high value-added products.

Technologies for storing CO_2 after its extraction from flue gases, generated by the combustion of hydrocarbon fossil fuels, are critical technologies for implementing CCS projects and achieving carbon neutrality targets [120,121]. Compressed carbon dioxide may be stored in geological formations, such as deep saline aquifers that have no other practical use, and oil, gas, or coal reservoirs. Storing CO_2 in porous geological media is a promising method for reducing anthropogenic greenhouse gas emissions [122]. A typical geological repository may contain dozens of millions of tons of CO_2 captured through a variety of physical and chemical methods. Typically, three different geological formations are considered for CO_2 storage: depleted (or nearly depleted) oil and gas reservoirs, stranded coal seams, and saline aquifers. The CO_2 storage potential may be as high as 400–10,000 GT for deep-saline aquifers, about 920 GT for depleted oil and gas fields, and >15 GT for undeveloped coal seams [123]. However, suitable geological sites for CO_2 storage must be carefully selected. The general requirements for the geological storage of CO_2 include the specific tectonic setting and geology of the basin, its geothermal regime, hydrology, hydrocarbon potential, maturity of the basin, porosity, the thickness and permeability of the reservoir rock, the presence of cap rock with a good sealing ability, and stable seismic conditions [122,124]. However, technologies for CO_2 storage in geological reservoirs have certain risks that must be taken into account when choosing the final pool for carbon dioxide injection. Injecting CO_2 into saline aquifers lowers the pH of the brine and dissolves iron carbonates and oxyhydrates. The dissolution of carbonates and minerals weakens the surrounding rocks and may create cracks, through which CO_2 will leak, so the chemical equilibrium of geological formations may change, creating mobile toxic trace elements and organic compounds [121,125].

Deep ocean storage technologies are another option for CO_2 immobilization. However, they are not technically mature, as they are at the stage of laboratory development and causing active discussion and criticism in the scientific community. Their essence lies in the fact that CO_2 liquefies at depths of more than 3 km and sinks to the bottom of the sea due to its higher density than the surrounding seawater. Mathematical models suggest that CO_2 introduced in this way may provide the permanent geological storage of CO_2 even under large geomechanical disturbances [112]. However, this approach is more controversial than other geological storage methods. The direct release of large amounts of CO_2 into the ocean may affect the chemistry of seawater, which may lead to catastrophic consequences for marine ecosystems. Comparatively less research has been conducted in this area, especially regarding the impact of CO_2 on marine ecosystems [126]. Although the Intergovernmental Panel on Climate Change has recognized the potential of ocean CO_2 storage, it has also noted the risks that this technology may pose [112].

Since CCS technologies involve the long-term immobilization of CO_2, monitoring storage locations with highly qualified personnel and appropriate infrastructure becomes necessary. According to an IPCC report, the monitoring of disposal sites will require a slight increase in energy consumption, but this increases significantly the cost of storage, so monitoring costs may be similar to the costs of transporting CO_2 to conservation sites [112,121].

3.4. CO_2 Utilization Technologies

Undoubtedly, underground CO_2 storage technologies in geological reservoirs are the fastest and largest-scale solution aimed at reducing anthropogenic greenhouse gas emissions to achieve carbon neutrality in the world economy [127]. However, it should be taken into account that the current volume of the secondary industrial use of CO_2 (>200 Mt per year) is clearly insufficient compared to the global CO_2 production (37,000 Mt per year). The conversion of large CO_2 volumes may only be achieved if carbon dioxide utilization processes are combined with renewable energy sources [128].

The use of CO_2 as an alternative carbon feedstock opens up new opportunities for the producing of fuels and valuable materials or chemicals with a high added value, complementing fossil fuel-based products, and then completely replacing them in the long term. The conversion of carbon into chemicals is an important pathway for CO_2 utilization, representing great potential for its sequestration [129]. By capturing and utilizing CO_2, it is possible to produce various chemicals such as urea, formic acid, salicylic acid, organic carbonates (e.g., acyclic carbonate), cyclic carbonates (e.g., ethylene carbonate), polycarbonates, and fine chemicals such as biotin, etc. [130].

Carbon dioxide may be converted to produce such fuels as methane, methanol, and synthesis gas (syngas). Dry methane reforming and hydrogenating are considered the main methods of converting CO_2 into fuel. The technical, economic, and environmental performance of the hydrocarbon synthesis process using CO_2 has been recently improved [130]. The hydrogenation process involves using CO_2 instead of CO to produce methanol. The conventional methanol production process is based on the conversion of syngas obtained from natural gas. Methanol is a liquid petrochemical used as an energy carrier in the transportation sector, as a feedstock and solvent, and for the production of other chemicals (e.g., acetic acid, formaldehyde, methylamines) and fuel additives [129]. It is a particularly valuable chemical because it may be produced by the low-temperature reaction of CO_2 with hydrogen and it is easy to store and transport [131].

Mineral carbonation is another method for capturing, storing, and/or using CO_2. This process includes the reaction of CO_2 with natural minerals or industrial wastes containing metal ions with the subsequent formation of inorganic carbonates [130]. Since there is no need to purify the gas to remove impurities ($NO_x$and SO_x) formed during fuel combustion, there is an obvious advantage to this method of CO_2 collecting. Nitrogen and sulfur oxides do not affect the carbonization reaction; therefore, this allows us to reduce the costs of the process of CO_2 capturing and purifying. The resulting mineral carbonates are widely used. In the construction industry, they are fillers and additives in building mixtures or compounds in the production of carbonate blocks, replacing Portland cement-based concrete blocks characterized by a negative carbon footprint. Wastes from the steel or cement industries (i.e., rich in calcium and magnesium oxides) may also be used as an alkali to form carbonates in the presence of CO_2. This is a promising technology with a potential CO_2 sequestration capacity of up to 3.3 Gt CO_2 per year, which could represent 5–12% of its total emissions by 2100. Mineral carbonates, such as hydrotalcite, may be used as catalysts in chemical reactions, for example, in polyester transesterification. In general, the mineral carbonization process is considered not only a method for obtaining high value-added products, but also a method for CO_2 storage in geological formations. One ton of CO_2 may be absorbed by approximately 1.6–3.7 tons of rock [132]. Along with the production of mineral carbonates, the production of organic carbonates is also of great industrial importance. Both linear and cyclic carbonates are generally non-toxic compounds that are widely used for the synthesis of important chemicals, including monomers, polymers, surfactants, plasticizers, and as fuel additives. Aromatic polycarbonates, which do not contain phosgene or aliphatic polycarbonates (such as polypropylene carbonate, polyethylene carbonate, polylimonene carbonate, and polyurethanes), are made from CO_2 [133].

4. Biological Methods for Capturing, Storing, and Using CO_2

Searching for the environmentally friendly technologies that make it possible to ensure the necessary level of economic growth without creating additional risks for the environment is one of the key areas of technological development worldwide [134,135]. Among the wide range of living organisms tested during the inventing and developing of innovative biotechnologies, green plants are the most popular and promising object of research, since they are widely used in various areas of human economic activity [136]. Currently, methods for the biological sequestration of climate-active gases are being actively developed simultaneously to physical and chemical approaches to capturing and storing CO_2. Biological carbon fixation technologies use the photosynthesis of green plants, inhabiting both aquatic and terrestrial ecosystems, to convert CO_2 into organic matter, ensuring the C–O balance in the atmosphere [137,138]. The technologies focused on these strategies for the biological assimilation of CO_2 include blue carbon sequestration and green carbon sequestration [19,139].

4.1. Technologies for CO_2 Sequestration by Terrestrial Ecosystems ("Green Carbon")

Under natural conditions, terrestrial ecosystems are sinks for atmospheric CO_2, influencing significantly the global carbon cycle [140]. A part of the carbon fixed by plants is converted into stable soil organic carbon (SOC) through forming organomineral complexes. Another part of the carbon contributes to the formation of soil inorganic carbon (SIC) due to the formation of carbonates/bicarbonates of calcium, magnesium, potassium, and sodium. These two systems provide soil carbon storage [141]. The gross primary productivity (GPP) of terrestrial ecosystems represents the annual flow of carbon between the atmosphere and the land surface. However, only about 8% of the GPP remains in the ecosystem as net primary production (NPP). The rest is lost to the atmosphere through plant and microbial respiration and heterotrophic nutrition. The main processes associated with terrestrial carbon sequestration include the retention of fixed carbon as NPP and the formation of SOC and SIC [142]. CO_2 sequestration by terrestrial ecosystems may be increased through technologies aimed at increasing the carbon content of biomass and soil, namely conservation agriculture, agroforestry, biochar applications, and forest and wetland restoration (Table 2).

Table 2. Approaches to increasing the soil carbon content.

Sequestration Strategy	Potential Increase in VOC Stocks	Advantages	Flaws	Source
Resource-saving rural farming	up to 1.01 t C ha^{-1} $year^{-1}$	• Increasing biodiversity • Improving soil nutrition • Increasing water retention	• Various data on effects on SOC • Various data on the impact on crop yields	[143]
Agroforestry	up to 5.3 Gt C $year^{-1}$ (global)	• Increase in aboveground biomass • Increasing carbon input into soil	• The level of SOC sequestration depends on the climate, soil type, management practices, age and type of organic feedstock	[144,145]
Reforestation	0.75–5.80 Gt C $year^{-1}$ depending on the price of land, region, and time	• Increase in aboveground biomass • Increasing carbon input into soil	• Different impacts on SOC stocks depending on the soil type, climate, tree species	[19,146]
Wetland restoration	0.35–1.10 t C ha^{-1} $year^{-1}$ depending on the landscape and depth	• Higher SOC content compared to cultivated wetlands	• Varying mitigation potential depending on natural and anthropogenic factors	[147]
Biochar	can offset up to 12% of annual net anthropogenic CO_2 emissions	• Initial carbon retention of 50% • Acts as both a source and sink for soil carbon	• Various data on effects on soil quality • Different effects on priming vary depending on soil type • Differential impacts on SOC stocks depending on biochar type and age	[19,148]

The Food and Agriculture Organization (FAO) defines conservation agriculture (CA) as a system of farming that promotes minimal soil disturbance (by using no-till or low-till practices) and crop diversification, and thus maintains permanent soil cover [143]. Because CA is often considered synonymous with low or no tillage, this issue demands assessing the potential of CA methods to improve the SOC and its yield due to data variability. Because three-part CA is often studied separately or applied in research or practice, the actual impact of CA on POC is unclear. The amount of carbon input plays a decisive role in increasing the SOC due to its GPP. The type of crop, intensity, and duration of cultivation predetermine the carbon input. Using deep-rooted plant species with high above- and below-ground biomass and increasing the number of harvests per year may thus increase the carbon storage capacity of CA systems [149]. In addition to the benefits associated with

SOC, CA improves farm economics, the planting schedule's flexibility, weed control, soil protection and fertilization, the efficiency of nutrient usage, and water usage and retention. This has accelerated the implementation of CA worldwide with the average rate of global expansion amounting to 10.5 million hectares of arable land per year [150].

Agroforestry is alternative climate change mitigation strategy. The system integrates trees into the agricultural landscape. The conversion of land use from forests and grasslands to plantations significantly reduces SOC stocks. Agroforestry may restore up to 35% of lost forest carbon reserves [151]. Initially, the carbon pool of agricultural biomass was considered insignificant compared to SOC. However, agroforestry makes a significant contribution to carbon storage in terms of agricultural biomass. In particular, trees have a positive effect on SOC through their deeper deposition and reduced decomposition capacity [152]. The changes in soil carbon stocks resulting from agroforestry vary with tree species, tree population density, and climate, but generally appear to fit the range between agricultural and forest carbon stocks [153]. All studies conducted to date in the field of agroforestry have shown an increase in SOC storage compared to agricultural monocultures, in which SOC storage rates were influenced by climate zones, the management methods used, the age of the system, the soil type, and the type of organic raw materials [154]. Agroforestry systems may store ~5.3 Gt of carbon over 944 million hectares worldwide, with the greatest potential in the tropics and subtropics [144].

The idea of forest restoration is central to climate change mitigation because it offers an effective alternative to other, more costly measures involving renewable energy or industrial CO_2 sequestration. Since the 1990s, afforestation has been widely adopted throughout the world, increasing the area of artificial planted forests by approximately 1.05×10^8 ha. However, achieving mitigation targets through afforestation depends on the area and carbon sequestration potential of each individual forest stand [112]. From a long-term perspective, the mitigation potential of climate change through afforestation varies widely from 1.5 to 4.9 Gt CO_2 year^{-1} by 2050 and from 1.1 to 5.8 Gt CO_2 year^{-1} by 2100 [155]. However, the effects of forest restoration on soil carbon dynamics are not well understood yet and a variety of assumptions have been made so far. SOC stocks may increase, decrease, or remain unchanged after afforestation under the influence of factors such as tree species, land use history, plant age, climate and soil type, etc. [156].

Currently, about 50% of the world's wetlands have been lost, due to either agriculture, industry, or urbanization. The loss of this species-rich habitat both has a major impact on biodiversity decline and increases CO_2 emissions. Wetlands and their associated soils represent a large soil carbon reservoir [147]. The drainage and anthropogenic transformation of these landscapes transform them from a major carbon sink into a major source of CO_2. Restoring wetlands by banning their development and replenishing their SOC is believed to be a potential approach for mitigating climate change [19]. However, assessing the potential of their restoration to meet decarbonization goals is problematic due to the many variables affecting wetland dynamics [157,158]. When analyzing the costs of wetland restoration in relation to the carbon sequestered, it appears that restoration is more cost-effective in coastal areas (such as mangroves) compared to inland wetlands. In the latter case, conservation rather than restoration is recommended [159].

Biochar is a biomass-derived solid material derived mainly through pyrolysis, a thermochemical process completed under high-temperature oxygen-deficit conditions. Syngas and bio-oil are formed in addition to biochar as a result of this process. Biochar is a stable product with a half-life of several hundred to several thousand years, which has emerged as a promising solution for soil carbon sequestration [160,161]. Compared to burning or decomposing crop residues, which retain only ~3% and 10−20% carbon, respectively, biochar retains about 50% of its original content [162]. It is estimated that biochar may offset up to 12% of annual net anthropogenic CO_2 emissions [163]. The biochar industry and market have grown around the world, realizing its potential for carbon capture and agricultural production. However, recent studies report contrasting results on the effects of biochar on soil quality, nutrient availability, and soil carbon mineralization [19].

Together, soil properties (intrinsic SOC content, pH, soil type) and biochar properties (pyrolysis temperature, source type, application rate, age, C:N ratio) jointly influence the effectiveness of the biochar addition to soil in terms of soil content [164]. Long-term field experiments with biochar are needed to assess the climate change mitigation potential of biochar [165]. Currently, various factors affecting the SOC uptake from biochar applications make it difficult to assess its decarbonization potential, so the economic feasibility of implementing large-scale biochar application is unclear [165]. The average increase in SOC content with biochar use is estimated to be 45.8%, but with large regional differences. The global potential of biochar for climate change mitigation using existing volumes of plant pyrolysis is estimated at 6.6 Mt C year^{-1} [148].

4.2. Technologies for CO_2 Sequestration by Aquatic Ecosystems ("Blue Carbon")

The term "blue carbon" was coined in 2009 and was initially used as a metaphor to draw attention to coastal ecosystems and their role in CO_2 sequestering and storing. This metaphor subsequently evolved into a strategy for mitigating and adapting to climate change through the conservation and restoration of biodiversity in coastal marine ecosystems [166]. The blue carbon concept places particular emphasis on areas with rich vegetation, which primarily include seagrass thickets, tidal marshes, and mangroves. Blue carbon ecosystems have a high potential for converting CO_2 into plant biomass. The average carbon sequestration potential is estimated at 24.0 $\pm$ 3.2 Mt C year^{-1} for mangroves, 13.4 $\pm$ 1.4 Mt C year^{-1} for salt marshes, and 43.9 $\pm$ 12.1 Mt C year^{-1} for seagrass thickets at the global scale [167]. The low oxygen concentration in their soil reduces the mineralization of organic matter in the plants' biomass, and improves their accumulation and preservation of organomineral detritus. That is why coastal biotopes, belonging to blue carbon ecosystems, are hotbeds of CO_2 sequestration [168].

Numerous studies of mangrove, tidal marsh, and seagrass ecosystems reveal their potential for an integrated approach to mitigate climate change. This led many countries to include measures for the restoration and conservation of coastal ecosystems in their national protocols for implementing the Paris Agreement goals [169]. However, the practice of destructive land use in coastal ecosystems turns these water areas from CO_2 accumulators into its sources. The disruption of ecosystem networks contributes to the mobilization of previously accumulated carbon and its release into the atmosphere. According to experts, disturbed mangroves and seagrass areas account for 18% and 29% of CO_2 emissions in all tropical coastal ecosystems, respectively [170]. Protecting existing blue carbon ecosystems could prevent the release of 304 Mt of inorganic carbon per year, with large-scale restoration potentially eliminating an additional 841 Mt per year by 2030, equivalent to 3% of annual global greenhouse gas emissions [171].

The potential of other marine ecosystems as CO_2 sequestration sites is the subject of ongoing debate. Calcifying organisms release CO_2 during the calcification process, making coral reefs and oyster banks a source of CO_2 rather than a sink. However, the environment-forming role of coral reefs have a beneficial effect on the accumulation of carbonate sediments, the development of sea meadows and mangroves; in turn, the latter prevent high-turbidity water from entering coral reefs. Therefore, coral reefs are interdependent with mangroves and seagrass, which enhances their inorganic carbon sequestration potential [172].

Pelagic ecosystems of the world ocean, especially macro- and microalgae, are considered another important link in the sequestration of CO_2 from the atmosphere [134,139,173,174]. The net primary production of phytoplankton in the world ocean is ~60 $\times$ 10^3 Mt of organic carbon per year, which corresponds to ~200 $\times$ 10^3 Mt of CO_2 captured by primary producers from the atmosphere [175]. However, only a small part of the assimilated carbon reaches the bottom and is buried in sediments (~250 Mt), equivalent to ~900–950 Mt CO_2. At the same time, the bottom sediments of the world ocean are one of the main reservoirs of carbon storage in the biosphere on a geological time scale [176–178].

Freshwater ecosystems are of no small importance. Despite the significant difficulty in estimating the total production of freshwater macro- and microalgae, it is believed that ~70–72 Mt of organic carbon per year accumulates in river sediments, which is equivalent to ~250 Mt CO_2 per annum [177].

The development of blue carbon programs may undoubtedly have a significant impact on our efforts to reduce and sequester CO_2 emissions. However, some uncertainties, such as the consequences of climate change for aquatic ecosystems, the degree of greenhouse gas emissions as a result of the anthropogenic transformation of aquatic landscapes, the role of freshwater and marine pelagic ecosystems in the global carbon cycle, etc., require further fundamental research involving large investments [179].

5. Technologies for Biological CO_2 Sequestration and the Production of Products with a High Added Value

The biotechnologies based on the use of the photosynthetic activity of microalgae and cyanobacteria have received widespread development in solving applied problems related to CO_2 capture and its recycling [134,180,181]. Historically, microalgae have been widely used as an alternative source of raw materials for the production of renewable green energy, so CO_2 sequestration by these means was initially established as one of the potential directions for sustainable energy development research in many countries around the world [182,183]. The uniqueness of microalgae is that they may capture CO_2 from various sources, including CO_2 from the atmosphere, from flue gases, and even in the form of soluble carbonates, and then process it into high-carbon organic biomass [138]. Historically, researchers have studied microalgae both for the discovery and development of alternative energy resources and for the development of technologies protecting the environment from air pollution and allowing the sequestration of climate-active gases, primarily CO_2 [184,185].

The efficiency of microalgae at assimilating CO_2 using solar energy is 10–50 times higher than that of terrestrial plants [186,187]. In terms of CO_2, 1.0 kg of algae biomass may assimilate ~1.83 kg of CO_2, which makes it possible to rear microalgae near thermal power plants or any other sources of greenhouse gases [181,182,188]. Currently, microalgae are actively used to obtain a wide range of biologically active components, such as proteins (including the production of amino acids), fats (including polyunsaturated fatty acids), carbohydrates (including starch and fiber), carotenoids, pigments, vitamins, and biologically active forms of major and trace elements [189–191]. This allows us to consider them alternative and industrially promising sources that ensure the sustainable production of many commercial products with a high added value [135,173,189].

Along with the physical and chemical methods of CO_2 sequestration, biological methods are dynamically developing [10]. The latter have some advantages. Firstly, their use makes it possible to reduce the volume of anthropogenic CO_2 emissions and to produce, simultaneously, a wide range of biologically active compounds that are highly commercially attractive for investment [185,192]. Secondly, the cultivation of microalgae may be carried out using wastewater to provide them with nutrients. This promotes a combined approach for solving the important environmental problems associated not only with the reduction of anthropogenic CO_2 emissions, but also with the development of water purification technologies [193]. Third, microalgae may survive and adapt to various extreme conditions. Their cultivation may be carried out on lands and in reservoirs, where the soil, water quality, or climate are not suitable for growing conventional crops or aquaculture, so they do not demand arable land or a source of clean water. This reduces their competition with agricultural crops for fertile land, increasing food crop areas [194–196]. This approach helps to redistribute income in dry regions and to create new jobs for the local population [197].

The main problem associated with the use of biological CO_2 sequestration is the high temperatures of the flue gases and the presence of CO, NO_x, SO_x, and certain amounts of other impurities in the fossil fuel used [10,181]. The process of CO_2 sequestration requires detailed knowledge of the component composition of flue gases and cell biology. The main factors influencing this process may be temperature, pH, SO_x and NO_x, light, microalgae strain, culture density, critical CO_2 concentration, CO_2 mass transfer, and O_2 accumulation. Growing algae also requires selecting the species and strain for cultivation and developing a suitable photobioreactor [138,198].

Despite the promise of using biological methods of CO_2 sequestration that use microalgae, there are still a large number of unresolved issues associated with them: as a rule, they concern assessing the economic profitability of the technological chains [181,183]. Currently, active work is underway, the main result of which is the development of a set of biotechnological approaches associated with the sequestration of CO_2 by microalgae and the production of biologically active components with a high added value [10]. Economic profitability, in this case, is achieved by localizing the entire biotechnological chain (sequestration → production of bioproducts → primary processing) to one location [134,181,185,199].

Despite all the difficulties associated with the development of innovative technologies for biological CO_2 sequestration, it is believed that this will be an economically feasible, environmentally friendly, and sustainable technology for CO_2 fixing and obtaining the biologically active components produced by microalgae in the long term [2,181,195,200].

6. Conclusions

Currently, the development of innovative approaches and technologies based on the results of modern scientific research is one of the key areas of technological development worldwide. This allows humanity to ensure its required level of economic growth without creating additional environmental risks. The presented review examines briefly the status and challenges of implementing carbon control technologies. Bridging the gap between reality and populist rhetoric about a climate-neutral future requires a transformation of global systems for the development and protection of natural resources. Interaction and collaboration are needed between researchers, policymakers, and investors around the world.

Innovative technologies and cutting-edge scientific research play a key role in achieving carbon neutrality and addressing climate challenges. These offer new ways and approaches to reducing greenhouse gas emissions, creating efficient energy use, the sustainable use of natural resources, and interacting with the environment. Funding and supporting such research and innovation is strategically important to transforming the economy and society in general.

Policy also plays a critical role in achieving carbon neutrality. Ambitious and effective measures must be adopted and implemented to reduce greenhouse gas emissions and support the transition to renewable energy sources. In addition, governments must create legislative and regulatory frameworks that encourage innovation and sustainable development.

Investors and consumers also play an important role in achieving carbon neutrality. Investments in clean energy technologies and sustainable projects will help support their development and expansion. In turn, consumers can influence the market by choosing products and services based on their carbon footprint, thus promoting the development of sustainable solutions.

Achieving carbon neutrality therefore requires coordination and collaboration between various stakeholders. Research and innovation in environmentally friendly and zero-carbon technologies must be supported by financial and policy incentives. At the same time, policies and consumer behavior must be aimed at reducing greenhouse gas emissions and moving towards a sustainable future. This will require a joint effort and the global partnership of all stakeholders.

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