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Contribution of renewable energy technologies in combating phenomenon of global warming and minimizing GHG emissions

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Abstract: The energy derived from fossil fuels significantly contributes to global warming (GW), accounting for over 75% of global greenhouse gas emissions and approximately 90% of all carbon dioxide emissions. It is crucial to rely on alternative energy from renewable energy (RE) to mitigate carbon emissions in the energy sector. Renewable energy sources have the potential to eliminate carbon from 90% of electricity generation by 2050, greatly reducing carbon emissions and helping alleviate the impacts of GW. By emphasizing the concept of zero emissions, the future of renewable energy becomes promising, with the possibility of replacing fossil fuels and limiting global temperature rise to 1.5 °C by 2050. In this article, renewable energy technologies and their role in various areas to combat GW are explored, examining trends and successes in supporting renewable energy policies and exploring available options to mitigate the effects of climate change and achieve a clean energy future. Moreover, RE offers a clean and sustainable alternative to fossil fuels, reducing reliance on them and minimizing greenhouse gas emissions. This paper also highlights the efforts of leading countries, including China, the United States, India, and Germany, in developing and utilizing renewable energy. These countries' renewable energy strategies reflect their commitment to combat global warming and reduce harmful emissions for the well-being of present and future generations.

Keywords: renewable energy; global warming; greenhouse effect; climate change; greenhouse gas (GHG) emission; carbon emissions; sustainable energy sources

1. Introduction

The concept of global warming, or the greenhouse effect, is generally defined as the increase in Earth's temperature, including its land and water bodies. The term "global warming" is used to describe the phenomenon of the rising temperature of the air near Earth's surface, which began to emerge a century or two ago as a result of human activity that accompanied the Industrial Revolution [1]. Swedish scientist Svante Arrhenius, a Nobel laureate, is credited with discussing the phenomenon of the greenhouse effect over 100 years ago. He noted that gases in the atmosphere trap the heat from the sun and prevent it from escaping into space. In a scientific paper published in 1895, he confirmed that even a small change in the emission of gases could lead to the retention of a significant amount of heat. Dr. Nerilie Abram from the Australian National University affirmed that the emergence of the global warming phenomenon was linked to the early stages of the Industrial Revolution between 1830 and 1850, contrary to the common belief that it is a recent phenomenon. By the late 19th century, the effects of global warming became evident, and the phenomenon began in the Northern Hemisphere and tropical oceans [2]. The Southern Hemisphere experienced global warming later due to the extensive expansion of the oceans, which absorb heat into deeper layers.

Global warming refers to the long-term increase in Earth's average surface temperature due to the buildup of greenhouse gases in the atmosphere. These greenhouse gases trap heat from the sun, preventing it from escaping back into space and causing a gradual warming effect [3]. The primary greenhouse gas responsible for global warming is carbon dioxide (CO₂), which is released into the atmosphere through various human activities, such as burning fossil fuels (coal, oil, and natural gas), deforestation, and industrial processes. Other significant greenhouse gases include methane, which is released during agricultural practices, livestock farming, and the decomposition of organic waste, as well as nitrous oxide, which is mainly generated by agricultural and industrial activities [4]. The consequences of global warming are far-reaching and impact various aspects of the planet. Rising temperatures lead to the melting of polar ice caps and glaciers, contributing to sea level rise. This poses a significant threat to coastal areas, increasing the risk of floods, erosion, and the displacement of populations. Global warming also influences weather patterns and can lead to more frequent and intense extreme weather events, such as heatwaves, droughts, hurricanes, and heavy rainfall [5]. These events have severe implications for agriculture, water availability, and human settlements, affecting food production, ecosystem stability, and overall societal well-being. Furthermore, global warming disrupts ecosystems and biodiversity. Many species struggle to adapt to rapidly changing conditions, resulting in habitat loss, shifts in migration patterns, and increased extinction rates. Coral reefs, for example, are highly vulnerable to rising ocean temperatures, leading to coral bleaching and the loss of valuable marine ecosystems. Addressing global warming requires collective efforts to reduce greenhouse gas emissions and transition to cleaner and more sustainable energy sources. This includes promoting renewable energy technologies, such as solar power, wind power, hydropower, and geothermal energy, which have lower carbon footprints compared with those of fossil fuels [6]. Additionally, implementing energy-efficient practices, improving waste management systems, and adopting sustainable land-use practices are essential in mitigating global warming. The international community has recognized the urgency of this issue, as evidenced by global agreements, such as the Paris Agreement, which aims to limit global warming to well within 2 °C above pre-industrial levels. By taking effective measures to combat global warming, we can mitigate its impacts, protect vulnerable ecosystems, and safeguard the well-being of present and future generations. The transition to a low-carbon and sustainable future is crucial for creating a resilient and thriving planet [7–10].

The measures reflect the commitment of countries to developing and utilizing renewable energy as part of their strategies to combat global warming and reduce harmful emissions. It is important to note that emission figures are subject to change over time as countries continue to make progress in renewable energy development [11–13].

Renewable energy technologies have emerged as indispensable tools in the global fight against the pressing issue of climate change. These sustainable energy sources possess the capacity to significantly mitigate the phenomenon of global warming by reducing greenhouse gas emissions and shifting the world towards a more environmentally friendly energy landscape [14]. The pivotal role of renewable energy

in addressing the climate crisis is undeniable. By harnessing the inherent clean and renewable nature of these power generation methods, we can collectively work towards a future where the negative environmental impacts associated with traditional fossil-fuel-based energy production are substantially diminished. The widespread adoption and continued advancement of renewable energy technologies hold the potential to drive tangible progress in curbing the alarming trajectory of global warming [15–17].

Figure 1 shows that fossil fuels have historically been a dominant source of electricity generation worldwide. However, the energy landscape is constantly evolving, and there may have been changes since then. Coal has traditionally been a significant contributor to global electricity generation. In 2021, China, India, and the United States were the largest consumers of coal for electricity generation [18–20]. These countries have relied heavily on coal due to factors such as large domestic reserves, affordability, and existing infrastructure. However, it is worth noting that many countries have been actively working to reduce their reliance on coal and transition to cleaner energy sources. Natural gas has also played a substantial role in global electricity generation. In 2021, China, the United States, and Russia were among the largest consumers of natural gas for power generation. Natural gas has been favored for its relatively lower carbon emissions compared with those of coal and its flexibility as a backup and peaking power source. In recent years, the global energy landscape has witnessed a remarkable surge in the adoption and deployment of renewable energy sources. Technologies such as solar, wind, hydropower, and biomass have been rapidly expanding their footprint, steadily increasing their share in the overall power generation mix worldwide [21–23]. This accelerated growth has been driven by a confluence of factors, including the declining costs of renewable energy infrastructure, enhanced policy support from governments, and heightened environmental awareness among both consumers and industry stakeholders.

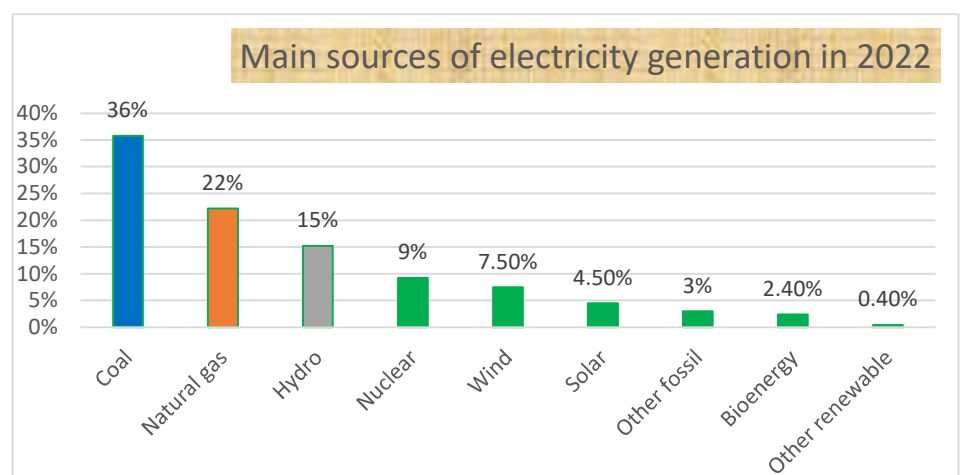


Figure 1. Main sources of electricity generation worldwide in 2022.

The main contribution of this research paper is the exploration of renewable energy (RE) technologies and their role in various areas to combat climate change. In this paper, the importance of relying on alternative energy from RE to mitigate global warming is discussed. It emphasizes the potential of RE sources to eliminate carbon

from a significant portion of electricity generation by 2050, thereby reducing carbon emissions and helping alleviate the impacts of climate change. The paper also highlights the concept of zero emissions and the possibility of replacing fossil fuels with renewable energy, with the goal of limiting global temperature rise to 1.5 °C by 2050. It provides insights into the consequences of global warming, such as rising temperatures, sea level rise, extreme weather events, and biodiversity loss. Additionally, it mentions the need for collective efforts to reduce greenhouse gas emissions and transition to cleaner and more sustainable energy sources. Furthermore, the research paper includes information on the contribution to combating global warming through renewable energy by leading countries, such as China, the United States, India, and Germany. It presents figures on their renewable energy generation capacity and investment in the renewable energy sector. Overall, the paper contributes to the existing body of research by providing an overview of renewable energy technologies, their potential in mitigating climate change, and the efforts of various countries in adopting these technologies.

The novelty of this research paper lies in its comprehensive and up-to-date examination of the role of renewable energy technologies in combating global warming and minimizing greenhouse gas emissions. Unlike many previous studies that focused on specific renewable energy sources, this paper takes a holistic approach, exploring the collective potential of diverse renewable technologies, including solar, wind, hydropower, and geothermal energy, in mitigating the effects of climate change. Additionally, the review juxtaposes the RE strategies and achievements of leading countries, such as China, the United States, India, and Germany, providing valuable comparative insights. Furthermore, the current state of renewable energy is not only examined in this paper but the discussion also delves into its promising future and potential to replace fossil fuels and limit global temperature rise by 2050. The review also highlights the importance of supportive policies and regulatory frameworks in driving the widespread adoption of RE, underscoring the significance of coordinated international action in addressing the global challenge of climate change. By addressing these novel aspects, this research paper makes a valuable contribution to the understanding of the pivotal role of renewable energy in creating a sustainable energy future.

The key aspects that contribute to its novelty include:

- **Multidimensional analysis:** The paper goes beyond a narrow focus on a single renewable energy technology. Instead, it provides a holistic examination of diverse renewable sources, including solar, wind, hydropower, and geothermal energy, and their collective potential in mitigating greenhouse gas emissions.
- **Temporal relevance:** The review incorporates the most up-to-date information and developments in the renewable energy sector as of August 2023. This timeliness allows the paper to capture the rapidly evolving landscape and offer insights that are highly relevant to the current energy and climate challenges.
- **Comparative case studies:** By juxtaposing the renewable energy strategies and achievements of leading countries, such as China, the United States, India, and Germany, the paper offers a unique cross-national perspective. This comparative

analysis highlights the diverse approaches and successes in promoting renewable energy solutions, providing valuable lessons for policymakers and stakeholders.

- **Future-oriented outlook:** In this review, the present state of renewable energy and its promising future potential are explored. The possibility of renewable energy sources replacing fossil fuels and limiting global temperature rise by 2050 is examined, offering a forward-looking vision for a sustainable energy future.
- **Policy implications:** The paper underscores the critical role of supportive policies and regulatory frameworks in driving the widespread adoption of renewable energy. From the examination of the efforts of various nations in this regard, the review emphasizes the significance of coordinated international action and policy interventions in combating the global challenge of climate change.
- **Interdisciplinary approach:** The paper's scope extends beyond the technical aspects of renewable energy technologies. It also addresses the broader environmental, economic, and societal implications of transitioning to a renewable-based energy system, making it a valuable resource for researchers and decision-makers across different disciplines.

By addressing these multifaceted aspects, this research paper sets itself apart as a comprehensive and innovative contribution to the literature on renewable energy and its pivotal role in mitigating global warming. Its depth, timeliness, and interdisciplinary perspective make it a valuable resource for scholars, policymakers, and practitioners in the energy and environmental sectors.

The organization of different sections in this paper can be outlined as follows. The introduction section provides an overview of global warming and its connection to the greenhouse effect. It explains how human activities, particularly during the Industrial Revolution, have contributed to the phenomenon of global warming. In the section, the consequences of global warming, such as rising temperatures, sea level rise, extreme weather events, and biodiversity loss, are also discussed. It highlights the need for collective efforts to reduce greenhouse gas emissions and transition to cleaner and more sustainable energy sources. The section concludes by mentioning the importance of renewable energy technologies in combating global warming and achieving a low-carbon future. In Section 2, lifecycle greenhouse gas (GHG) emissions associated with electricity production are discussed. Renewable electricity generation technologies are stated to generally have lower GHG emissions compared with those of fossil-fuel-based technologies. The information is supported by findings from the Life Cycle Assessment (LCA) Harmonization project, which emphasized the environmental benefits of renewable energy sources. In Section 3, the importance of RE by reduction of carbon emissions is emphasized, the potential of renewable energy sources to eliminate carbon from electricity generation by 2050 is discussed, and the concept of zero emissions and the possibility of replacing fossil fuels with renewable energy to limit global temperature rise is highlighted. A discussion will be reported in Section 4. Finally, the conclusion and recommendations for future studies are given in Section 5.

2. Lifecycle GHG emissions from electricity production

Renewable electricity generation technologies generally exhibit lower lifecycle GHG emissions compared with those of fossil-fuel-based technologies, as supported by findings from the LCA Harmonization project. The assessment of GHG emissions throughout the entire lifecycle of these technologies reveals variations in the contribution of emissions at different stages. In the case of fossil-fueled technologies, the combustion of fuels during the operational phase constitutes the primary source of GHG emissions [24–26]. This includes the burning of coal, oil, or natural gas to generate electricity, which releases significant amounts of CO₂ and other emissions into the atmosphere. On the other hand, for nuclear and renewable energy technologies, a considerable portion of GHG emissions occurs upstream of the operational phase. These technologies generate electricity without direct emissions during their operational phase, contributing to their lower lifecycle emissions compared with those of fossil-fuel-based technologies. It is important to note that while RE technologies have lower lifecycle GHG emissions, specific emissions can vary based on several factors, such as the energy source used in the manufacturing process, the efficiency of the technology, and the geographical location of the facility. Understanding the lifecycle GHG emissions of different electricity generation technologies is crucial for informing sustainable energy policies and guiding the transition towards low-carbon and climate-friendly energy systems. By considering emissions throughout the entire life cycle, stakeholders can make informed decisions on the environmental impacts of different technologies and prioritize those with lower GHG emissions.

For each power generation option, the lifecycle GHG emissions can be broken down into the following key sources:

- Coal-fired power [25]:
 - 1) Fuel extraction and processing (coal mining, transportation, etc.): Accounts for ~20%–30% of total lifecycle emissions
 - 2) Combustion at power plant: Responsible for ~60%–70% of lifecycle GHG emissions, primarily CO₂
 - 3) Construction, operation, and decommissioning of power plant: Contributes ~10%–15% of lifecycle emissions
- Natural gas combined cycle [26]:
 - 1) Fuel extraction, processing, and transportation (natural gas production, pipelines, etc.): ~30%–40% of lifecycle GHG emissions
 - 2) Combustion at combined cycle power plant: ~50%–60% of emissions, mostly CO₂
 - 3) Plant construction, operation, and decommissioning: ~10%–15% of lifecycle GHG footprint
- Wind power [27]:
 - 1) Turbine manufacturing, installation, and grid connection: Accounts for ~70%–80% of wind power's lifecycle GHG emissions
 - 2) Operation and maintenance over turbine's lifetime: ~20%–30% of wind power's GHG impact
 - 3) Negligible direct emissions during electricity generation

- Solar photovoltaic (PV) power [28]:
 - 1) Solar PV module manufacturing: Responsible for ~60%–70% of lifecycle GHG emissions
 - 2) Balance of system components (inverters, mounting, etc.): ~20%–30% of solar PV module’s GHG footprint
 - 3) Installation, operation, and decommissioning: Contributes the remaining ~10%–15%

In terms of GHG species breakdown, fossil-fuel-based technologies (coal, natural gas, etc.) are dominated by CO₂ emissions, accounting for over 90% of their total lifecycle GHG impact. Renewable technologies, such as wind and solar, have a more varied GHG profile, with a higher relative contribution from gases, such as methane and nitrous oxide, associated with manufacturing, material extraction, and supply chain activities. Providing this level of detail on GHG emission sources and their relative magnitudes would strengthen the analysis presented in Section 2. It would give readers a more comprehensive understanding of the environmental tradeoffs between different electricity generation options.

The National Renewable Energy Laboratory (NREL) conducted an extensive analysis that encompassed approximately 3000 published life cycle assessment (LCA) studies. These studies focused on various utility-scale electricity generation technologies, including wind power, solar PV, concentrating solar power (CSP), biopower, geothermal, ocean energy, hydropower, nuclear, natural gas, and coal technologies. To ensure the reliability and quality of the selected studies, a systematic review process was undertaken. Multiple experts conducted three rounds of screening, applying strict criteria for assessing the studies’ quality, relevance, and transparency. Less than 15% of the original pool of studies successfully passed this rigorous review process. The inclusion of battery and hydrogen storage technologies in the analysis introduced specific challenges and assumptions when compiling emissions factors. These challenges arose from the unique characteristics of storage technologies, which can be categorized into two different types of capacity: energy capacity and power capacity [28].

These capacity metrics are crucial in understanding the capabilities and limitations of energy storage technologies. They influence a system’s ability to store and release energy efficiently, manage peak demand, and support grid stability. By considering the unique characteristics and capabilities of energy storage technologies, the analysis aimed to provide comprehensive insights into their environmental impacts and integration into an electricity generation system. This information is important for policymakers, energy planners, and stakeholders to make informed decisions regarding the deployment and optimization of renewable energy sources and storage technologies, ultimately supporting the transition to a more sustainable and low-carbon energy future. Furthermore, certain storage technologies, particularly lithium-ion batteries, can be designed to provide a range of grid services, such as time-shifting (storing excess energy during low-demand periods for later use) or frequency regulation (maintaining grid stability by adjusting power output). For the purpose of aligning the estimates of GHG emissions impacts from storage technologies with those of other generation technologies, the analysis focused on references that allowed the

calculation of emissions per unit of electricity delivered throughout the storage system's lifetime. References that only reported emissions factors per unit of power capacity were excluded. The analysis compared published estimates of lifecycle GHG emissions for various electricity generation technologies, including biomass, solar (both photovoltaic and concentrating solar power), geothermal, hydropower, ocean energy, wind (both land-based and offshore), nuclear, oil, and coal. It also included storage technologies. These estimates provide a comprehensive overview of the environmental impacts associated with different technologies.

3. CO₂ emissions from energy combustion and industrial processes

The combustion of fossil fuels for energy generation and industrial processes is a major contributor to global CO₂ emissions. In the power sector, coal, natural gas, and oil-fired power plants are responsible for significant CO₂ releases, accounting for a large share of total energy-related emissions. Technological advancements, such as the development of clean coal technologies and carbon capture and storage (CCS) systems, offer potential pathways to mitigate emissions from conventional power generation. Similarly, the transportation sector, including road vehicles, aviation, and maritime shipping, is a significant source of CO₂ emissions due to the widespread use of petroleum-based fuels. Emerging alternative fuels and the electrification of transportation can help reduce these emissions. Industrial processes, particularly in energy-intensive sectors, such as cement, iron and steel, and chemical sectors, also contribute substantially to CO₂ emissions, both from fuel combustion and the chemical reactions inherent in production. Innovations in industrial process optimization, fuel switching, and carbon capture and utilization (CCU) technologies present opportunities to address these process-related emissions. Addressing CO₂ emissions from energy combustion and industrial processes will require a multi-faceted approach, including improvements in energy efficiency, increased integration of RE sources, and the deployment of carbon capture and storage/utilization technologies, supported by comprehensive policy frameworks and regulations.

Figure 2 presents a comparative assessment of lifecycle GHG emissions for the mentioned electricity generation and storage technologies. This visual representation allows for a clear understanding of the relative emissions performance of different electricity generation options. Comparing the emissions of different technologies is important for evaluating their environmental sustainability and informing policy decisions. By considering emissions per unit of electricity delivered over the lifetime of the storage systems, the analysis provides a fair and consistent basis for assessing the environmental impacts of storage technologies in relation to other generation technologies. This information is valuable for policymakers, energy planners, and stakeholders seeking to make informed decisions about the integration and deployment of these technologies, taking into account their climate and environmental implications.

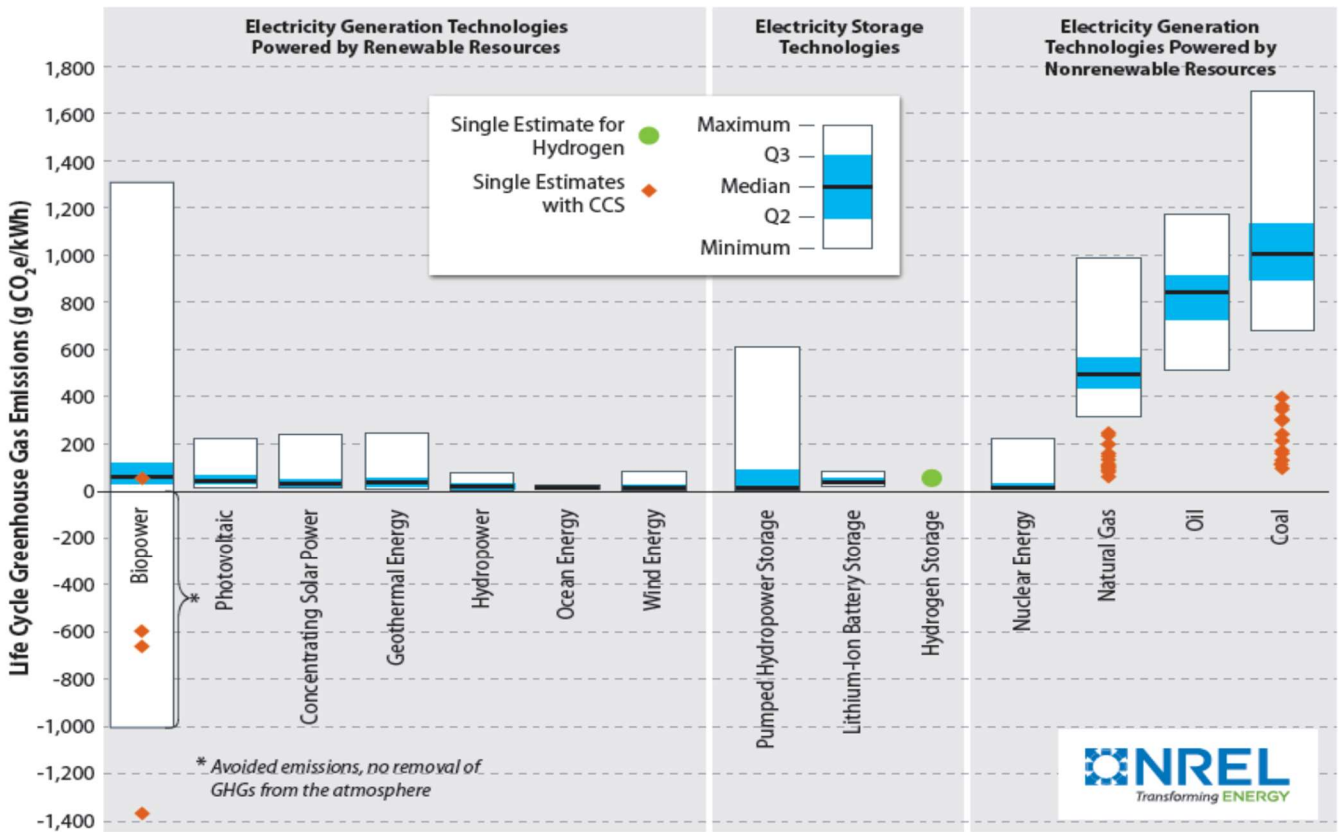


Figure 2. Lifecycle GHG emission estimates for selected electricity production and storage technologies, including CCS integration [29].

The comparative assessment of emissions in **Figure 2** provides a visual representation of the environmental performance of different generation technologies and storage technologies. This alternative formulation maintains the key points about the rapid growth of renewable energy sources and the driving factors behind this trend, while also emphasizing the broader context and importance of this energy transition in the global climate change mitigation efforts [30].

3.1. Mathematical model of GHG emission reduction strategy

The Kaya identity provides a useful framework for analyzing and formulating strategies to reduce CO₂ emissions associated with energy consumption. By decomposing energy-related CO₂ emissions into four distinct factors, namely population, gross domestic product (GDP) per capita, energy intensity (measured as the total primary energy supply per GDP), and carbon intensity (measured as CO₂ emissions per total primary energy supply), it allows for a comprehensive understanding of the drivers of emissions. This decomposition helps policymakers and researchers identify specific areas for intervention and develop targeted measures to curb CO₂ emissions effectively [31,32].

3.1.1. Objective functions

$$CO_{2e} = P \cdot \left(\frac{GDP}{P}\right) \cdot \left(\frac{TPES}{GDP}\right) \cdot \left(\frac{CO_2}{TPES}\right) \quad (1)$$

where:

CO_{2e} : CO₂ emissions; P : Population; GDP : Gross domestic product; $TPES$: Total primary energy supply.

Equation (1) represents the Kaya identity, which provides a comprehensive framework for understanding the drivers of CO₂ emissions associated with energy consumption and serves as a basis for developing strategies to reduce emissions by targeting specific factors within the equation.

$$[MAX]z = \sum_{h=1}^H \alpha_h \cdot NProf_h \quad (2)$$

where:

z : Quantity of raw material (CO_{2e}); α_h : Actualization coefficient for period h ; $NProf_h$: Profit in the period h ($h = 1, \dots, H$). [euro].

$$\sum_{i \in W} \sum_{m \in M_i} \sum_{t \in T} x_{ijmtp} = D_{jph} \forall j \in B; \forall p \in P; h = 1, \dots, H \quad (3)$$

where:

x_{ijmtp} : Quantity of product p shipped between nodes i and j in period h , with node i under environmental protection level m , in transport type t ($\forall i \in F, \forall j | (i, j) \in A, \forall m \in M_i, \forall t \in T, \forall p \in P, h = 1, \dots, H$) (in ton)

D_{jph} : Distance between nodes i and j using transport type t ($\forall (i, j) \in A; \forall t \in T$) (in km)

$$\sum_{i | (i, j) \in A} \sum_{m \in M_i} \sum_{t \in T} x_{ijmtp} = \sum_{k | (j, k) \in A} \sum_{m \in M_i} \sum_{t \in T} x_{jkmtp} \forall j \in W; \forall p \in P; h = 1, \dots, H \quad (4)$$

$$\sum_{j | (i, j) \in A} \sum_{m \in M_i} \sum_{t \in T} x_{ijmtp} \leq f c_i \sum_{m \in M_i} v_{imh} \forall i \in F; h = 1, \dots, H \quad (5)$$

where:

$f c_i$: Capacity of the facility i ($\forall i \in F$) [ton]; v_{imh} : $v_{imh} \in \{0, 1\}$ 1 if facility i is running in period h under a protection level m ($\forall i \in F, \forall m \in M_i, h = 1, \dots, H$)

$$\sum_{m \in M_i} v_{imh} \leq 1 \forall i \in F; h = 1, \dots, H \quad (6)$$

$$v_{imh} \geq v_{in, h-1} + v_{imh} - 1 \forall i \in F; \forall n, m \in M_i | n \neq m; h = 2, \dots, H \quad (7)$$

$$\sum_{j \in S | (j, i) \in A} \sum_{t \in T} z_{jitrh} = \sum_{k \in W | (i, j) \in A} \sum_{m \in M_i} \sum_{t \in T} \sum_{p \in P} f_{rp} \cdot x_{ikmtp} \forall i \in K; \forall r \in R; h = 1, \dots, H \quad (8)$$

where:

z_{jitrh} : Quantity of raw material r shipped between supplier i and factory j in period h in a transport type t ($\forall i \in S, \forall j \in K | (i, j) \in A, \forall t \in T, \forall r \in R, h = 1, \dots, H$) [ton]; f_{rp} :

Quantity of raw material r to produce one ton of product p ($\forall r \in R, \forall p \in P$) [ton];

x_{ikmtp} : Quantity of product p shipped between nodes i and j in period h , being node i under environmental protection level m , in a transport type t ($\forall i \in F, \forall j | (i, j) \in A, \forall m \in M_i, \forall t \in T, \forall p \in P, h = 1, \dots, H$) [ton]

$$Lm_{ijth} = \left(\sum_{p \in P} \sum_{m \in M_i} \frac{x_{ijmtp}}{t c_t} \right) \forall (i, j) \in A \setminus S; \forall t \in T; h = 1, \dots, H \quad (9)$$

where:

Lm_{ijth} : Minimum number of trips shipped between nodes i and j by transport type t in period h ($\forall (i, j) \in A; \forall t \in T; h = 1, \dots, H$)

tc_t : Transport cost between nodes i and j by transport type t in period h ($\forall (i, j) \in A; \forall t \in T; h = 1, \dots, H$) (in euro)

$$Lm_{ijth} = \left(\sum_{r \in R} \frac{x_{ijmtrph}}{tc_t} \right) \forall i \in S; \forall j | (i, j) \in A; \forall t \in T; h = 1, \dots, H \quad (10)$$

$$L_{ijth} \geq Lm_{ijth} \cdot (1 + Vlf_{ijth}) - M \cdot (1 - y_{ijth}) \forall (i, j) \in A; \forall t \in T; h = 1, \dots, H; n = 1, \dots, N \quad (11)$$

where:

L_{ijth} : Number of trips shipped between nodes i and j by transport type t in period h ($\forall (i, j) \in A; \forall t \in T; h = 1, \dots, H$); Vlf_{ijth} : Value of empty proportion for n option for transport type t between nodes i and j ($\forall (i, j) \in A; \forall t \in T; n = 1, \dots, N_{ijt}$); M : Large enough number (for modeling purposes; $y_{ijth}: y_{ijth} \in \{0, 1\}$ 1 if n option for empty proportion for transport type t between nodes i and j is chosen in period h (i.e., $lfn = Vlf_n$ and $tr \& h = Vtr \& n$) ($\forall (i, j) \in A; \forall t \in T; n = 1, \dots, N_{ijt}; h = 1, \dots, H$)

$$\sum_{n=1}^N y_{ijtnh} = 1 \forall (i, j) \in A; \forall t \in T; h = 1, \dots, H \quad (12)$$

3.1.2. Constraints

$$CO_{2h} = \sum_{i \in F} \sum_{j | (i, j) \in A} \sum_{m \in M_i} \sum_{t \in T} \sum_{p \in P} ef_{im} \cdot x_{ijmtrph} + \sum_{i \in S} \sum_{j | (i, j) \in A} \sum_{t \in T} \sum_{r \in R} es_{jr} \cdot z_{ijtr} + \sum_{(i, j) \in A} \sum_{t \in T} et_t \cdot d_{ijt} \cdot L_{ijth} \quad (13)$$

$= 1, \dots, H$

where:

CO_{2h} : Total quantity of CO_{2e} emission in period h ($h = 1, \dots, H$) (in kg CO_{2e}) ef_{im} : CO_{2e} emission into facility i with a protection level m ($\forall i \in F; \forall m \in M_i$) (in kg CO_{2e}/ton) es_{jr} : CO_{2e} emission from supplier i for raw material r ($\forall i \in S, \forall r \in R$) (in kg CO_{2e}/ton) et_t : CO_{2e} emission in transport type t ($\forall t \in T$) (in kg CO_{2e}/km)

$$\frac{CO_{2h}}{\sum_{i \in B} \sum_{p \in P} D_{ip}} \leq \varphi_h \quad h = 1, \dots, H \quad (14)$$

where:

φ_h : Carbon target in period h ($h = 1, \dots, H$) (in kg $CO_{2e}/\text{ton sold}$)

3.2. CO₂ emissions in 2022

In 2022, global energy-related CO_2 emissions experienced a modest growth of 0.9% or 321 million tons (Mt), reaching a new record high of over 36.8 gigatons (Gt) [33–35]. This increase followed two years of exceptional fluctuations in energy use and emissions, largely influenced by the COVID-19 pandemic. However, the growth in emissions was significantly slower compared with the rebound of more than 6% observed in 2021. The rise in emissions from energy combustion accounted for an increase of 423 Mt, while emissions from industrial processes decreased by 102 Mt. Despite facing challenges, such as energy price shocks, rising inflation, and disruptions to fuel trade flows, the global growth in emissions was lower than anticipated. This was partially attributed to the increased deployment of clean energy technologies, including renewables, electric vehicles, and heat pumps, which helped avoid an additional 550 Mt of CO_2 emissions. Additionally, industrial production curtailment, particularly in China and Europe, contributed to averting additional

emissions. Specific factors contributing to the growth in emissions in 2022 included 60 Mt of CO₂ attributed to the cooling and heating demand during extreme weather conditions and another 55 Mt of CO₂ resulting from offline nuclear power plants. It is noteworthy that the growth in CO₂ emissions in 2022 was well below the global GDP growth of 3.2%, which indicates a return to the decade-long trend of decoupling emissions from economic growth. However, improvements in the CO₂ intensity of energy use were slightly slower compared with the average of the past decade. Emissions from natural gas experienced a decline of 1.6% or 118 Mt, mainly due to tightening supply exacerbated by Russia's invasion of Ukraine. Reductions in gas emissions were particularly significant in Europe, where they decreased by 13.5%. The Asia Pacific region also witnessed unprecedented reductions, with a decrease of 1.8%. On the other hand, emissions from coal surpassed the reduction in natural gas emissions. CO₂ emissions from coal grew by 1.6% or 243 Mt, exceeding the average growth rate of the past decade and reaching a new all-time high of almost 15.5 Gt. Emissions from oil exhibited an even more substantial growth compared with that of coal, rising by 2.5% or 268 Mt to 11.2 Gt. Approximately half of this increase was attributed to aviation, as air travel rebounded from pandemic-period lows, approaching 80% of 2019 levels. However, the increase in electric vehicle sales, with over 10 million cars sold in 2022, helped offset some of oil emission growth. The electricity and heat generation sector experienced the largest increase in emissions in 2022, with a rise of 1.8% or 261 Mt. Notably, emissions from coal-fired electricity and heat generation grew by 2.1%, primarily driven by emerging economies in Asia. The expansion of renewables played a significant role in limiting the rebound of emissions from coal power. Renewables accounted for 90% of the global growth in electricity generation in 2022. Solar PV power and wind power generation both achieved new annual records, with an increase of approximately 275 terawatt-hours (TWh) each. Emissions from the industry sector decreased by 1.7% to 9.2 Gt in 2022. While several regions witnessed manufacturing curtailments, China's industry emissions contributed significantly to the global decline, with a decrease of 161 Mt CO₂. This reduction was primarily driven by a 10% decline in cement production and a 2% decline in steel making. China's emissions remained relatively flat in 2022, decreasing by 23 Mt or 0.2%. The decline in emissions from industrial processes offset the emission growth from combustion [36,37]. Factors such as weaker economic growth, declining construction activity, and strict COVID-19 measures contributed to the reduction in industrial and transport emissions. However, power sector emissions still experienced growth, reaching 2.6% but at a slower pace compared with the past decade's average. The European Union achieved a notable reduction in CO₂ emissions, with a decrease of 2.5% or 70 Mt. This reduction occurred despite disruptions in the oil and gas markets, hydroelectric shortfalls due to drought, and the offline status of numerous nuclear plants. The buildings sector witnessed a significant decline in emissions, aided by a mild winter. Although power sector emissions increased by 3.4%, coal usage was lower than expected. Moreover, for the first time, the combined electricity generation from wind and solar PV modules exceeded that from gas or nuclear sources. In the United States, emissions grew by 0.8% or 36 Mt. The buildings sector experienced the highest emission growth, primarily due to extreme temperatures. However, emission

reduction in electricity and heat generation, driven by substantial increases in solar PV power and wind power generation, as well as coal-to-gas switching, helped offset this increase. While many countries reduced their natural gas usage, the United States saw an increase of 89 Mt in CO₂ emissions from gas, as it was necessary to meet peak electricity demand during summer heat waves. Among Asia's emerging markets and developing economies, excluding China, emissions grew more than in any other region in 2022, with an increase of 4.2% or 206 Mt CO₂. Over half of the region's emission growth came from coal-fired power generation. The details concerning the summary CO₂ emission are presented in **Table 1**. **Figure 3** presents global CO₂ emissions from energy combustion and industrial processes from 1990 to 2022.

Table 1. Summary of CO₂ emissions.

Specific factors, sectors, and regional emissions	CO ₂ emissions (Mt)	Change from previous year (%)
Global total	36,800	+0.9%
Energy combustion	423	-
Industrial processes	-102	-
Specific factors contributing to growth:		
Cooling and heating demand in extreme weather	60	-
Offline nuclear power plants	55	-
Emissions by energy source:		
Natural gas	-118	-1.6%
Coal	+243	+1.6%
Oil	+268	+2.5%
Emissions by sector:		
Electricity and heat generation	+261	+1.8%
Industry	-1.7%	
Emissions by country:		
China	-23	-0.2%
European Union	-70	-2.5%
United States	+36	+0.8%
Asia's emerging market and developing economies (excluding China)	+206	+4.2%

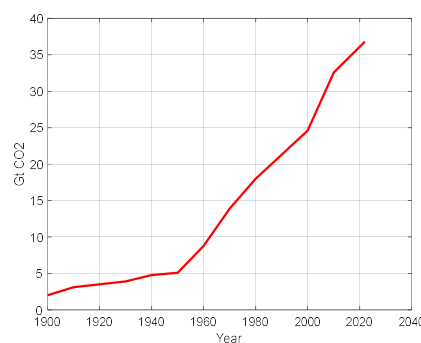


Figure 3. Global CO₂ emissions from energy combustion and industrial processes (1900–2022).

Figure 4 represents the annual changes in global CO₂ emissions from energy combustion and industrial processes from 2000 to 2022. It shows the fluctuations in the annual changes in global CO₂ emissions from energy combustion and industrial processes during the period from 2000 to 2022. There were years with significant increases, periods of slower growth, and years with decreases in emissions. The data reflect the complex interplay of various factors such as economic activity, energy consumption, policy measures, and global events that influence global CO₂ emissions.

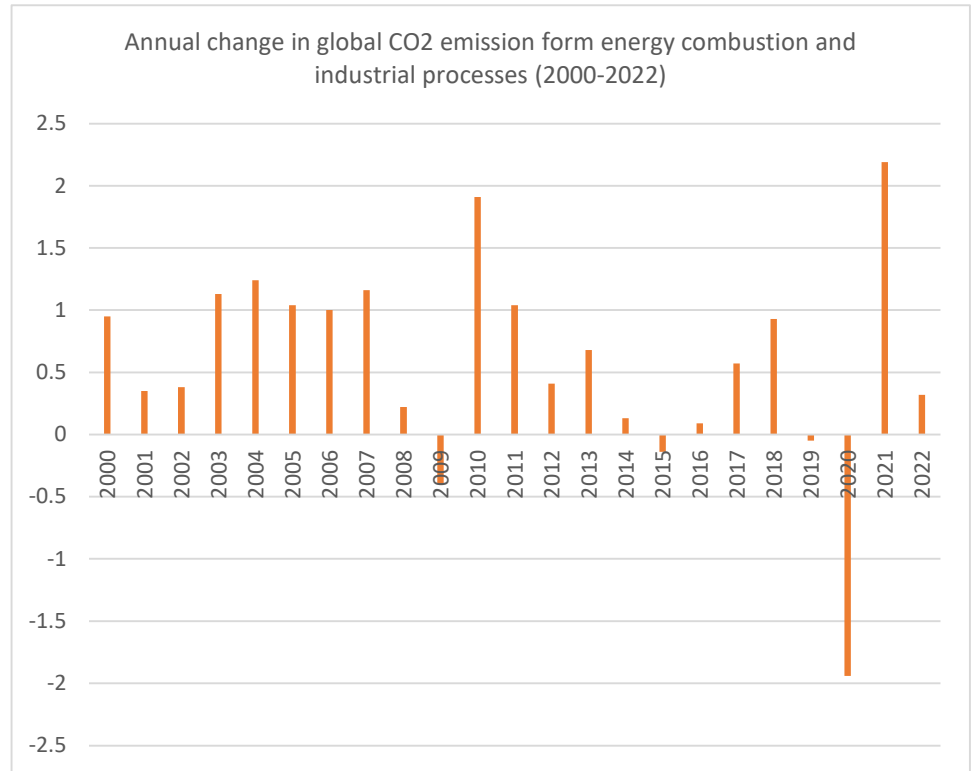


Figure 4. Annual change in global CO₂ emissions from energy combustion and industrial processes (2000–2022).

There are several key reasons behind the sharp decline in global CO₂ emissions observed in 2020:

- COVID-19 global pandemic:
 - 1) Governments in many countries imposed lockdown measures and restrictions to combat the spread of the virus.
 - 2) These measures led to a significant slowdown in economic activity, industrial operations, and transportation globally.
- Reduction in energy demand:
 - 1) Due to the lockdowns and decreased economic activities, the demand for fossil fuels declined sharply.
 - 2) This resulted in reduced combustion of fossil fuels and the associated emissions.
- Cutbacks in heavy industries:
 - 1) Heavy industries, such as iron, steel, and cement, are major sources of CO₂ emissions.

- 2) Production in these industries was significantly curtailed during the pandemic, leading to a drop in emissions.
- Decline in transportation and mobility:
 - 1) Travel restrictions and reduced transportation activities led to a decrease in fuel combustion in the transportation sector.
 - 2) The transportation sector is one of the largest contributors to global CO₂ emissions.

In general, the sharp decline in emissions in 2020 was a direct result of the negative impacts of the global pandemic on economic activities, industrial operations, and transportation worldwide. However, emissions are expected to rebound as the global economy recovers.

3.3. Tracking average global atmospheric CO₂ levels from 1960 to 2022

Tracking average global atmospheric CO₂ levels is of paramount importance in combating the phenomenon of global warming. Here are some key reasons why [38-40]:

- 1) Understanding the problem: By monitoring CO₂ levels, scientists can better understand the extent and pace of global warming. This data provides a clear picture of how human activities contribute to the rise in CO₂ concentrations and its impact on Earth's climate system.
- 2) Assessing progress: Tracking CO₂ levels allows us to assess the effectiveness of mitigation efforts and policies aimed at reducing greenhouse gas emissions. It helps determine whether emission reduction targets are met and provides insights into the success or shortcomings of various strategies and initiatives.
- 3) Identifying trends and patterns: Long-term tracking of CO₂ levels helps identify trends and patterns in atmospheric concentrations. This information aids in identifying areas or sectors that contribute significantly to CO₂ emissions, enabling targeted actions to mitigate those emissions effectively.
- 4) Guiding climate action: Tracking CO₂ levels provides a sense of urgency and reinforces the need for climate action.
- 5) Supporting scientific research: CO₂ data is invaluable for scientific research on climate change. It serves as a foundation for climate models, projections, and scenario development. Researchers use this data to better understand the complex interactions between greenhouse gases, climate patterns, and potential impacts on ecosystems, biodiversity, and human societies.
- 6) Promoting international cooperation: Tracking CO₂ levels on a global scale fosters international cooperation and collaboration in addressing global warming.

Therefore, tracking average global atmospheric CO₂ levels plays a crucial role in combating global warming. It provides essential information for understanding the problem, assessing progress, informing policies, guiding climate action, supporting scientific research, and promoting international cooperation. By monitoring CO₂ levels, we can make informed decisions, take effective measures to mitigate climate change, and work towards a more sustainable future.

The global average atmospheric concentration of CO₂ from 1960 to 2022, as reported by Zhang et al. [41], reached a record high of 418.56 parts per million (ppm) in 2022, representing a year-on-year increase of 0.5%. Typically, monthly atmospheric

CO₂ concentrations peak in May and June. The substantial increase in CO₂ concentrations is primarily attributed to human activities. Over the past two centuries, the widespread burning of fossil fuels and deforestation have released trillions of tons of CO₂ into the atmosphere. As a result, atmospheric CO₂ levels have risen by more than 50% above pre-industrial levels. Prior to the industrial revolution, CO₂ concentrations were relatively stable at around 280 ppm, according to the National Oceanic and Atmospheric Administration (NOAA). The rising concentrations of greenhouse gases (GHGs), including carbon dioxide, methane, and nitrous oxide, pose significant concerns for the planet, as they contribute to the climate crisis. These GHGs trap heat radiating from Earth's surface, preventing it from escaping into space. Consequently, Earth's atmosphere heats up, leading to higher surface temperatures and increasing sea surface temperatures.

Figure 5 illustrates the global average atmospheric concentration of CO₂ from 1960 to 2022. The impact of high atmospheric GHG levels is evident in various ways. The elevated surface temperatures can trigger severe weather conditions, such as extreme heatwaves and droughts. Additionally, there may be a higher frequency of high-intensity tropical storms. These events can have far-reaching consequences, including disruptions to ecosystems, agriculture, and human livelihoods. The climate crisis and its associated impacts highlight the urgent need for global efforts to mitigate GHG emissions, transition to renewable energy sources, and adopt sustainable practices to address and minimize further environmental damage.

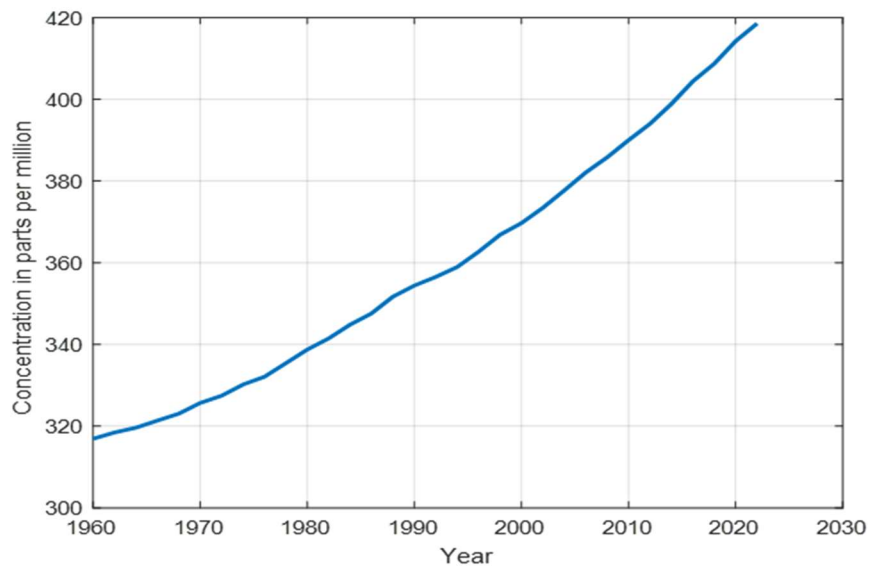


Figure 5. Global average CO₂ levels in atmosphere (1960–2022).

Understanding the causes and consequences of rising atmospheric CO₂ concentrations is crucial for informed decision-making and global cooperation to mitigate climate change. By reducing GHG emissions, promoting sustainable practices, and investing in resilience-building measures, there is hope for mitigating the worst effects of climate change and creating a more sustainable future.

Thus, tracking average global atmospheric CO₂ levels is vital for understanding climate change, assessing the effectiveness of mitigation efforts, informing policy

decisions, and promoting global cooperation to address one of the most significant challenges humanity faces today.

4. Renewable energy technologies and global warming

Global warming refers to the long-term increase in the average temperature of Earth's surface and lower atmosphere. It is a subset of climate change and is primarily caused by the accumulation of greenhouse gases in the atmosphere. Earth's atmosphere naturally contains greenhouse gases, such as water vapor, carbon dioxide, methane, nitrous oxide, and ozone. It is worth emphasizing the fact that while renewable energy has significant benefits in reducing greenhouse gas emissions, a comprehensive approach to addressing global warming is required. This includes not only transitioning to renewables but also implementing energy efficiency measures, promoting sustainable practices, and adopting policies that encourage the reduction of GHG emissions across all sectors of the economy [41,42].

The various forms of renewable energy given in **Figure 6** offer diverse options for reducing greenhouse gas emissions, increasing energy independence, and mitigating climate change.

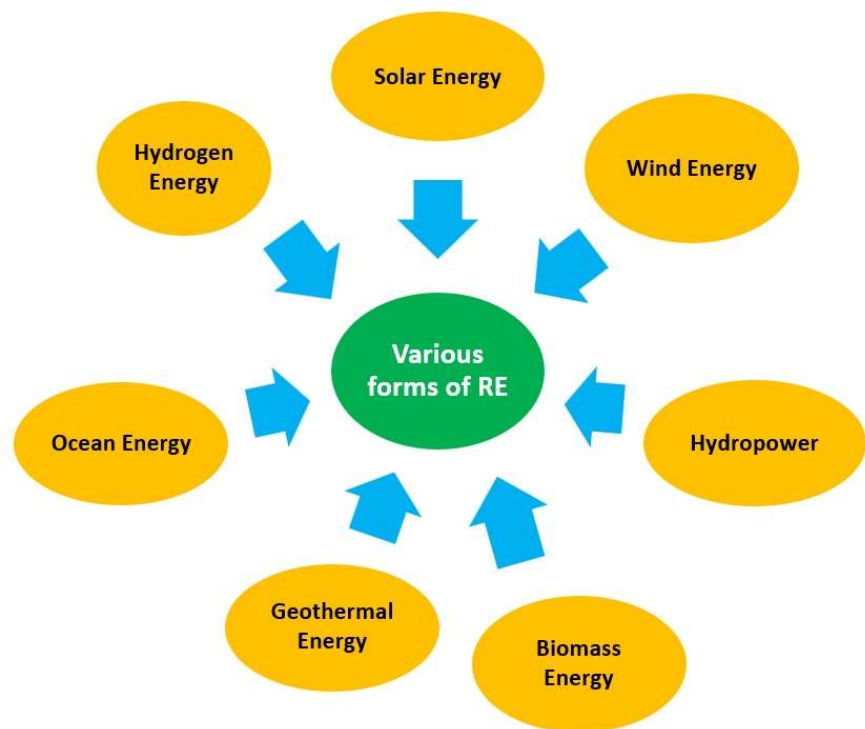


Figure 6. Summary of various forms of renewable energy.

By considering the aspects of renewable energy shown in **Figure 7**, policymakers, researchers, and industry stakeholders can better understand the multifaceted benefits and challenges associated with renewable energy and develop strategies to maximize its positive impacts on carbon emission reduction, air quality improvement, resource conservation, integration, and technological advancements.

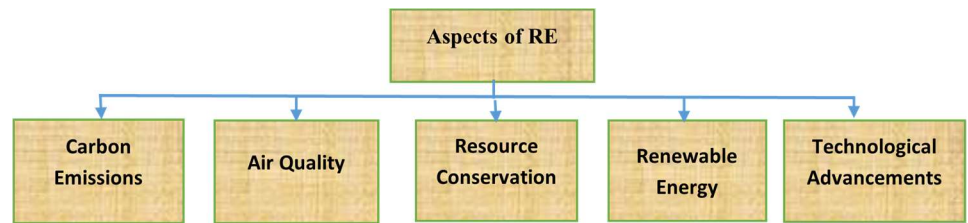


Figure 7. Classification of aspects of renewable energy.

Figure 8 summarizes the positive environmental impacts of renewable energy, its contribution to GHG emission reduction, and the challenges in combating the phenomenon of global warming (GW).

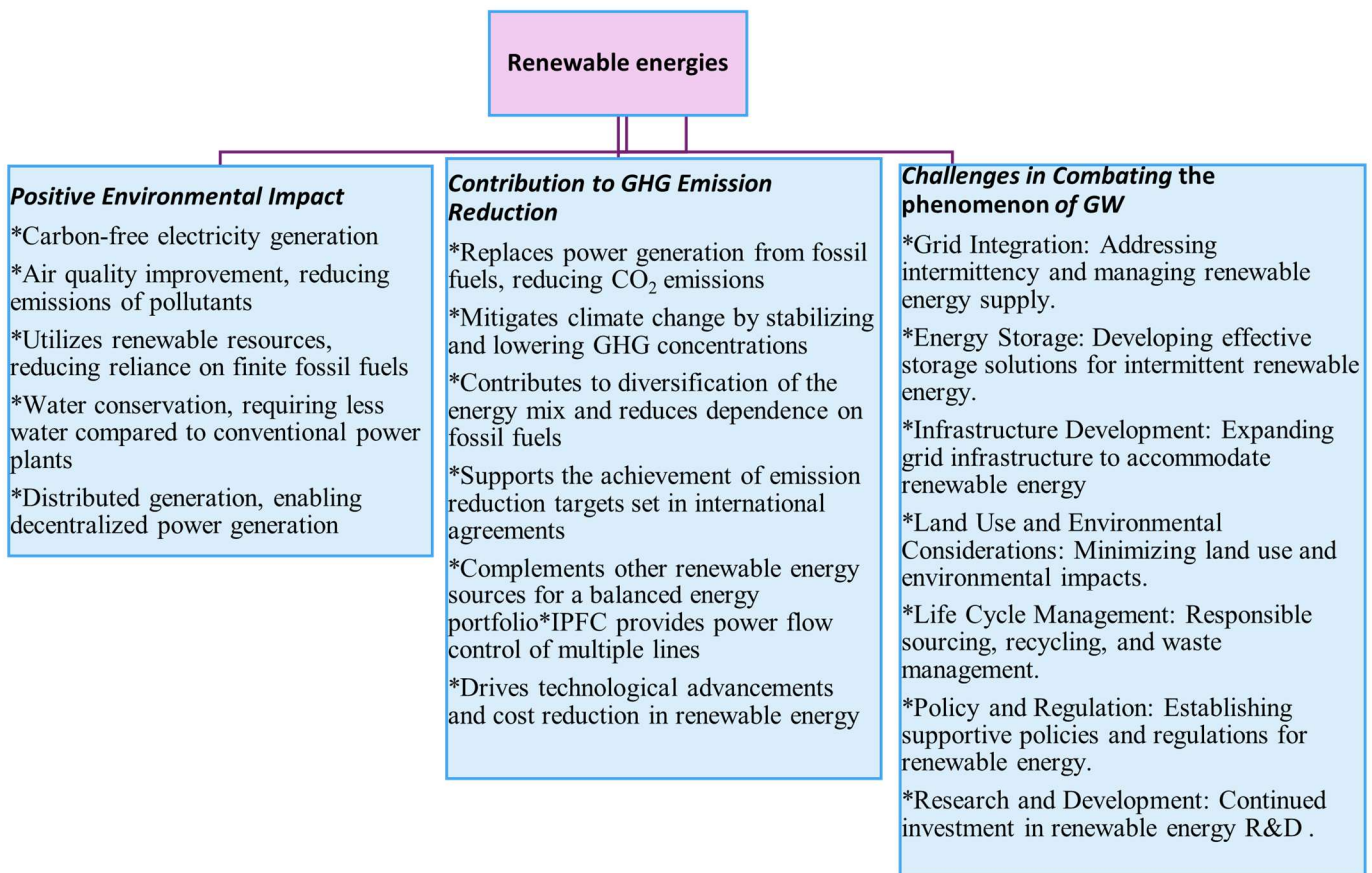


Figure 8. Summary of benefits of RE and challenges in combating phenomenon of GW.

4.1. Solar energy

Solar energy is an abundant and renewable resource that holds immense potential in addressing global energy needs. It is characterized by its cleanliness, renewability, and wide availability, making it a crucial component of the global renewable energy supply. While fossil fuels, such as oil, coal, and natural gas, continue to be the primary sources of energy consumption worldwide, there is a growing recognition of the need to transition towards cleaner and more sustainable alternatives. Solar energy offers several advantages over fossil fuels [43]. Firstly, it is an inexhaustible resource, meaning that sunlight will continue to be available for billions of years. This stands in contrast to fossil fuels, which are finite and depleting resources. By harnessing the

power of the sun, we can tap into an abundant and virtually limitless energy source. Additionally, solar energy is clean and emits minimal greenhouse gases during its generation. Solar energy systems produce electricity without contributing to air pollution or climate change. This makes solar energy a vital tool in mitigating the harmful effects of greenhouse gas emissions and combating climate change. Furthermore, solar energy is widely distributed and accessible. Sunlight is available across the globe, making solar power a viable option for diverse geographical regions. This decentralization of energy production can enhance energy security and reduce reliance on centralized fossil fuel infrastructure, which is susceptible to disruptions and price fluctuations.

The advancement of PV technology has garnered significant recognition as an exceptionally potent method for harnessing solar energy. Photovoltaic systems, composed of solar panels converting sunlight directly into electricity, offer numerous advantages that have contributed to their rapid development and widespread adoption [44]. Firstly, PV technology has experienced significant advancements in efficiency and cost-effectiveness over the years. Improvements in materials, manufacturing processes, and system design have led to higher conversion efficiencies, allowing solar panels to generate more electricity from the same amount of sunlight. Moreover, economies of scale and technological innovations have contributed to a substantial reduction in the cost of PV systems, making solar energy more accessible and economically viable. Another key advantage of photovoltaic technology is its modularity and scalability. PV systems can be deployed on various scales, ranging from small residential installations to large-scale utility projects. This flexibility enables PV systems to be integrated into diverse environments and applications, including rooftops, solar farms, and off-grid systems in remote areas. It also allows for incremental expansion and adaptation based on evolving energy demands. Furthermore, the environmental benefits of PV technology are significant. Solar energy is a clean and renewable energy source, and the operation of PV systems produces zero greenhouse gas emissions. By generating electricity without relying on fossil fuels, PV technology helps mitigate climate change and reduce air pollution, contributing to a more sustainable and greener energy landscape. The decentralized nature of PV systems is another advantage worth mentioning. Solar panels can be installed close to the point of electricity consumption, reducing transmission and distribution losses associated with long-distance power transmission. This decentralized approach enhances energy security, resilience, and grid stability, particularly in regions with limited grid infrastructure or vulnerable to power disruptions. The versatility of PV technology extends beyond electricity generation. Solar panels can be integrated into various applications, such as building-integrated photovoltaics (BIPV), where solar modules are incorporated into the design of buildings, providing both energy generation and architectural functionality. This integration further expands the potential for solar energy utilization in urban environments. Overall, the remarkable progress in photovoltaic technology has positioned it as a leading method to harness solar energy. Its improving efficiency, decreasing costs, modular scalability, environmental benefits, decentralized nature, and versatility make it an attractive solution for transitioning towards a sustainable and

renewable energy future. Continued research, development, and supportive policies are expected to further enhance the potential of photovoltaics and accelerate its adoption worldwide [45].

The installation of solar cell panels and PV grid-connected systems has become increasingly important in the pursuit of carbon neutrality [46]. Solar energy is a clean and renewable source of power that can significantly contribute to reducing GHG emissions. Recent research has shown that installing solar panels on rooftops can have a substantial impact on GHG emission reduction. In the near term, which is approximately 10 years, the installation of solar panels may lead to a decrease in GHG emissions by 57%. This reduction is attributed to the displacement of electricity generated from fossil fuels, resulting in lower CO₂ emissions. Furthermore, the long-term benefits of solar panel installations are even more significant. Over a period of about 30 years, the deployment of solar panels on rooftops has the potential to achieve carbon neutrality. This means that emissions resulting from electricity generation and usage are offset by the renewable energy produced by solar panels, resulting in a net-zero carbon footprint.

On the other hand, solar thermal technologies harness solar energy through the process of photothermal conversion to produce heat, steam, and electricity, offering a distinct approach compared with PV techniques. Unlike PV systems, which directly convert sunlight into electricity using semiconductors, solar thermal technologies utilize the sun's energy to generate heat. This heat can then be utilized in various ways, including [47–49]:

- 1) Heat production: Solar thermal systems can generate high-temperature heat, which can be used for industrial processes, space heating, water heating, and other thermal applications. By replacing fossil-fuel-based heat sources with solar heat, solar thermal technologies contribute to reducing greenhouse gas emissions and achieving carbon-neutral operations.
- 2) Steam generation: Solar thermal power plants employ concentrated solar power (CSP) technology, which uses mirrors or lenses to concentrate sunlight onto a receiver. The concentrated sunlight heats a working fluid, typically water or molten salt, to generate steam. The steam is then used to drive a turbine and produce electricity. CSP plants can store excess thermal energy, allowing for electricity generation even when the sun is not shining, enhancing their dispatchability and grid integration capabilities.
- 3) Combined heat and power (CHP) systems: Solar thermal technologies can be integrated into combined heat and power systems, also known as cogeneration. These systems simultaneously produce electricity and useful heat, maximizing the overall energy efficiency of the solar thermal installation. CHP systems find applications in district heating, industrial processes, and commercial buildings, where both electricity and heat are required.

Solar thermal technologies offer several advantages over PV systems in certain applications. They have a higher overall energy conversion efficiency, since heat can be efficiently utilized in addition to electricity generation. Solar thermal power plants with energy storage capabilities can provide dispatchable power, contributing to grid stability and reliable electricity supply. Additionally, solar thermal systems can

operate at higher temperatures, enabling applications that require process heat in industries such as chemical manufacturing and food processing. However, it is important to note that solar thermal technologies also face some challenges. They typically require larger land areas compared with those for PV systems due to the deployment of mirrors or receivers. The cost of solar thermal installations, especially CSP plants, has historically been higher than PV systems, although it has been declining in recent years. Furthermore, the availability of direct sunlight and the geographical location play a significant role in the performance and viability of solar thermal technologies. Despite these challenges, solar thermal technologies continue to be an important part of the renewable energy landscape. They offer unique capabilities for heat and electricity production, particularly in applications that require high-temperature heat or dispatchable power. Continued research, technological advancements, and supportive policies can further enhance the efficiency, cost-effectiveness, and integration of solar thermal systems, contributing to the transition towards carbon-neutral operations and a sustainable energy future.

Several countries and regions have made significant progress in adopting solar energy as part of their energy mix. **Figure 9** presents examples of countries or regions that successfully adopted solar energy, along with their respective installed solar capacity as of 2021. These examples highlight the diverse approaches and success stories in solar energy adoption worldwide. Many other countries and regions, including Spain, Italy, Japan, and various countries in the Middle East, Africa, and Latin America, have also made significant strides in embracing solar power as part of their energy transition efforts [50].

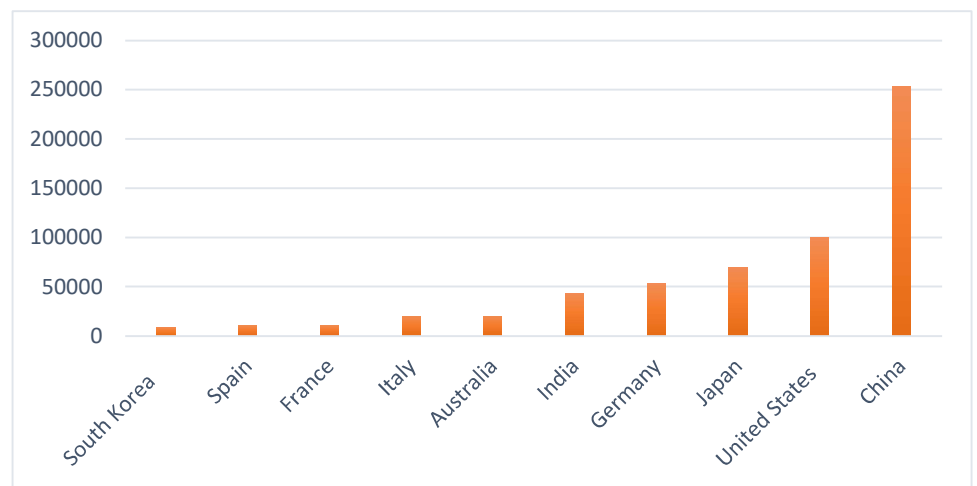


Figure 9. Installed capacity (MW) of solar energy in leading countries.

Figure 10 provides information on the solar power capacity of China, the United States, and Japan from 2016 to 2022. The values represent the solar power capacity in megawatts (MW) for each respective year. China has consistently been the leader in solar power capacity, with the highest values recorded in 2022. The United States and Japan have also shown growth in their solar power capacities over the years, but they have generally remained behind China in terms of total capacity [51]. Thus, in 2022, China had the highest solar power capacity in the world, reaching 86,059 MW. The United States had 17,806 MW, and Japan had 4642 MW.

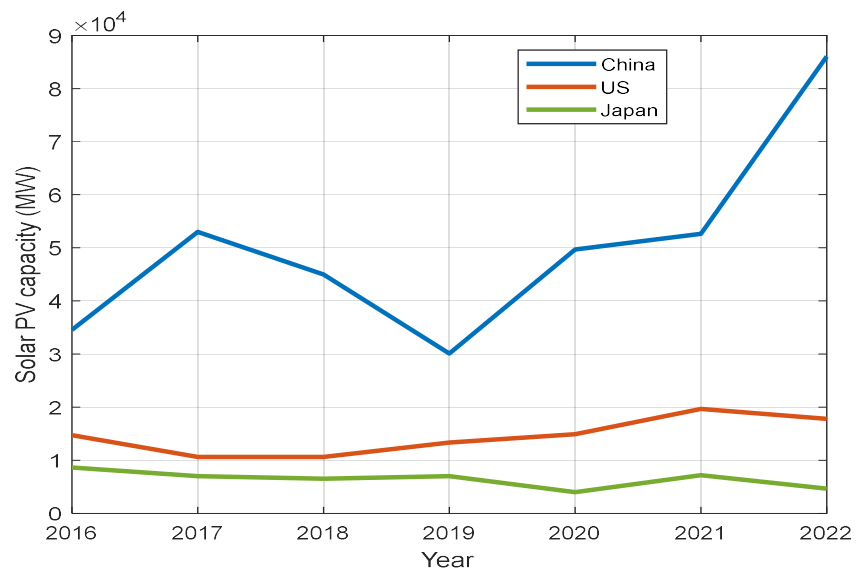


Figure 10. Solar PV energy capacity (MW) of top-three countries.

4.2. Wind energy

Wind power is derived from the movement of air caused by the uneven heating of Earth's surface by the sun. As such, wind energy can be seen as an indirect form of solar energy. Just like solar power, wind power is expected to play a crucial role in achieving “peak carbon” and carbon neutrality, contributing to global efforts to combat climate change. Earth possesses vast wind resources that are primarily found in grasslands, deserts, coastal areas, and islands. These regions are characterized by consistent wind patterns and high wind speeds, making them ideal for harnessing wind energy. However, the location of wind farms has a significant influence on the economic viability, technical feasibility, and implementation of wind power projects. Factors such as wind speed, accessibility, grid infrastructure, and environmental considerations all come into play when determining the suitability of a site for wind energy development. The global community recognizes the importance of wind power and actively supports its development. Governments, organizations, and industry stakeholders worldwide are promoting policies and incentives to accelerate the deployment of wind farms. These initiatives include feed-in tariffs, tax incentives, research and development funding, and streamlined permitting processes. The goal is to expand wind power capacity, increase renewable energy generation, and reduce reliance on fossil fuels. The benefits of wind power extend beyond its environmentally friendly nature. Wind energy projects create jobs, stimulate local economies, and contribute to energy security by diversifying the energy mix. Moreover, wind power is a RE, meaning it does not deplete over time, unlike finite fossil fuel reserves. This long-term sustainability makes wind energy an attractive option for meeting growing energy demands, while minimizing greenhouse gas emissions [52].

By expanding wind power capacity and integrating wind power into the energy mix, we can reduce GHG emissions, mitigate GW, foster sustainable development, and transition towards a low-carbon future. However, it is important to address challenges related to grid integration, land use, wildlife protection, and community engagement to maximize the positive impact of wind power and minimize any

potential negative effects. Its widespread availability, coupled with the global focus on renewable energy, position wind power as a key player in achieving carbon peak and carbon neutrality objectives. By tapping into abundant wind resources, countries can leverage wind energy to reduce greenhouse gas emissions, drive economic growth, and foster a sustainable energy future [53–66].

These installed wind energy capacities in leading countries presented in **Figure 11** demonstrate the global progress in adopting wind power as a clean and renewable energy source. Wind energy plays a crucial role in reducing greenhouse gas emissions, diversifying the energy mix, and transitioning to a more sustainable and low-carbon future. The growth of wind power installations worldwide reflects the increasing recognition of wind energy’s potential and the ongoing efforts to combat climate change.

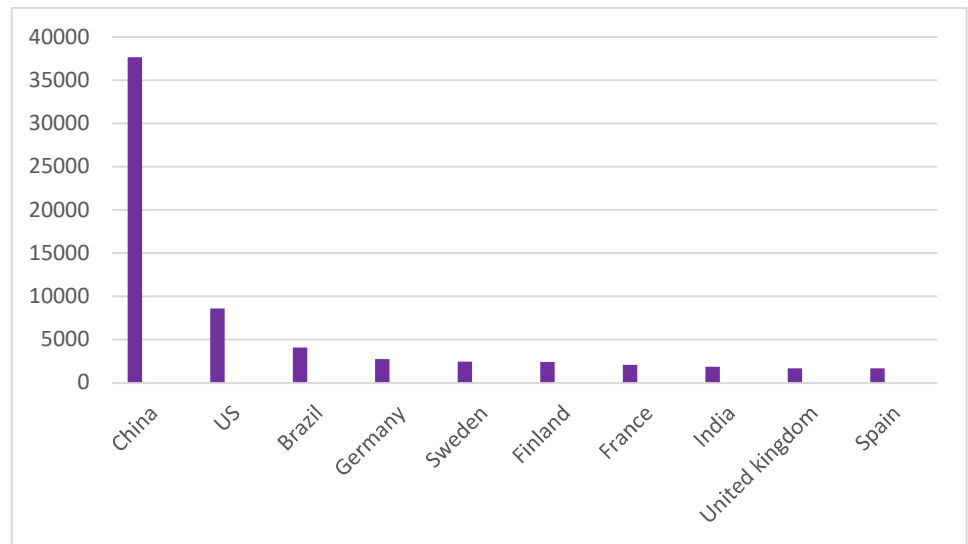


Figure 11. Installed capacity (MW) of wind energy worldwide in 2022.

4.3. Hydropower

Hydropower plants can be classified into four main types based on their operational characteristics, which are run-of-river, storage, pumped storage, and offshore hydropower, as given in **Figure 12**.

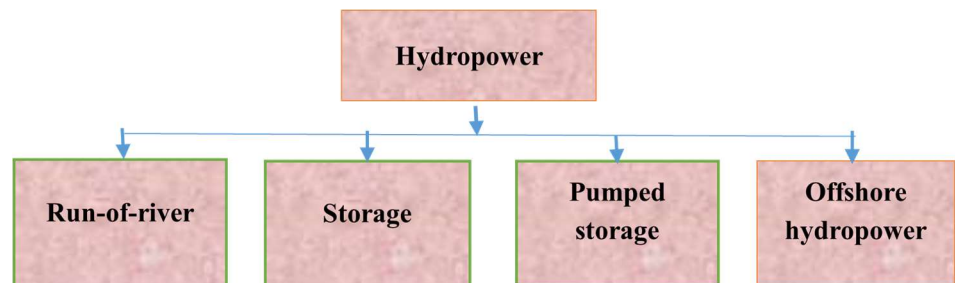


Figure 12. Types of hydropower.

- 1) Run-of-river hydropower: Run-of-river plants utilize the natural flow of a river or stream to generate electricity. These plants do not require large reservoirs and typically have minimal impact on the natural flow regime. They divert a portion

of the river flow through turbines to generate electricity and then return the water back to the river downstream. Run-of-river hydropower is particularly suitable in areas with consistent water flow throughout the year [67].

- 2) **Storage hydropower:** Storage hydropower plants, also known as reservoir hydropower, involve the construction of dams to create large reservoirs. These reservoirs store water, which is released through turbines to generate electricity as needed. Storage hydropower provides flexibility in electricity generation, as water can be stored during periods of low demand and released during peak demand to meet electricity needs. These plants also offer additional benefits, such as flood control and water supply.
- 3) **Pumped storage hydropower:** Pumped storage plants are a unique form of hydropower that combines both storage and generation capabilities. They have two reservoirs, one at a higher elevation and one at a lower elevation. Pumped storage hydropower provides grid stability by balancing electricity supply and demand, acting as a form of energy storage.
- 4) **Offshore hydropower:** Offshore hydropower refers to the generation of electricity from the kinetic energy of ocean tides and currents. This form of hydropower utilizes underwater turbines placed in tidal or ocean currents to capture the energy of moving water and convert it into electricity. Offshore hydropower has the advantage of a predictable and consistent energy source, as tides and currents follow regular patterns.

While hydropower has significant potential for electricity generation, it is worth noting that only a minority of the world's dams are specifically built for hydropower purposes. The majority of dams are primarily constructed for other purposes, such as irrigation, water supply, flood control, navigation, and recreation. However, the multifunctionality of dams allows for the integration of hydropower generation alongside these other uses, contributing to sustainable development and resource optimization [68].

Hydropower, also known as hydroelectric power, is the generation of electricity from the energy of moving water. It has significant significance and contributes to combating the phenomenon of GW in several ways:

- 1) **Renewable and low-carbon energy:** Hydropower is a RE source that relies on the natural water cycle. It does not consume water during operation and emits negligible GHG emissions. Compared with fossil-fuel-based energy, hydropower plays a crucial role in reducing CO₂ emissions, which are the primary contributors to global warming.
- 2) **Carbon sequestration:** Hydropower reservoirs can act as carbon sinks. The vegetation submerged by reservoirs accumulates organic matter, which decomposes underwater, releasing methane (a potent GHG). However, well-managed reservoirs can mitigate methane emissions through practices such as maintaining a high oxygen level in the water, minimizing the flooded area, and avoiding excessive nutrient input. Additionally, the carbon sequestered in the submerged vegetation can offset some of the GHG emissions associated with power generation.

- 3) **Energy storage and flexibility:** Some hydropower systems, such as pumped storage hydropower (PSH), offer energy storage capabilities. PSH plants store excess electricity by pumping water uphill into a reservoir during periods of low demand or high renewable energy generation. The stored water is then released through turbines to generate electricity during periods of high demand or low renewable energy availability. By providing energy storage and flexibility, hydropower helps integrate intermittent renewables into the grid and contributes to a more reliable and resilient energy system.
- 4) **Water resource management:** Hydropower projects often involve the construction of reservoirs, which can serve multiple purposes, including flood control, irrigation, and water supply for various sectors. Effective water management helps mitigate the impacts of climate change, such as extreme weather events and water scarcity. By regulating water flows, hydropower projects can provide additional benefits, such as flood prevention and drought mitigation, thus supporting climate change adaptation efforts.
- 5) **Sustainable development and job creation:** Hydropower projects can contribute to local economic development and job creation. They often require skilled workers for construction, operation, and maintenance, providing employment opportunities. Additionally, revenue generated from hydropower projects can be invested in social and economic development initiatives, improving living standards and promoting sustainable growth in local communities.

While hydropower has numerous benefits, there are also environmental and social considerations associated with its development. Large-scale hydropower projects can have significant ecological impacts, including habitat alteration, disruption of fish migration, and displacement of communities. Therefore, it is essential to carefully plan and manage hydropower projects to minimize their environmental and social footprints. Nevertheless, hydropower is a renewable, low-carbon energy source that provides stable electricity, contributes to grid stability, offers energy storage capabilities, supports water resource management, and promotes sustainable development. By displacing fossil-fuel-based electricity generation and providing multiple benefits, hydropower plays a significant role in combating global warming and transitioning towards a more sustainable energy future [69].

Hydropower continues to be a crucial component of the global energy transition and the fight against global warming. Its reliable electricity generation, flexibility, and significant carbon emission reductions make it a valuable renewable energy source. However, it is essential to balance hydropower development with environmental and social considerations to ensure its sustainability and minimize potential adverse impacts [70–73].

Renewable hydropower stands as a reliable, versatile, and cost-effective source of clean electricity generation, while also playing a crucial role in responsible water management. Modern hydropower plants have emerged as catalysts in accelerating the transition to clean energy, offering vital services, such as power generation, energy storage, flexibility, and climate mitigation. Hydropower serves as a valuable asset in constructing secure and sustainable electricity systems and contributes significantly to achieving global net-zero targets. In 2020, the global installed capacity of hydropower

illustrated in **Figure 13** reached an impressive 1330 GW, with electricity generation hitting a record-breaking 4370 TWh. Notably, China, Brazil, the United States, Canada, and India lead the pack as the largest hydropower producers in terms of installed capacity. The advantages of hydropower extend beyond its capacity for electricity generation. It provides a multitude of benefits, including flood control, irrigation, water supply, and recreational opportunities. By harnessing the power of flowing water, hydropower offers a clean and sustainable alternative to fossil-fuel-based energy sources, reducing greenhouse gas emissions and mitigating climate change. The growth and utilization of hydropower contribute to energy diversification, grid stability, and the integration of intermittent renewable energy sources. Its ability to store large amounts of energy and provide flexibility in electricity generation makes it a vital component of a balanced and resilient power system. Therefore, hydropower showcases its significance as a key player in the global energy landscape, offering a reliable, versatile, and environmentally friendly solution for clean electricity generation, responsible water management, and the pursuit of ambitious climate goals.

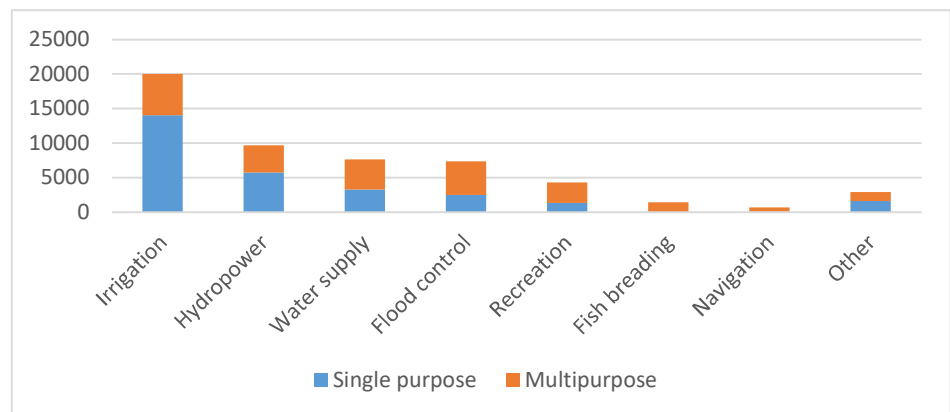


Figure 13. Types of hydropower and their installed capacities (GW) in 2020.

4.3.1. Key points

- RE source: Hydropower harnesses the energy of flowing water to generate electricity, making it a reliable and renewable energy source with low greenhouse gas emissions.
- Large-scale power generation: Hydropower plants can provide a significant amount of electricity, making them suitable for meeting baseload power demand and supporting grid stability.
- Water resource management: Hydropower projects often involve the construction of dams, which can facilitate water resource management, including flood control and irrigation.
- Long lifespan and durability: Hydropower facilities have long lifespans and can operate for several decades, providing a consistent and dependable source of electricity.
- Ancillary benefits: Hydropower projects can offer additional benefits, such as recreational opportunities, water supply for domestic and industrial use, and habitat creation.

4.3.2. Challenges

- Environmental impact: Hydropower projects can have environmental consequences, including habitat disruption, alteration of river ecosystems, and impacts on fish migration. Ensuring sustainable and environmentally friendly project development is crucial.
- Land and community displacement: The construction of large-scale hydropower projects may require land acquisition and resettlement of local communities, which can present social and cultural challenges.
- Climate change impacts: Climate change can affect water availability and precipitation patterns, potentially impacting hydropower generation and project viability. Adapting to climate change and considering its long-term impacts is necessary.
- Upfront investment and lead time: Building hydropower facilities often requires significant upfront investment and long lead times for planning, permitting, and construction.
- Balancing energy and environmental priorities: Balancing the need for clean energy generation with the environmental and social impacts associated with hydropower development is an ongoing challenge. Implementing sustainable practices and considering stakeholder engagement is crucial in achieving a balanced approach.

The considerable advantages of hydropower in terms of renewable energy generation and its potential for decarbonization make it a valuable asset. However, to ensure its widespread adoption and successful integration into the energy transition, it is crucial to address the challenges associated with its implementation. By effectively tackling these challenges, hydropower can fulfill its potential and play a pivotal role in achieving sustainable and low-carbon energy systems.

4.4. Bioenergy

Bioenergy refers to the use of biomass as a renewable source of energy derived from plants. Biomass can come from various sources, including agricultural and forestry residues, biogenic materials in municipal solid waste, animal waste, human sewage, and industrial wastes. It is estimated that biomass contributes around 13% to 14% of global energy consumption each year. To convert biomass into energy, different processes are employed, including thermochemical conversion methods. Thermochemical conversion involves gasification, pyrolysis, and combustion. Combustion, which involves the burning of biomass, accounts for approximately 90% of the total renewable energy generated from biomass. Pyrolysis is a thermochemical conversion process that can transform biomass into solid, liquid, or gaseous products by subjecting it to thermal decomposition at temperatures ranging from 400 °C to 1000 °C in the absence of oxygen. This process produces components such as acids, esters, and alcohols. Gasification is a process that converts carbonaceous materials, including biomass, into combustible or synthetic gas. This is achieved by reacting the biomass with air, oxygen, or vapor at temperatures exceeding 500 °C, preferably above 700 °C. The resulting gases from gasification can include H₂ (hydrogen), CO (carbon monoxide), and CH₄ (methane). These thermochemical conversion processes play a

significant role in harnessing the energy potential of biomass, enabling its utilization as a renewable energy source. By converting biomass into energy through combustion, pyrolysis, or gasification, bioenergy contributes to reducing reliance on fossil fuels and helps mitigate greenhouse gas emissions [74,75].

Bioenergy, when produced and utilized sustainably, can contribute to a more sustainable energy system, reduce greenhouse gas emissions, and promote energy security. However, it is important to ensure responsible sourcing, efficient conversion processes, and comprehensive sustainability assessments to maximize the benefits and minimize potential drawbacks.

Bioenergy can play a significant role in combating the phenomenon of global warming by reducing GHG emissions and promoting carbon neutrality [76,77].

It is important to note that the environmental benefits of bioenergy depend on sustainable sourcing, efficient conversion technologies, and comprehensive lifecycle assessments. Care must be taken to ensure that bioenergy production does not lead to deforestation, land use conflicts, or other negative environmental impacts. By adopting responsible practices, bioenergy can contribute to the global efforts to mitigate climate change and transition towards a low-carbon economy.

Bioenergy refers to the use of biomass, such as organic materials derived from plants and animals, for the generation of heat, electricity, or biofuels. It is a renewable energy source that can help reduce greenhouse gas emissions and dependence on fossil fuels. The installed bioenergy capacities in the leading countries given in **Figure 14** highlight their commitment to utilizing biomass resources for sustainable energy generation and reducing reliance on fossil fuels. Bioenergy plays a crucial role in the global transition towards a low-carbon and more sustainable energy future. Therefore, the installed bioenergy capacities in these leading countries highlight their commitment to sustainable energy solutions and reducing greenhouse gas emissions. By scaling up bioenergy deployment, countries can make significant contributions to mitigating climate change, achieving their emission reduction targets, and transitioning to a low-carbon economy. However, it is important to ensure sustainable biomass sourcing practices, minimize environmental impacts, and prioritize the use of non-food biomass to avoid potential conflicts with food production and land use.

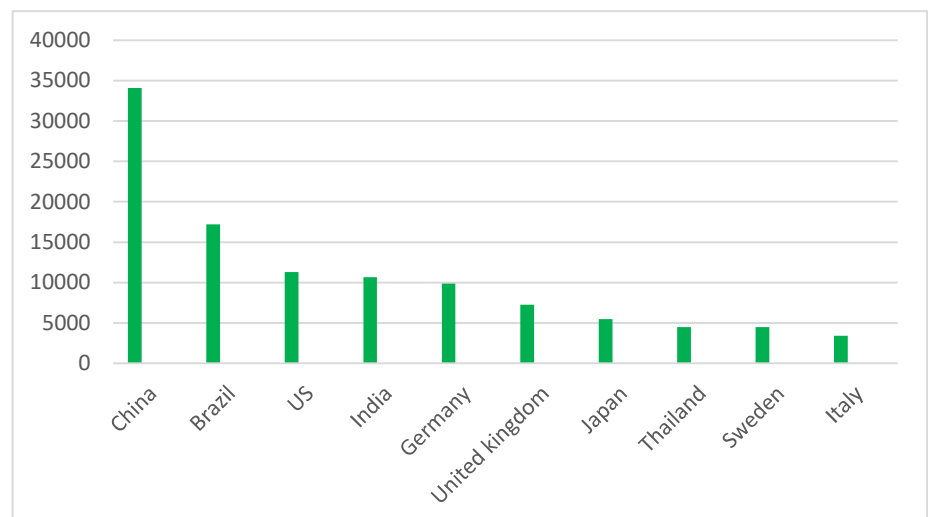


Figure 14. Installed capacity (MW) of bioenergy worldwide in 2022.

4.5. Ocean energy

Ocean energy is a vast and renewable source of clean energy derived from the water body in the ocean. It holds immense potential and has the capacity to power the entire world [78]. There are five primary forms of ocean energy, which are tidal energy, wave energy, ocean current energy, thermal energy, and osmotic energy, as given in **Figure 15**.

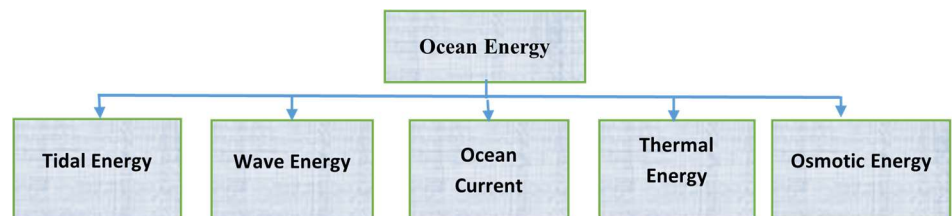


Figure 15. Primary forms of ocean energy.

The research and development of ocean energy technologies began several decades ago, aiming to harness this abundant and sustainable energy source. However, the geographical distribution of each energy form varies widely, and the technologies for harnessing them differ accordingly. The optimal locations for tidal, wave, and current energy projects depend on factors such as tidal range, wave height, and current strength, while thermal and osmotic energy projects require access to suitable temperature and salinity gradients.

As the understanding and utilization of ocean energy continue to advance, ocean energy holds great promise for contributing to the global energy mix and reducing reliance on fossil fuels. Ongoing research and innovation aim to overcome technical challenges and improve the efficiency and cost-effectiveness of harnessing ocean energy on a larger scale [79,80].

Advantages of ocean energy:

- 1) **Abundant and renewable:** Ocean energy is virtually inexhaustible, as it relies on natural forces, such as tides, waves, currents, and temperature gradients, which occur continuously.
- 2) **Clean and environmentally friendly:** Ocean energy technologies produce electricity without emitting GHG or other harmful pollutants, contributing to cleaner air and reduced carbon emissions.
- 3) **Predictable and reliable:** Tides, waves, and currents are highly predictable, which makes ocean energy a reliable source of power. This predictability allows for better integration with electrical grids and helps with energy planning.
- 4) **High energy density:** The energy density of ocean resources is relatively high compared with those of other RE sources. For example, the power contained in ocean waves is much higher than those in wind and solar resources.
- 5) **Long lifespan:** Ocean energy systems are designed to withstand harsh marine environments, and many components can have a long operational lifespan.

Current state of ocean energy:

- 1) While ocean energy is a promising RE source, it is still in the early stages of commercial deployment. The ocean energy industry is working on advancing

technologies, reducing costs, and addressing technical and environmental challenges.

- 2) Several demonstration projects and small-scale commercial installations exist worldwide, showcasing the feasibility and potential of ocean energy. These projects are helping to gather data, refine designs, and improve the understanding of environmental impacts.
- 3) The deployment of ocean energy projects is influenced by factors such as resource availability, grid connection, regulatory frameworks, and stakeholder engagement. Some countries, such as the United Kingdom, France, Ireland, and Canada, have been at the forefront of ocean energy development and have implemented supportive policies and funding programs.

Challenges and considerations:

- 1) **Technology development:** Ocean energy technologies require further innovation, research, and development to improve performance, reliability, and cost-effectiveness. Advancements in materials, engineering, and design are necessary to optimize system efficiency and reduce maintenance requirements.
- 2) **Grid integration:** Integrating ocean energy into existing electrical grids can present technical and logistical challenges. Upgrading transmission infrastructure, grid stability management, and developing appropriate grid codes are essential for seamless integration.
- 3) **Environmental impacts:** Like any industrial activity in the marine environment, ocean energy projects must carefully consider potential environmental impacts. These include noise and electromagnetic disturbances, habitat alteration, and interactions with marine life. Environmental impact assessments and monitoring programs are crucial to minimize and mitigate these effects.
- 4) **Financing and policy support:** Ocean energy projects require significant upfront investment, and securing financing can be challenging. Supportive policies, financial incentives, and regulatory frameworks that provide long-term stability are vital to attract investment and drive industry growth.

Ocean energy has the potential to contribute significantly to the global renewable energy portfolio and help combat climate change. Continued research, collaboration, and advancements in technology, along with supportive policies and investment, will be key to unlocking the full potential of this valuable renewable energy resource.

Ocean energy can contribute to combating the phenomenon of global warming in several ways [81]:

- 1) **Renewable energy transition:** By diversifying the energy mix and incorporating ocean energy into the renewable energy portfolio, we can accelerate the transition away from fossil fuels. This shift helps reduce overall carbon emissions and dependence on non-renewable resources, which are major drivers of global warming.
- 2) **Replacement of fossil-fuel-based power generation:** Ocean energy can replace or supplement fossil-fuel-based power plants, particularly in coastal areas. By displacing the use of coal, oil, or natural gas for electricity generation, ocean energy reduces the release of CO₂ and other greenhouse gases into the atmosphere.

- 3) **Avoided emissions from remote communities:** Ocean energy can have a significant impact on remote coastal communities that rely on diesel generators for electricity. By providing a clean and reliable source of power, ocean energy systems can reduce or eliminate the need for diesel fuel, thereby avoiding the associated greenhouse gas emissions.
- 4) **Potential for offshore renewable hydrogen production:** Ocean energy can also be utilized in the production of renewable hydrogen. Through electrolysis, excess electricity generated from ocean energy sources can be used to split water into hydrogen and oxygen. Renewable hydrogen has the potential to replace fossil fuel-derived hydrogen, which is currently a major contributor to greenhouse gas emissions.
- 5) **Climate resilience and adaptation:** Rising sea levels and increased storm activity due to climate change pose significant challenges to coastal communities. Ocean energy systems can contribute to climate resilience by providing a local, reliable source of electricity that is less vulnerable to climate-related disruptions. This can support adaptation efforts and enhance the resilience of coastal areas to the impacts of global warming.
- 6) **Blue economy and job creation:** The development and deployment of ocean energy technologies can stimulate the growth of the blue economy, creating job opportunities in manufacturing, installation, operations, and maintenance. This can contribute to economic growth while simultaneously addressing climate change.

It is worth noting that the development and deployment of ocean energy technologies face challenges, such as high upfront costs, technological complexities, and potential environmental impacts. However, with continued research, technological advancements, and supportive policies, ocean energy has the potential to play a significant role in combatting global warming and achieving a sustainable and low-carbon future.

Ocean energy, also known as marine energy, refers to the harnessing of power from the ocean's renewable resources, such as waves, tides, and currents. It is a promising field that offers significant potential for clean and sustainable electricity generation. South Korea has emerged as a global leader in ocean energy, with a substantial installed capacity of 256 MW in 2022, as shown in **Figure 16**. The country has made significant investments in research, development, and deployment of various ocean energy technologies, particularly in wave and tidal energy. South Korea's favorable coastal conditions and supportive government policies have contributed to its strong position in this sector. France is another prominent player in ocean energy, with an installed capacity of 211 MW. The country has been actively developing and deploying marine energy technologies, including tidal and offshore wind energy. France's strategic coastal locations, such as the Bay of Biscay and the English Channel, provide favorable conditions for harnessing ocean energy resources. In contrast, the Netherlands and Russia currently have smaller ocean energy capacities, with 2 MW each in 2022. However, it is worth noting that both countries have been exploring and investing in marine energy projects to tap into their ocean resources. The Netherlands, for instance, has been focusing on tidal energy projects in the Eastern

Scheldt storm surge barrier, while Russia has been exploring wave energy potential in the Black Sea. The global ocean energy sector is still in its early stages of development, and the installed capacities vary across countries. However, ongoing advancements in technology, increasing investments, and supportive policies are expected to drive further growth in this sector. Ocean energy has the potential to contribute significantly to the global renewable energy mix, reducing reliance on fossil fuels and mitigating GW.

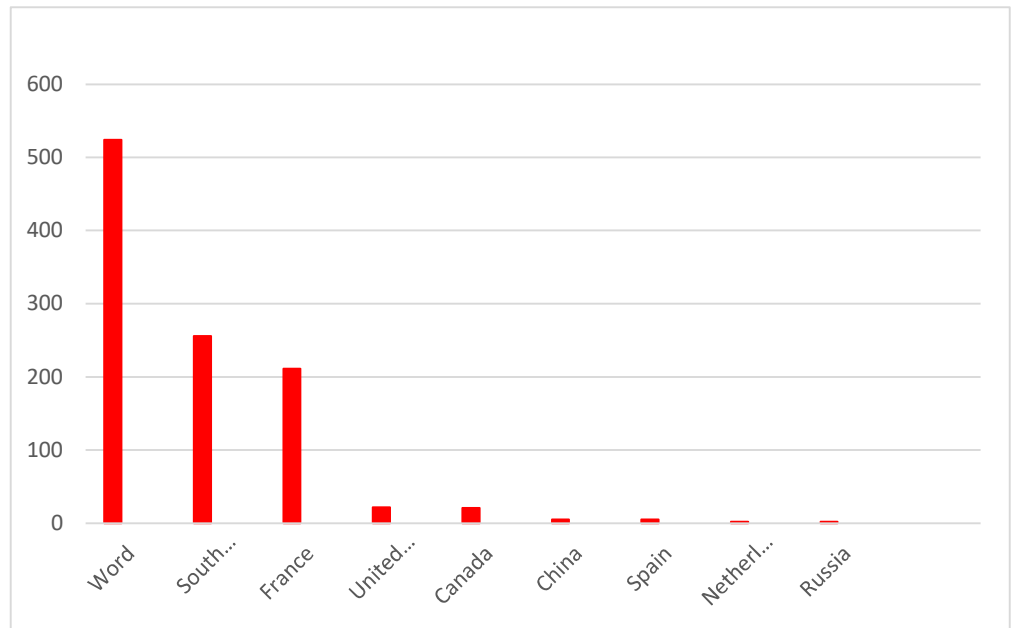


Figure 16. Installed capacity (MW) of ocean energy worldwide in 2022.

4.6. Geothermal energy

Geothermal energy is a form of non-carbon-based heat energy that is naturally present within Earth's interior. It offers several advantages, including stability, continuity, and high capacity [82]. These characteristics make geothermal energy a promising source for providing stable and continuous baseload power in future energy systems. Geothermal power generation is the primary utilization method for geothermal energy. Currently, there are three main geothermal power generation technologies:

- **Dry steam power:** This method utilizes natural dry steam from geothermal reservoirs to directly drive a turbine.
- **Flash power:** Flash power systems utilize high-pressure geothermal fluid to generate steam, which is then used to drive a turbine.
- **Binary power:** Binary power systems employ a working fluid with a lower boiling point than water. The hot geothermal fluid heats the working fluid, causing it to vaporize and drive a turbine.

In 2020, geothermal energy accounted for 62% of Iceland's energy production, contributing significantly to the country's goal of becoming carbon-neutral. In the United States, the Department of Energy's Frontier Observatory for Research in Geothermal Energy has allocated funding for 17 cutting-edge geothermal projects, aiming to advance domestic and carbon-free enhanced geothermal technologies.

Turkey has also experienced significant growth in geothermal energy, with a geothermal power generation capacity of 1549 MW as of 2020. On a global scale, geothermal utilization has achieved substantial reductions in CO₂ emissions. In 2020 alone, it resulted in an annual reduction of approximately 300 Mt of CO₂ emissions. In China, geothermal utilization has led to an annual reduction of around 100 Mt of CO₂ emissions. Geothermal heating has made a significant contribution to carbon reduction in buildings, with a combined building area of shallow and deep geothermal heating reaching nearly 1.4 billion square meters. Geothermal energy plays a vital role in providing clean heating solutions, particularly in northern China, where several major geothermal projects have been implemented. Examples include the “Xiongxin model” and infrastructure projects, such as the Beijing Sub-center and Beijing Daxing International Airport, which incorporate geothermal energy for their heating needs [83–85].

Here are some additional points to further elaborate on the topic. In terms of environmental benefits, geothermal energy is considered a clean energy source because it produces minimal greenhouse gas emissions and has a low environmental impact compared with those of fossil fuels. It does not require the combustion of fuel, which helps reduce air pollution and mitigate the effects of climate change.

As research and development efforts continue, geothermal energy is expected to play an increasingly important role in the transition to a sustainable and low-carbon energy future. Continued investments, technological innovation, and supportive policies can further unlock the vast potential of geothermal energy worldwide.

Geothermal energy makes a significant contribution to combating global warming and reducing GHG emissions in several ways:

- Carbon-free power generation: Geothermal power plants produce electricity without combustion, which means they do not emit CO₂ or other GHGs. By displacing fossil-fuel-based power generation, geothermal energy helps reduce the overall carbon footprint of the electricity sector.
- Replacement of fossil-fuel-based heating systems: Geothermal energy can be utilized for direct heating applications, replacing fossil-fuel-based systems, such as natural gas or oil boilers. This substitution reduces the combustion of fossil fuels and associated CO₂ emissions, particularly in residential, commercial, and industrial sectors, where heating demands are significant.
- Avoid emissions from backup power sources: Geothermal power’s reliability and baseload capacity enable it to replace backup power sources that rely on fossil fuels, such as diesel generators. By ensuring a continuous and sustainable power supply, geothermal energy helps eliminate the need for backup systems and the associated GHG emissions.
- Reduced methane emissions: Geothermal energy can indirectly contribute to GHG emission reduction by reducing the extraction of methane gas. Methane, a potent greenhouse gas, is often emitted during the extraction of fossil fuels, including natural gas and oil. By displacing the need for fossil fuels, geothermal energy helps minimize methane emissions throughout the extraction and supply chain.

- Geothermal heat pumps: Ground source heat pumps (GSHPs) utilize geothermal energy from shallow ground sources for space heating and cooling. GSHPs are highly efficient and can provide heating and cooling with minimal electricity consumption, resulting in reduced GHG emissions compared with those of conventional heating and cooling systems that rely on fossil fuels.
- Carbon capture and geothermal: Geothermal systems can potentially integrate carbon capture, utilization, and storage (CCUS) technologies. This involves capturing CO₂ emissions from power plants or industrial processes and injecting them into deep geothermal reservoirs for long-term storage. This approach helps reduce CO₂ emissions to the atmosphere, while utilizing the natural storage potential of geothermal reservoirs.

It is important to note that the actual GHG emission reduction from geothermal energy depends on various factors, including the type of energy source being displaced, the efficiency of geothermal systems, and the overall energy mix of a specific region. However, geothermal energy's inherent characteristics and its ability to provide reliable and sustainable power and heat make it a valuable tool in global efforts to combat climate change and reduce GHG emissions [86,87]. An installed geothermal energy capacity (MW) worldwide in 2022 is illustrated in **Figure 17**.

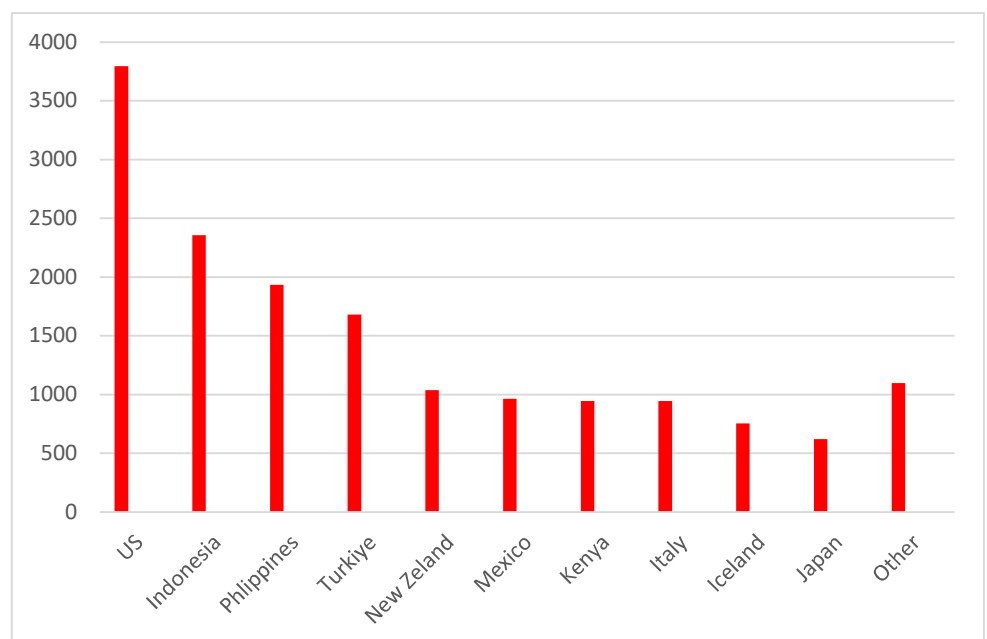


Figure 17. Installed capacity (MW) of geothermal energy worldwide in 2022.

4.7. Hydrogen energy

Hydrogen energy has emerged as a pivotal player in the global effort to combat the phenomenon of climate change and reduce GHG emissions. As a clean, versatile, and renewable energy carrier, hydrogen holds immense potential to transform the energy landscape and accelerate the transition towards a low-carbon future. Unlike traditional fossil fuels, the combustion of hydrogen produces only water vapor, making it an exceptionally promising solution for emissions-intensive sectors, such as transportation, as well as for power generation and industrial processes. The

widespread adoption of hydrogen-based technologies can contribute significantly to minimizing the overall carbon footprint of energy systems. Hydrogen can be produced through various sustainable methods, including water electrolysis powered by renewable sources, such as solar, wind, and hydropower, as well as through the reformation of biogas or the gasification of biomass. These production pathways ensure that hydrogen can be generated with minimal to no net GHG emissions, making hydrogen a compelling alternative to conventional energy sources. Furthermore, the integration of hydrogen into the energy mix can facilitate the effective storage and distribution of renewable electricity, addressing the intermittency challenges associated with some clean energy technologies. By serving as a flexible energy carrier, hydrogen can help to balance supply and demand, enabling the increased utilization of renewable resources and, in turn, driving down the overall carbon intensity of energy systems. As global efforts to mitigate climate change intensify, the role of hydrogen energy in combating global warming and minimizing greenhouse gas emissions becomes increasingly vital. Continued advancements in hydrogen production, storage, and distribution technologies, coupled with supportive policy frameworks, will be crucial in unlocking the full potential of this clean energy solution and accelerating the transition towards a more sustainable and resilient energy future [88–91]. The environmental impacts of different types of hydrogen can vary significantly. Blue hydrogen and gray hydrogen still contribute to carbon emissions, although blue hydrogen has the potential to mitigate some of its emissions through carbon capture and storage. Brown and black hydrogen production processes release substantial amounts of CO₂ into the atmosphere, contributing to GHG emissions. Green hydrogen, on the other hand, is considered the most environmentally friendly option, as it relies on renewable energy sources and produces zero carbon emission during production. The shift towards green hydrogen is a crucial step in decarbonizing the energy sector and reducing greenhouse gas emissions. However, the current cost of producing green hydrogen is relatively high compared with those of other types due to the cost of renewable energy sources and electrolysis technology. Efforts are underway to reduce costs through technological advancements, scaling up production, and increasing renewable energy capacity. Governments, industries, and research institutions worldwide are actively investing in the development of green hydrogen technologies and infrastructure to accelerate its adoption. This includes the establishment of electrolyzer manufacturing facilities, the construction of renewable energy projects, and the implementation of policies and incentives to promote green hydrogen production and utilization. In summary, the classification of hydrogen by color helps distinguish the various production methods and their environmental impacts. Blue hydrogen, gray hydrogen, brown hydrogen, and black hydrogen are associated with carbon emissions, while green hydrogen is produced using renewable energy sources and does not contribute to carbon emissions. The transition to green hydrogen is critical for achieving a sustainable and low-carbon future [92–95]. Color-classified hydrogen energies and their technology, cost, and CO₂ emissions are given in **Table 2**.

Table 2. Color-classified hydrogen energies and their production technology, cost, and CO₂ emissions.

Hydrogen color	Production technology	Cost	CO ₂ emissions
Blue	Steam reforming of natural gas with carbon capture and storage	Moderate	9–12 kg CO ₂ /kg H ₂
Gray	Steam reforming of natural gas without carbon capture and storage	Low	16–18 kg CO ₂ /kg H ₂
Brown	Gasification of coal or other hydrocarbon-rich feedstocks	Moderate	19–25 kg CO ₂ /kg H ₂
Black	Coal gasification with hydrogen separation and other gases released into the atmosphere	High	24–28 kg CO ₂ /kg H ₂
Green	Electrolysis of water using renewable energy sources	High	Zero CO ₂ emissions

Indeed, the cost and CO₂ emissions figures provided are meant to illustrate general trends and may vary depending on various factors. The specific technology employed for hydrogen production, the cost of energy and feedstock, and the efficiency of the production process can all influence the actual costs and emissions associated with hydrogen production. The cost of hydrogen production can vary depending on the availability and cost of the energy source used for electrolysis or the feedstock used in processes, such as steam methane reforming or gasification. Renewable energy prices have been decreasing in recent years, which contributes to the potential cost competitiveness of green hydrogen. Additionally, advancements in electrolysis technology and economies of scale can further drive down production costs. Similarly, CO₂ emissions associated with hydrogen production depend on the specific production method. Green hydrogen produced through electrolysis using renewable energy sources results in zero direct emissions. On the other hand, hydrogen produced from fossil fuels, such as natural gas or coal, can result in direct emissions, unless carbon capture and storage technologies are employed, as in the case of blue hydrogen. It is important to consider the evolving nature of hydrogen technologies, the ongoing research and development efforts, and the potential for future advancements in cost-effectiveness and emission reduction. As the hydrogen industry continues to grow and mature, innovations and economies of scale are expected to contribute to further cost reductions and emissions mitigation. Policy support, investment in research and development, and collaboration between industries, research institutions, and governments are crucial for driving the deployment of cost-effective and low-emission hydrogen technologies. These efforts will help maximize the potential of hydrogen energy in combating global warming and reducing greenhouse gas emissions.

For the past two centuries, hydrogen has played a crucial role in industrial applications. The demand for hydrogen has significantly increased, surpassing 80 Mt per year, which is more than three times the demand in 1975, and this demand continues to rise. However, the current production of hydrogen relies heavily on fossil

fuels. Approximately 6% of global natural gas and 2% of global coal are consumed in the production of hydrogen. Unfortunately, this process leads to the emission of around 830 Mt of CO₂ annually. In recent years, there has been a growing interest in hydrogen energy due to its potential to establish a fully renewable energy system, similar to an electricity grid. Hydrogen has the capacity to enable sector integration, which is essential for transitioning to a sustainable and low-carbon energy system. By utilizing renewable energies, such as wind power, solar power, or hydropower, to produce hydrogen through electrolysis, it is possible to decarbonize energy end uses [96,97]. The concept of a renewable hydrogen energy system involves producing hydrogen using renewable energy sources, storing it, and utilizing it in various sectors, including transportation, industry, and power generation. Hydrogen can be stored and transported easily, making it a versatile energy carrier. It can be used in fuel cells to generate electricity or directly burned as a clean fuel, emitting only water vapor as a byproduct. Implementing a renewable hydrogen energy system offers several benefits. It enables the integration of intermittent renewable energy sources into an energy grid by providing energy storage capabilities. Excess renewable energy generated during periods of low demand can be used to produce hydrogen, which can then be stored and converted back to electricity during peak demand periods. This helps to stabilize the grid and maximize the utilization of renewable energy resources. Furthermore, utilizing hydrogen as an energy source can help decarbonize sectors that are challenging to electrify directly, such as heavy-duty transportation, industrial processes, and heating applications. By replacing fossil fuels with hydrogen, these sectors can significantly reduce their carbon emissions, contributing to global efforts to mitigate climate change. To fully realize the potential of hydrogen energy, further advancements are required in areas such as hydrogen production technologies, storage methods, and infrastructure development. Additionally, the cost of renewable hydrogen production needs to be reduced to achieve competitiveness with fossil-fuel-based hydrogen. Governments, industries, and research institutions are actively investing in research and development to accelerate the deployment of renewable hydrogen technologies. Initiatives and pilot projects are underway globally to explore the feasibility and scalability of renewable hydrogen production and utilization. Hence, hydrogen energy presents an opportunity to establish a fully renewable energy system and decarbonize various sectors of the economy. By shifting from fossil-fuel-based hydrogen production to renewable hydrogen production, it is possible to reduce greenhouse gas emissions, promote sustainability, and support the transition to a clean and low-carbon future.

Hydrogen production through the use of renewable energy sources is poised to become technologically and economically viable in the near future. The declining costs of renewable energy technologies and the increasing market share of variable renewable power sources have created significant opportunities for cost-effective water electrolysis, a key process in hydrogen production. These advancements have paved the way for the development of cheaper and more efficient electrolyzers. The integration of artificial intelligence (AI) technology has also played a crucial role in accelerating the deployment of renewable hydrogen production. AI algorithms can optimize the performance of electrolyzers, enabling enhanced efficiency and

productivity [98,99]. Moreover, through deployment and learning-by-doing, the costs associated with electrolyzer manufacturing and supply chain logistics are expected to decrease further. Following the production of hydrogen via electrolysis, the development of safe and low-cost storage and transportation technologies is essential. Hydrogen can be stored in different states, which are as a gas or liquid, or in a solid-state material. Each storage method has its advantages and considerations:

- 1) **Gas storage:** Hydrogen gas can be stored in high-pressure tanks or in underground caverns. High-pressure storage is suitable for stationary applications, while underground storage is more suitable for large-scale and long-term storage. The challenge lies in ensuring the safety and integrity of high-pressure systems and addressing potential leakage issues.
- 2) **Liquid storage:** Hydrogen can be liquefied by cooling it to extremely low temperatures ($-253\text{ }^{\circ}\text{C}/-423\text{ }^{\circ}\text{F}$). Liquid hydrogen occupies less space compared with that of its gaseous form, enabling more efficient storage and transportation. However, liquefaction requires energy-intensive processes, and there are challenges associated with maintaining low temperatures and preventing boil-off.
- 3) **Solid-state storage:** Solid-state materials, such as metal hydrides or chemical compounds, can absorb and release hydrogen under specific conditions. These materials offer the advantage of dense hydrogen storage and improved safety. Research is ongoing to develop advanced solid-state storage materials with enhanced hydrogen storage capacity and release kinetics.

Hydrogen energy can play a significant role in combating global warming and reducing GHG emissions. The contributions of hydrogen energy toward these goals are as follows [100–102]:

- 1) **Decarbonizing energy systems:** Hydrogen can serve as a clean energy carrier that helps decarbonize various sectors, including transportation, industry, and power generation. By replacing fossil fuels, such as coal, oil, and natural gas, with hydrogen, carbon emissions can be significantly reduced. Hydrogen produced using renewable energy sources through electrolysis (green hydrogen) enables a carbon-neutral energy system.
- 2) **Zero emissions in use:** Hydrogen holds the advantage of producing zero emissions during its use. For instance, in the transportation sector, hydrogen fuel cell vehicles (FCVs) produce only water vapor as a byproduct of the chemical reaction between hydrogen and oxygen. This eliminates CO_2 and other harmful emissions associated with conventional combustion engines.
- 3) **Sector coupling and energy integration:** Hydrogen has the potential to facilitate sector coupling, which involves integrating different energy sectors to achieve greater efficiency and emission reduction. For example, surplus renewable energy can be used to produce hydrogen through electrolysis during times of high generation. The stored hydrogen can then be utilized in power generation during periods of low renewable energy availability. This enables the balancing of intermittent renewable energy sources and improves overall grid stability.
- 4) **Industrial decarbonization:** Hydrogen can be used as a clean fuel and feedstock in various industrial processes, such as refining, chemical production, and steelmaking. By replacing fossil fuels with hydrogen, emissions from these

energy-intensive industries can be significantly reduced. Additionally, hydrogen can enable the production of synthetic fuels, such as hydrogen-based ammonia or synthetic methane, which can act as low-carbon alternatives to conventional fuels.

- 5) Carbon capture and storage (CCS): Hydrogen production processes, such as steam methane reforming (SMR), can be coupled with carbon capture and storage technologies (CCS). This results in the production of blue hydrogen, where the CO₂ emissions generated during production are captured and stored underground. CCS can effectively reduce GHG emissions associated with hydrogen production from fossil fuel sources.
- 6) Renewable energy integration: Hydrogen can help address the intermittency of renewable energy sources by storing excess renewable energy for later use. This allows for better integration of renewable energy into grids, as hydrogen can be used as a form of energy storage and dispatched when there is high demand or low renewable energy availability. This flexibility helps to reduce the curtailment of renewable energy and maximize its utilization.
- 7) Global collaboration and policy support: Governments, international organizations, and industry stakeholders are recognizing the potential of hydrogen energy in combating global warming. Several countries have developed hydrogen strategies and are implementing supportive policies, including financial incentives, research and development funding, and regulatory frameworks. International collaborations have also been established to accelerate the deployment of hydrogen technologies and foster knowledge sharing.

It is important to note that the overall impact of hydrogen energy on reducing GHG emissions depends on how it is produced. Green hydrogen, produced using renewable energy sources, offers the greatest potential for significant emission reduction. However, the deployment of hydrogen technologies at scale and the continued growth of renewable energy capacity are essential to maximize hydrogen energy's positive contribution to combating global warming and reducing GHG emissions.

The decarbonization of the global energy system relies on several key pillars, including energy efficiency, behavioral change, electrification, renewables, hydrogen and hydrogen-based fuels, and carbon capture, utilization, and storage (CCUS). Hydrogen plays a crucial role in achieving a net zero emissions scenario, as evidenced by its increasing share in cumulative emission reduction. This highlights the growing significance of hydrogen in driving the transition to a low-carbon future.

The importance of hydrogen stems from its ability to address sectors that are challenging to decarbonize, such as heavy industry and long-distance transport, where emission reduction is particularly difficult. The strong growth in hydrogen demand and the adoption of cleaner technologies for hydrogen production enable hydrogen and hydrogen-based fuels to make a substantial contribution in the net zero emissions scenario. By leveraging hydrogen as an energy carrier, these sectors can significantly reduce their greenhouse gas emissions.

In practical terms, adopting hydrogen and hydrogen-based fuels offers a pathway to decarbonize sectors that heavily rely on fossil fuels, such as steel production, cement

manufacturing, and long-haul transportation. Hydrogen can be used as a clean fuel source, either directly or in fuel cells, providing a viable alternative to conventional energy sources. Additionally, hydrogen can be utilized as a feedstock for the production of synthetic fuels, such as hydrogen-based ammonia or synthetic methane, further expanding its applicability in various industries [103].

By integrating hydrogen into the energy system and promoting the adoption of cleaner hydrogen production technologies, the net zero emissions scenario can be achieved more effectively. This underscores the importance of hydrogen as a key solution for decarbonization, particularly in sectors where emission reduction is challenging, contributing to a sustainable and low-carbon future. A cumulative emission reduction of CO₂ between 2021–2050 is presented in **Table 3**.

Table 3. Cumulative emission reduction of CO₂ (2021–2050).

Mitigation measure in net zero scenario	Cumulative emission reduction
Electrification	19%
Renewable	35%
Hydrogen	6%
Technology performance	13%
Behavior and avoided demand	11%
Other fuel shifts	5%
CCUS (carbon dioxide capture, utilization, and storage)	11%

From **Figure 18**, Australia has made a noteworthy entry in the field of renewable energy, particularly due to the Australia Renewable Energy Hub project. This project is anticipated to commence in 2030. However, any delays in its implementation could push back Australia's target of reaching 1.5 Mt of green hydrogen production annually to 2030 instead of the initially projected year of 2029. The difference of 10,000 tons between Australia and the United States in terms of their capacity in 2030 signifies that, at present, these two countries can be considered on equal footing. This is particularly significant considering that Australia's position is contingent upon the successful installation of precisely a single project in 2030. Spain's prominent position among the top players in renewable energy comes as no surprise. The Spanish government has already approved ten major projects, including Fertiberia and Iberdrola's Puertollano project. The Puertollano project was commissioned in 2023 and is expected to have an annual production of 200,000 tons of green hydrogen. These developments further establish Spain's strong presence and commitment to the renewable energy sector. Canada secures the fourth position in hydrogen production in 2030, with an estimated quantity of 1.5552 Mt. This signifies Canada's significant contribution to the global production of hydrogen, highlighting its growing role in the renewable energy landscape. The country's efforts in advancing hydrogen technologies and infrastructure have positioned it as a key player in the industry, further solidifying its commitment to sustainable energy solutions [104,105].

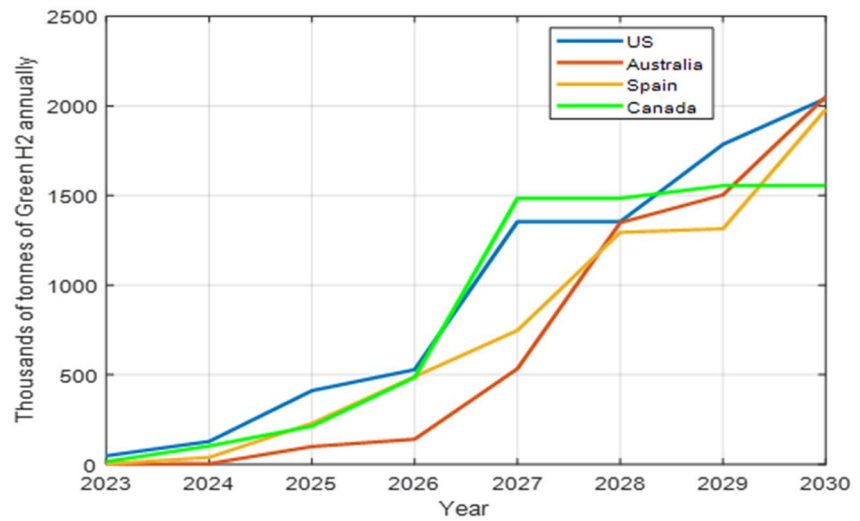


Figure 18. Leading countries for green hydrogen production (2023–2030).

4.7.1. Key points

- **Versatile energy carrier:** Hydrogen is a versatile energy carrier that can be produced from various sources, such as renewable energy (e.g., electrolysis) or fossil fuels (e.g., steam methane reforming). It can be used in fuel cells to generate electricity with high energy efficiency or directly burned in combustion engines.
- **Clean and zero emissions:** Hydrogen combustion or fuel cell operation produces only water vapor as a byproduct, making it a clean energy option with zero greenhouse gas emissions when produced from renewable sources.
- **Energy storage and grid balancing:** Hydrogen can be used for long-term energy storage, allowing excess renewable energy to be stored and utilized when demand exceeds supply. It can also help balance intermittent renewable energy generation and enhance grid stability.
- **Decarbonizing difficult sectors:** Hydrogen has the potential to decarbonize sectors that are challenging to electrify directly, such as heavy industries, long-haul transportation, and aviation.
- **Scalability and infrastructure:** Hydrogen infrastructure, including production, storage, transportation, and distribution networks, needs further development to support widespread adoption. Scaling up hydrogen production and ensuring a reliable supply chain are crucial challenges.

4.7.2. Challenges

- **Cost competitiveness:** One of the main challenges is reducing the cost of hydrogen production, which is currently higher compared with that of conventional fuels. Advancements in technology, economies of scale, and policy support are needed to drive down costs.
- **Renewable hydrogen production:** Scaling up renewable hydrogen production through electrolysis requires significant investments in renewable energy sources and efficient electrolysis technologies.

- Storage and transportation: Developing cost-effective hydrogen storage and transportation methods, such as compressed hydrogen or hydrogen carriers, is crucial to ensure reliable supply and distribution.
- Safety considerations: Hydrogen has different safety considerations compared with those of conventional fuels, such as its flammability and potential for leaks. Robust safety protocols and standards are necessary to address these concerns.
- Policy and market support: Establishing supportive policies, incentives, and regulations that promote hydrogen infrastructure development, research and development, and market uptake is vital to overcoming barriers and creating a favorable market environment.

Therefore, hydrogen energy offers significant benefits in terms of renewable energy generation and decarbonization potential, addressing the challenges associated with their applications is essential for their widespread adoption and successful integration into the energy transition.

5. Technical analysis

While the paper provides a comprehensive overview of various renewable energy sources and their potential impacts, a more in-depth technical examination of the underlying principles, performance metrics, and engineering/technological advancements could strengthen the review.

5.1. Technological innovations and improvements in RE systems

1) Solar PV modules' efficiency advancements:

- The development of new solar cell materials, such as perovskites and tandem cell structures, has led to record-breaking solar PV module efficiencies in the laboratory, reaching over 29% for single-junction cells and 30% for multi-junction cells.
- Innovations in manufacturing processes, including the use of advanced thin-film deposition techniques and the implementation of intelligent tracking systems, have further enhanced the efficiency and cost-effectiveness of commercial solar PV modules.
- The integration of smart inverter technologies and the optimization of module-level power electronics have improved the overall system-level efficiency and performance of solar PV module installations.

2) Wind turbine design improvements:

- Advancements in blade aerodynamics, including the use of longer and more efficient blades, have increased the swept area and power output of wind turbines.
- The adoption of variable-speed generators and advanced pitch control systems has enhanced the ability of wind turbines to adapt to changing wind conditions, improving overall energy generation.
- Innovations in tower design, such as the use of taller and lighter structures, have enabled the deployment of wind turbines in sites with higher wind speeds, further boosting energy production.

- Improvements in nacelle and drivetrain components, including the use of permanent magnet synchronous generators and advanced gearbox technologies, have led to increased reliability and reduced maintenance costs for wind turbines.
- 3) Energy storage solutions:
- The rapid development of lithium-ion battery technology has resulted in significant improvements in energy density, power output, and cycle life, making battery energy storage systems more viable for grid-scale applications.
 - Advancements in flow battery technologies, such as vanadium redox and zinc–air batteries, have demonstrated the potential for long-duration energy storage to complement the intermittency of renewable energy sources.
 - Innovations in thermal energy storage, including the use of molten salt and phase change materials, have enabled the storage of excess renewable energy for later use, improving the overall dispatchability of renewable power.
 - The integration of artificial intelligence and machine learning algorithms into energy storage management systems has optimized charging and discharging cycles, enhancing the efficiency and cost-effectiveness of energy storage solutions.

5.2. Comparative evaluation of technical capabilities and limitations

- 1) Power generation:
- Solar PV power: Highly modular and scalable, with the ability to generate electricity from small-scale rooftop systems to large-scale utility-scale plants; however, solar power generation is intermittent and dependent on available sunlight.
 - Wind power: Capable of generating large-scale utility-level power, especially in areas with high wind resources; wind turbines can be deployed both onshore and offshore, but their power output is variable and dependent on wind conditions.
 - Hydropower: Able to provide consistent and reliable baseload power, with the added benefit of energy storage capabilities through reservoir management; however, hydropower projects are typically site-specific and limited by geographic and environmental constraints.
 - Geothermal energy: Provides a reliable and consistent source of baseload power, with the potential for long-term sustainability; geothermal resources are, however, limited to specific regions with suitable geological conditions.
- 2) Grid integration:
- Solar PV power and wind power: Require advanced grid management techniques, including forecasting, energy storage, and flexible generation, to address the intermittent nature of their power output and ensure grid stability.
 - Hydropower and geothermal energy: More easily integrated into grids due to their consistent and predictable power generation, which can be readily dispatched to meet demand.

- All renewable technologies: Benefit from the development of smart grid technologies, improved transmission infrastructure, and energy storage solutions to enhance grid integration capabilities.
- 3) Scalability:
- Solar PV power and wind power: Highly scalable, with the ability to rapidly deploy distributed and utility-scale projects to meet growing energy demands.
 - Hydropower and geothermal energy: Scalability is limited by site-specific resource availability and environmental constraints, requiring careful planning and long-term development timelines.
 - All renewable technologies: Scaling up renewable energy capacity requires significant investments in manufacturing, supply chain, and infrastructure development to support large-scale deployment.

5.3. Assessment of cutting-edge research and development efforts

- 1) Solar PV module advancements:
- Perovskite solar cells: Research has demonstrated the potential for perovskite materials to achieve high efficiencies (over 25%) at low manufacturing costs, with ongoing efforts to improve stability and commercial viability.
 - Tandem solar cells: Combining multiple solar cell layers, such as silicon and perovskite, has shown the ability to exceed the Shockley-Queisser limit, reaching efficiencies over 30% in the lab.
 - Bifacial solar modules: Capturing light from both the front and rear surfaces of solar cells can increase energy yield by up to 30%, with advancements in module design and materials.
- 2) Wind turbine innovations:
- Larger, more efficient blades: Researchers are exploring innovative blade designs, such as curved tips and adaptive pitching, to enhance aerodynamic performance and energy capture.
 - Floating offshore wind turbines: Developing platforms and mooring systems to enable the deployment of wind turbines in deeper waters, hence expanding available wind resources.
 - Superconducting generators: The use of high-temperature superconducting materials in wind turbine generators can lead to a significant reduction in mass and increased power density.
- 3) Energy storage breakthroughs:
- Solid-state batteries: Ongoing research into solid-state electrolytes promises to increase the energy density, safety, and cycle life of battery storage systems.
 - Flow batteries: Advancements in flow battery technologies, such as organic-based and metal-air systems, aim to provide long-duration energy storage at lower costs.
 - Thermal energy storage: Innovations in materials and system design, including the use of phase change materials and thermochemical storage, can improve the efficiency and cost-effectiveness of thermal energy storage.
- 4) System integration and grid optimization:

- Advanced power electronics: Developing more efficient, compact, and intelligent power conversion systems to better integrate renewable energy sources into grids.
- Artificial intelligence and machine learning (ML): Applying AI and ML algorithms to optimize renewable energy forecasting, grid dispatch, and energy storage management, hence improving overall system performance.
- Sector coupling: Exploring the integration of renewable energy with other sectors, such as transportation, heating/cooling, and industrial processes, to enhance system-wide efficiency and flexibility.

5.4. Technical challenges and feasibility

1) Intermittency and variability:

- The intermittent and variable nature of renewable energy sources, such as solar and wind, can create challenges in maintaining reliable and stable electricity grids.
- Addressing this issue requires a multi-pronged approach, including improved forecasting, flexible generation, and the deployment of large-scale energy storage solutions.

2) Grid integration and modernization:

- Integrating a high penetration of renewable energy sources into existing grid infrastructures can be technically complex, requiring upgrades to transmission and distribution systems, as well as advancements in smart grid technologies.
- Enhancing grid flexibility, through the use of advanced power electronics, intelligent control systems, and improved demand-side management, is crucial for seamless integration of renewable energy.

3) Scalability and manufacturing capacity:

- Transitioning to a renewable-based energy system at scale requires a significant ramp-up in manufacturing capacity for solar PV cells, wind turbines, batteries, and other renewable energy components.
- Developing robust supply chains, streamlining production processes, and investing in R&D to improve manufacturing efficiency and reduce costs are essential for achieving the required deployment rates.

4) Geographic and resource constraints:

- The distribution of renewable energy resources, such as solar irradiation and wind patterns, is often uneven across regions, which can pose challenges in ensuring equitable access to renewable energy.
- Overcoming these geographic constraints may require the development of large-scale, interconnected transmission networks, as well as the exploration of alternative renewable energy sources, such as offshore wind and geothermal energy.

5) Energy storage and flexibility:

- The ability to store and dispatch renewable energy when needed is crucial for the successful transition to a renewable-based system.
- Advancements in energy storage technologies, including batteries, pumped-storage hydropower, and thermal energy storage, as well as the integration of

these solutions with smart grid infrastructure, are essential for providing the required flexibility and reliability.

- 6) Social acceptance and regulatory frameworks:
 - Achieving a successful transition to a renewable-based energy system also requires addressing social acceptance challenges, such as concerns about visual impacts, land use, and environmental impacts of renewable energy projects.
 - Developing appropriate regulatory frameworks, policies, and incentives can help facilitate the large-scale deployment of renewable energy technologies and ensure a just and equitable transition.

6. Discussion

6.1. Challenges of integration of RE in electrical networks

The integration of renewable energy sources into existing electrical networks poses several challenges. These challenges are primarily related to the intermittent and variable nature of renewable resources such as sunlight, wind, and ocean waves. The following issues are commonly encountered when incorporating renewable energy technologies into AC grids, as illustrated in **Figure 19**:



Figure 19. Main challenges of RE integration

- 1) Power quality: The fluctuating nature of renewable energy generation can affect the stability and quality of power supplied to a grid. Variations in voltage and frequency can lead to issues, such as voltage sags, swells, and harmonics.

Maintaining consistent power quality standards becomes crucial to ensure the reliable and efficient operation of electrical grids.

- 2) **Cost:** The cost of implementing renewable energy technologies, such as solar panels or wind turbines, can be a significant challenge. The initial capital investment required for infrastructure development, equipment installation, and grid integration can be substantial. Additionally, the costs associated with intermittency management, energy storage systems, and backup power sources add to the overall expenses.
- 3) **Availability of power:** Unlike traditional power plants, renewable energy sources are dependent on natural resources, which can vary in availability. For example, solar power generation is affected by weather conditions and the availability of sunlight, while wind power is influenced by wind speed and consistency. Ensuring a reliable and steady power supply becomes challenging when relying solely on these intermittent resources.
- 4) **Location of renewable energy resources:** The optimal locations for renewable energy generation, such as areas with high solar irradiation or strong wind resources, may not always coincide with existing grid infrastructures. Developing transmission lines and grid connections from remote renewable energy sites to load centers can involve significant logistical and financial challenges.
- 5) **Changes in power:** The integration of large amounts of renewable energy can result in significant changes in power flow patterns within a grid. This can lead to congestion in certain parts of the grid and necessitate upgrades and modifications to the existing transmission and distribution infrastructure.
- 6) **Speed of power changes:** Renewable energy sources can experience rapid changes in output due to weather conditions or other factors. The sudden injection or reduction of power into the grid can strain the stability of a system and require robust control and balancing mechanisms to maintain grid reliability.
- 7) **Power forecasting:** Accurate forecasting of renewable energy generation is crucial for grid operators to effectively plan and manage the energy supply. However, forecasting renewable energy output can be challenging due to the inherent variability of weather patterns and the limited predictability of natural resources.

Addressing these challenges requires the development of advanced grid management technologies, energy storage systems, demand response mechanisms, and flexible grid infrastructure. Ongoing research and technological advancements aim to improve the integration of renewable energy sources into grids, ensuring a reliable, cost-effective, and sustainable energy supply.

6.2. Challenges of production of RE

The production of renewable energy faces several challenges that can hinder its widespread adoption and implementation. Some of the key challenges include:

- 1) **Intermittency and variability:** Unlike conventional power generation methods, renewable energy sources such as solar and wind are intermittent and variable in nature. They depend on factors, such as weather conditions and natural resources availability, which can result in fluctuations in power output. This intermittency

poses challenges to grid stability and requires efficient energy storage and grid management systems to balance supply and demand.

- 2) **Grid integration:** Integrating renewable energy into existing electrical grids can be challenging. Grid infrastructures and transmission systems have been primarily designed for centralized fossil-fuel-based power plants. Incorporating decentralized renewable energy sources, such as rooftop solar panels or small wind turbines, requires upgrades and modifications to ensure efficient and reliable grid integration.
- 3) **Cost and financial barriers:** While the cost of renewable energy technologies has been decreasing, the upfront investment costs can still be significant. The installation, maintenance, and grid connection expenses may pose financial barriers, particularly for individuals, communities, or developing countries with limited financial resources. Access to affordable financing options and supportive policies are crucial to overcoming these cost barriers.
- 4) **Land and resource requirements:** Large-scale deployment of renewable energy infrastructure, such as solar farms or wind parks, requires considerable land availability. Identifying suitable locations and addressing land-use conflicts can be challenging, particularly in densely populated areas or regions with competing land uses. Additionally, renewable energy technologies may also require specific resources, such as rare earth elements for wind turbines or lithium for energy storage, which can present supply chain and environmental sustainability challenges.
- 5) **Technological advancements and infrastructure:** Continued advancements in renewable energy technologies are necessary to improve efficiency, reliability, and cost-effectiveness. Research and development efforts are focused on developing more efficient solar panels, advanced wind turbine designs, energy storage solutions, and grid management systems. The deployment of these technologies also requires the development of supporting infrastructure, such as charging stations for electric vehicles or smart grid systems.
- 6) **Policy and regulatory frameworks:** Clear and consistent policy frameworks are essential to support the growth and development of renewable energy. Favorable regulations, including feed-in tariffs, tax incentives, and renewable energy targets, can stimulate investment and create a conducive environment for renewable energy production. Inconsistent or changing policies, lack of supportive regulations, and bureaucratic barriers can impede progress in renewable energy production.
- 7) **Public acceptance and social factors:** Public acceptance and support play a crucial role in the successful deployment of renewable energy projects. Concerns related to visual impacts, noise, land-use conflicts, and perceived health effects may lead to public resistance and opposition. Effective communication, community engagement, and addressing these concerns are essential to gain public acceptance and ensure the social sustainability of renewable energy projects.

Overcoming these challenges requires a multi-faceted approach involving technological advancements, supportive policies, financial incentives, public awareness, and stakeholder collaboration. Addressing these challenges will contribute

to the increased adoption of renewable energy sources and the transition towards a more sustainable and low-carbon energy future.

6.3. Challenges of renewable energy in combating phenomenon of global warming

Renewable energy play a crucial role in combating the phenomenon of global warming by reducing greenhouse gas emissions. However, they also face several challenges in their deployment and integration. Some of the key challenges of renewable energy in combating global warming include:

- 1) **Grid integration and infrastructure:** Integrating large-scale renewable energy sources into existing electrical grids can be technically challenging. The grid infrastructure, designed for centralized fossil-fuel-based power plants, may require upgrades and modifications to accommodate decentralized and variable renewable energy sources. Expanding transmission networks and grid infrastructure to connect renewable energy sites to load centers can also present logistical and financial challenges.
- 2) **Cost and financing:** While the costs of renewable energy technologies have been declining, they still face financial barriers. The initial installation costs, including equipment and infrastructure, can be high. Integration costs, such as energy storage systems, grid upgrades, and backup power sources, further add to the expenses. Access to affordable financing options, supportive policies, and incentives are crucial to overcoming cost barriers and promoting renewable energy deployment.
- 3) **Resource availability and land use:** The availability of renewable energy resources, such as suitable land for solar or wind farms, can pose challenges. Identifying appropriate locations with high resource potential, while minimizing environmental impacts and land-use conflicts, can be complex. Competing land uses, regulatory restrictions, and community acceptance can also affect the development of renewable energy projects.
- 4) **Policy and regulatory frameworks:** Clear and consistent policy frameworks are essential to support the deployment of renewable energy. Favorable regulations, including feed-in tariffs, renewable portfolio standards, and carbon pricing mechanisms, can incentivize investments in renewable energy projects. However, inconsistent or inadequate policies, regulatory barriers, and uncertainties in government support can hinder the growth and deployment of renewable energy.
- 5) **Public acceptance and social factors:** Public acceptance and support are vital for the successful deployment of renewable energy projects. Concerns about visual impacts, noise, land use, and potential environmental effects can lead to opposition and delays in project development. Effective community engagement, stakeholder involvement, and addressing these concerns are crucial for gaining public acceptance and ensuring the social sustainability of renewable energy initiatives.

Addressing these challenges requires a comprehensive approach involving technological innovation, supportive policies and regulations, financial incentives,

public awareness, and stakeholder engagement. Collaboration between governments, businesses, communities, and research institutions is crucial to overcoming these challenges and accelerating the adoption of renewable energy in combating global warming.

6.4. Potential solutions to intermittency and variability of RE sources

There are several potential solutions to address the intermittency and variability of renewable energy sources:

- 1) **Energy storage systems:** Energy storage technologies, such as batteries, pumped hydro storage, and thermal storage, can store excess energy generated during periods of high renewable energy production and release it during periods of low generation. Energy storage systems help balance the supply and demand of electricity, improve grid stability, and provide a reliable power supply when renewable sources are not actively generating electricity.
- 2) **Demand response programs:** Demand response programs involve adjusting electricity consumption in response to supply conditions. Consumers can shift their electricity usage to align with periods of high renewable energy production. For example, charging electric vehicles or running industrial processes during times of surplus renewable energy. By actively managing demand, grids can better match supply and demand, reducing the impact of intermittency.
- 3) **Grid flexibility and interconnection:** Enhancing the flexibility and interconnection of electrical grids allows for the efficient integration of renewable energy sources. A well-connected grid can balance renewable energy generation across different regions, taking advantage of variations in weather conditions and renewable resource availability. It enables surplus energy from one area to be transmitted to another area experiencing higher demand.
- 4) **Hybrid systems and diversification:** Combining multiple renewable energy sources and technologies can help mitigate intermittency. Hybrid systems, such as wind-solar or solar-battery combinations, can provide a more consistent and reliable electricity supply. Diversifying the renewable energy mix, including geothermal, biomass, and tidal energy, can also contribute to a more balanced and less intermittent energy generation profile.
- 5) **Forecasting and advanced grid management systems:** Accurate weather forecasting and advanced grid management systems can help anticipate and optimize renewable energy generation. By leveraging weather data and predictive analytics, grid operators can better forecast renewable energy generation patterns and plan grid operations accordingly. Real-time monitoring and control systems enable rapid adjustments to ensure grid stability and balance supply and demand.
- 6) **Interconnection with other energy systems:** Integrating renewable energy systems with other energy sectors, such as heat and transportation, can enhance their flexibility and reduce curtailment. Power-to-heat technologies can convert excess electricity into heat for industrial or residential use, while power-to-gas technologies can produce renewable hydrogen or synthetic natural gas for energy storage or transportation applications.

- 7) **Smart grid technologies and microgrids:** Smart grid technologies, including advanced metering, grid automation, and intelligent energy management systems, enable more efficient and dynamic grid operations. They facilitate real-time monitoring, optimization, and coordination of renewable energy generation, energy storage, and demand response. Microgrids, which are localized energy systems, can operate autonomously or in coordination with the main grid, providing localized resilience and balancing intermittent generation with local demand.

It is important to note that the optimal solution or combination of solutions may vary depending on the specific characteristics of the renewable energy resource, the local grid infrastructure, and the energy demand patterns. A holistic and integrated approach considering technical, economic, and regulatory aspects is necessary to effectively address the intermittency and variability of renewable energy sources.

7. Conclusion

The phenomenon of global warming poses significant challenges to our planet and requires urgent action to mitigate its impacts. The paper has highlighted the crucial role of renewable energy technologies in combating global warming by reducing greenhouse gas emissions and transitioning to sustainable energy sources. Renewable energy offers promising solutions to the energy sector, with the potential to eliminate carbon from a significant portion of electricity generation by 2050. By harnessing renewable sources, such as solar power, wind power, hydropower, and geothermal power, we can minimize our reliance on fossil fuels and mitigate the release of greenhouse gases into the atmosphere. In this paper, the commitment of leading countries, such as China, the United States, India, and Germany, to renewable energy development has also been discussed. These countries have made significant investments and achieved substantial renewable energy generation capacities, demonstrating their dedication to combating global warming. However, it is essential to note that the energy landscape is constantly evolving, and further progress is expected in renewable energy development.

While renewable energy technologies have made significant strides, there is still much work to be done to combat global warming effectively. The following areas can be explored for future research and action:

- 1) **Technological advancements:** Continued research and development in renewable energy technologies are vital for improving efficiency, reducing costs, and expanding their scalability. This includes advancements in energy storage solutions, grid integration, and innovative approaches to harnessing renewable sources.
- 2) **Policy and regulatory frameworks:** Governments and policymakers should continue to implement supportive policies and regulatory frameworks that promote renewable energy adoption. This includes incentives, subsidies, and targets for renewable energy generation to accelerate the transition away from fossil fuels.
- 3) **International collaboration:** Global cooperation and knowledge sharing among countries are essential for addressing the challenges of global warming.

Collaborative efforts can involve sharing best practices, technology transfer, and joint research initiatives to accelerate renewable energy deployment worldwide.

- 4) Education and awareness: Public awareness and understanding of the benefits of renewable energy are crucial for driving individual and collective action. Educational campaigns, outreach programs, and information dissemination can play a significant role in promoting renewable energy adoption and behavioral changes.
- 5) Sustainable land use and ecosystem preservation: Protecting ecosystems and promoting sustainable land use practices are essential for mitigating the impacts of global warming. This includes preserving forests, promoting sustainable agriculture, and minimizing land degradation, which can contribute to carbon sequestration and biodiversity conservation.
- 6) Decentralized energy systems: Exploring decentralized energy systems, such as community-based renewable energy projects and microgrids, can enhance energy resilience, reduce transmission losses, and increase access to clean energy in remote areas.

Briefly, future efforts should focus on technological advancements, supportive policies, international collaboration, education and awareness, sustainable land use, and decentralized energy systems to further accelerate the transition to renewable energy and combat global warming effectively. By collectively addressing these areas, we can strive towards a low-carbon and sustainable future, mitigating the impacts of global warming and ensuring a resilient planet for future generations.

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