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Renewable energy sources: Progress, challenges, and environmental benefits

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ABSTRACT

Available online–This paper presents an integrated analysis of renewable energy sources in 2023 using international energy and climate datasets published during 2023 and 2024. The study examines developments in solar, wind, hydropower, bioenergy, geothermal, marine, and hydrogen technologies and evaluates their contribution to global energy supply in the context of Net Zero Emissions (NZE) targets. Renewable energy deployment continued to expand during 2023 and reached its highest annual growth on record. Global renewable capacity additions amounted to 510 GW, while solar and wind technologies represented 96% of new installations. As a result, renewable electricity generation increased to 30% of global electricity production. The strongest growth was observed in solar PV, whose installed capacity increased by 346 GW and reached 1419 GW by the end of 2023. Despite these developments, the global energy system remained heavily dependent on fossil fuels. Fossil fuels accounted for 81.47% of total primary energy consumption, whereas the contribution of renewable energy sources was 14.56%. At the same time, global greenhouse gas emissions reached 53.0 $GtCO_{2eq}$, atmospheric CO_2 concentration increased to 419.3 ppm, and global temperature rose to $1.45 \pm 0.12^{\circ}C$ above pre-industrial levels. The study shows that several challenges continue to slow the expansion of renewable energy. Limitations in grid infrastructure, insufficient investment, policy and regulatory barriers, and inadequate energy storage capacity remain major constraints, particularly in developing economies. Although renewable energy deployment reached record levels in 2023, progress remained below the pace required to achieve NZE targets. Stronger policy support, expanded grid infrastructure, increased climate finance, and greater international cooperation will be necessary to close this gap and support further progress toward NZE targets.

1. Introduction

Since the Industrial Revolution, human activities have increased global temperatures and altered the Earth's climate system. The expansion of fossil fuel use, deforestation, and intensive livestock production has substantially increased the concentration of greenhouse gases (GHGs) in the atmosphere. Carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and fluorinated gases (F-gases) enhance the greenhouse effect and contribute significantly to climate change [1,2].

Major reductions in GHG emissions are necessary across key sectors such as power generation, industry, transportation, buildings, agriculture, and waste management to address climate change [3]. Renewable energy is a key part of this transition because it reduces reliance on fossil fuels and helps lower emissions. Renewable energy also provides benefits beyond environmental protection. It improves energy security, supports sustainable development, and creates economic opportunities. For these reasons, many countries have included renewable energy targets in their national energy policies and long-term energy transition plans [4].

Over the past two decades, clean energy sources have become an important part of sustainable development strategies [5]. Renewable energy sources generally have lower environmental impacts and produce fewer GHG emissions than fossil fuels [6]. In the past, many renewable energy technologies were considered too costly for

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Table 1
Summary of international energy and climate reports incorporated in the analysis.

Title	Publisher	Release Date	Features	Reference
Statistical Review of World Energy	Energy Institute	2024 (73rd edition)	• Global and Regional Data • Historical Perspective/Trends • World Energy Production, Consumption, and Emissions.	[10]
World Energy and Climate Statistics	Enerdata	Yearbook 2024	• Comprehensive Data: production, consumption, and trade of oil, gas, coal, power, and renewables, along with CO2 emissions from fuel combustion. • Global Coverage	[11]
Climate Change: Atmospheric Carbon Dioxide (Annual Report)	NOAA's Global Monitoring Lab	April 9, 2024	• Climate science • Climate-related events	[12]
WMO Global Annual to Decadal Climate Update (2024-2028)	World Meteorological Organization (WMO)	June 5, 2024	• Climate monitoring • Climate services • Climate change	[13]
Renewables 2023	International Energy Agency	January, 2024	• Forecasts the deployment of renewable energy technologies in electricity, transport and heat to 2028. • Exploring key challenges to the industry and identifying barriers to faster growth.	[15]
Renewables 2024	International Energy Agency	October, 2024	• Forecasts the deployment of renewable energy technologies in electricity, transport and heat to 2030. • Exploring key challenges facing the industry and identifying barriers that are preventing faster growth.	[16]
Global Electricity Review	EMBER	May, 2024	• An overview of the changes in global power generation in 2023, the trends behind them and the likely implications for energy sources and power sector emissions in the near future.	[21]
Renewable capacity statistics 2024	IRENA	2024	• Growth of renewables in new installed electricity generation capacity for 2014-2023.	[22]
Renewable energy statistics 2024	IRENA	2024	• Provide datasets on power-generation capacity for 2014-2023, actual power generation for 2014-2022 and renewable energy balances for over 150 countries and areas for 2021-2022.	[23]
Solar Heat Worldwide	IEA Solar Heating & Cooling Programme	June, 2024	• Provide an overview of the general trends in the solar thermal industry. • Highlight unique applications and noteworthy projects within the sector. • Document the installed solar thermal capacity across key global markets. • Assess the contribution of solar thermal systems to energy supply and quantify the reduction in CO_2 emissions resulting from their operation.	[25]
GHG emissions of all world countries	Publications Office of the European Union	September, 2024	• Provides GHG emissions time series for all countries and for all anthropogenic sectors from 1970 until 2023, including emissions and removals from land use and forestry.	[26]
Global Hydrogen Review 2024	International Energy Agency	October, 2024	• Provides hydrogen production and demand worldwide, as well as progress in critical areas such as infrastructure development, trade, policy, regulation, investments and innovation.	[17]
IPCC Sixth Assessment Report	Intergovernmental Panel on Climate Change	2023	• Assessment of the scientific basis of climate change, its impacts and vulnerabilities, and the options for adaptation and mitigation.	[27]
Tracking Clean Energy Progress 2023	International Energy Agency	2023	• Assessment of the recent developments for over 50 components of the energy system that are critical for clean energy transitions. The components assessed include sectors, subsectors, technologies, infrastructure and cross-cutting strategies.	[18]
State of the Global Climate 2023	World Meteorological Organization	2024	• Provides overview of changes in the climate system.	[14]
Net Zero Roadmap: A Global Pathway to Keep the 1.5°C Goal in Reach	International Energy Agency	September, 2023	• Set out a narrow but feasible pathway for the global energy sector to contribute to the Paris Agreement's goal of limiting the rise in global temperatures to 1.5°C above pre-industrial levels.	[19]
World Energy Transitions Outlook 2023: 1.5°C Pathway	IRENA	June, 2023	• Presents a pathway to achieve the 1.5°C target by 2050, positioning electrification and efficiency as key transition drivers, enabled by renewable energy, clean hydrogen and sustainable biomass.	[24]
Emissions Gap Report 2023: Broken Record - Temperatures hit new highs, yet world fails to cut emissions	United Nations Environment Programme	2023	• To track the gap between where global emissions are heading with country commitments as of 2023 and where they ought to be to limit warming to 1.5°C.	[28]
Global EV Outlook 2024	International Energy Agency	April, 2024	• Identifies and assesses recent developments in electric mobility across the globe.	[20]

large-scale deployment. However, technological progress, improved manufacturing processes, and declining costs have increased their economic competitiveness. As a result, several renewable energy technologies are now cost-effective options for households, businesses, and governments [7]. Many countries have increased investments in advanced energy technologies and energy systems to reduce carbon emissions and expand clean energy production [8]. Renewable energy deployment helps lower GHG emissions, supports climate change mitigation, and decreases reliance on fossil fuels [9]. Although renewable energy has been widely studied, there is still a need for integrated assessments that combine international energy statistics with climate indicators across multiple sectors. Most existing studies focus on specific areas such as renewable energy deployment, electricity demand, GHG emissions, or climate indicators. Only a limited number of studies examine these factors together by using international energy and climate data. This paper addresses this gap through an integrated assessment of renewable energy developments, related challenges, and environmental impacts in 2023. The study also evaluates these

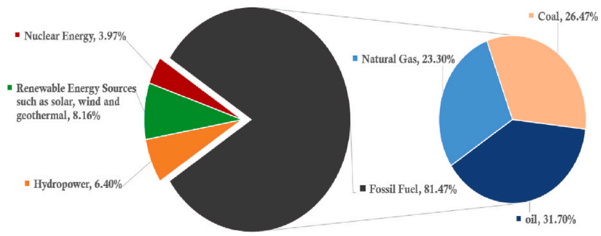

Fig. 1. World total primary energy consumption in 2023.

developments in relation to international climate agreements and the Net Zero Emissions (NZE) pathway.

This study examines solar, wind, hydropower, bioenergy, geothermal, marine, and hydrogen technologies. These technologies vary in maturity and deployment levels. However, they face similar challenges, including infrastructure limitations, financing constraints, and insufficient policy support.

The paper provides an integrated overview of global primary energy consumption in 2023. It examines the continued dominance of fossil fuels and the growing contribution of renewable energy. It also assesses renewable energy developments in 2023 using international energy and climate data. The analysis evaluates trends in renewable energy consumption and electricity demand and identifies the countries and technologies associated with recent growth. It also examines renewable energy developments in 2023, global greenhouse gas emissions, and the distribution of emissions across major economic sectors. The contribution of renewable energy systems to emission reduction is assessed together with the economic, infrastructure, and policy barriers that limit large-scale deployment. Progress toward the 2050 NZE target is also evaluated. The main contributions of this paper are summarized as follows:

- Provides an assessment of the global status of renewable energy sources in 2023 using international energy and climate data.
- Examines climate change indicators, major international climate agreements, and the NZE pathway.
- Identifies the countries with the highest greenhouse gas emissions and renewable energy deployment levels in 2023.
- Evaluates the contribution of renewable energy sources to greenhouse gas emission reduction.
- Examines the economic, infrastructure, and policy barriers associated with large-scale renewable energy deployment.

The remainder of this paper is organized as follows. Section 2 describes the data sources and methodology. Section 3 presents global trends in primary energy consumption, renewable energy, and electricity demand, while Section 4 reviews the status of renewable energy sources in 2023. Section 5 examines greenhouse gas emissions, their sources, and sectoral distribution. Section 6 discusses climate change trends, near-term climate projections, and major international climate agreements. Section 7 evaluates the contribution of renewable energy sources to environmental protection, and Section 8 discusses the challenges and barriers associated with renewable energy deployment. Finally, Section 9 presents the conclusions and recommendations.

2. Data and methodology

This study used publications indexed in IEEE Xplore, Scopus, Web of Science, and Google Scholar. Relevant literature was identified through keyword searches and screened according to subject area, source title, publication type, and relevance to the study objectives. Journal articles, conference papers, and technical reports from different countries were included in the review.

The analysis also used data published by international organizations and energy agencies. These sources included the Energy Institute (EI) [10], Enerdata [11], the National Oceanic and Atmospheric Administration (NOAA) Global Monitoring Lab [12], the World Meteorological Organization (WMO) [13,14], the International Energy Agency (IEA) [15–20], EMBER [21], the International Renewable Energy Agency (IRENA) [22–24], the IEA Solar Heating & Cooling Programme [25], the Publications Office of the European Union [26], the Intergovernmental Panel on Climate Change [27], and the United Nations Environment Programme [28]. Table 1 summarizes these organizations and their contributions to the data employed in this study. The integration of data from multiple authoritative sources strengthens the reliability of the analysis and supports the validity of the results and conclusions presented in this paper.

The methodology relies on these reports to obtain comprehensive data on energy production, energy consumption, renewable energy deployment, and GHG emissions. For example, the Statistical Review of World Energy and World Energy and Climate Statistics provide global and regional datasets that support the analysis of long-term energy trends, including changes in energy consumption and the relative contributions of fossil fuels and renewable energy sources. The Global Electricity Review and Renewables 2023 provide data on renewable energy deployment in 2023 and identify key barriers that constrain further expansion. Climate related reports published by NOAA and the WMO provide indicators for evaluating the relationship between energy consumption, GHG emissions, and climate change. These sources provide consistent and internationally recognized datasets for assessing energy trends, renewable energy development, and environmental

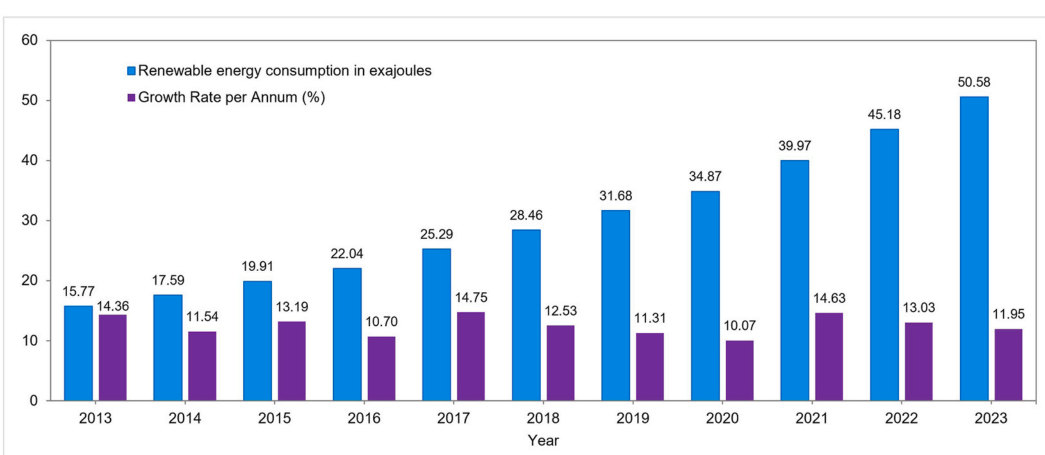

Fig. 2. Renewable energy consumption worldwide from 2013 to 2023.

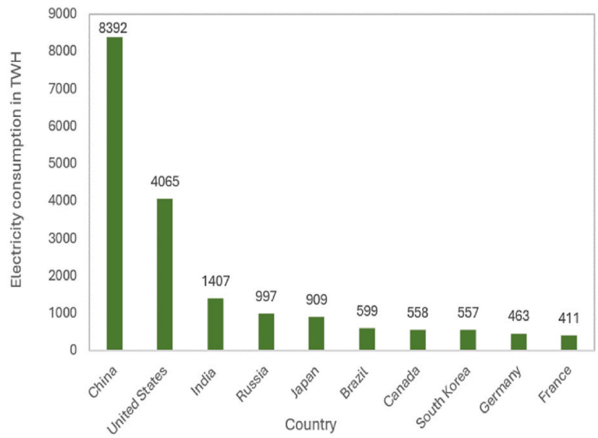

Fig. 3. Top ten electricity consumption countries in 2023.

impacts. Their inclusion supports a comprehensive analysis and strengthens the reliability of the study findings.

3. World's primary energy, renewable energy, and electricity consumption

Despite significant progress during the 21st century, many countries depended heavily on fossil fuels for electricity generation in 2023. Limited access to technology, resource constraints, and insufficient infrastructure restricted large scale renewable energy adoption. According to the IEA's Renewables 2024 report [16], many renewable energy projects faced delays due to regulatory and transmission constraints, despite record capacity additions. Growing environmental concerns also accelerated renewable energy adoption in the power sector [29].

The EI's Statistical Review of World Energy 2024 reports that global primary energy consumption reached a record 620 EJ in 2023, an increase of 2% compared with 2022 [10]. Fig. 1 shows that fossil fuels remained dominant in the global primary energy mix in 2023. This trend indicates that renewable energy growth has not yet reduced global dependence on fossil fuels at the required scale. Global renewable energy consumption reached 50.58 EJ in 2023, as presented in Fig. 2. Renewable energy continued to grow strongly, although the annual growth rate slowed slightly compared with 2022.

According to Enerdata [11], global electricity consumption increased by 2.6% in 2023, which was slightly lower than the historical average annual growth rate of 2.7%. The BRICS countries recorded a 6% increase in electricity demand, which exceeded the global average. China reported the highest growth rate at 6.9%, followed by India at 6.7% and Brazil at 3.2%. China accounted for nearly one third of global electricity consumption. Russia recorded growth of 1.4%, while South

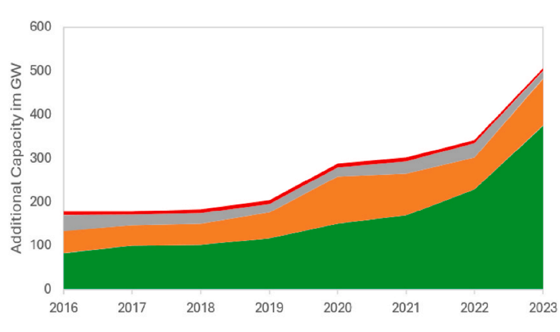

Fig. 4. Renewable electricity capacity additions by technology and segment from 2016 to 2023.

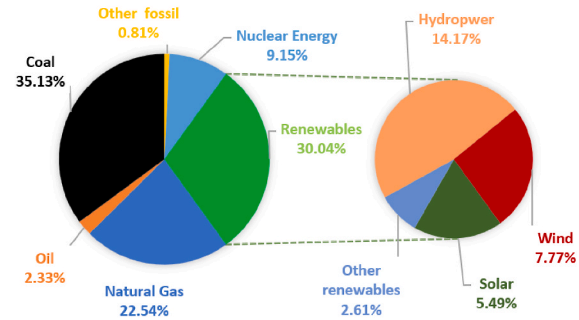

Fig. 5. Share of global electricity production in 2023, by source.

Africa recorded a 4% decline due to power supply constraints. In OECD countries, electricity consumption decreased by 1.4% despite moderate economic growth. Consumption declined by 1% in the United States, 1.9% in Japan, 1.3% in South Korea, and 3% in Europe. Germany recorded a decline of 5.3%, while France and the United Kingdom each recorded declines of 3%. Mexico recorded growth of 4.1%, driven mainly by economic expansion. Electricity consumption also increased in the Middle East, large African economies, Indonesia, Thailand, and Vietnam. Fig. 3 shows the top ten countries by electricity consumption in 2023.

EMBER's Global Electricity Review [21] reported that five rapidly expanding end use technologies accounted for more than half of global electricity demand growth in 2023. These technologies included electric vehicles, heat pumps, green hydrogen electrolysers, data centers, and air conditioning systems. Electrification of transportation, heating, and green hydrogen production accounted for 29% of the increase in global electricity demand, while data centers and air conditioning systems accounted for an additional 28%.

4. Status of renewable energy sources in 2023

According to IEA's Renewables 2023 report [15], global renewable capacity additions increased by nearly 50% in 2023, reaching approximately 510 GW, the highest annual increase recorded during the past two decades. Solar PV and wind accounted for 96% of the new capacity additions. Fig. 4 presents renewable electricity capacity additions by technology and segment from 2016 to 2023. The figure shows that solar PV accounted for the largest share of new capacity additions, followed by wind. Hydropower additions declined, while other renewable technologies showed only limited changes over the study period.

According to EMBER [21], the share of renewables in global electricity generation reached 30% in 2023, compared with 19% in 2000. Solar and wind were the main contributors and together accounted for a record 13.4% of global electricity production. Based on the EI report [10], global renewable electricity generation increased by 5.4% between 2022 and 2023. Solar generation recorded the highest growth and increased by 24.2%, equivalent to 319.7 TWh. Wind generation increased by 10.3%, equivalent to 206 TWh. Hydropower generation decreased by 1.9%, equivalent to 83.4 TWh, while other renewable sources increased by 0.6%, equivalent to 4.7 TWh. Fig. 5 presents the global electricity production mix in 2023 by source and shows the percentage share of energy sources in worldwide electricity generation. Fig. 6 shows the increase in the renewable share of global electricity capacity from 2014 to 2023, which reached 43.2% at the end of 2023 [22,23].

China led global RE consumption in 2023. Fig. 7, based on EI data [10], shows the leading countries by RE consumption in that year together with their annual growth rates over the previous decade. The data includes geothermal, wind, solar, biomass, hydro, and waste consumption, but exclude cross-border electricity trade.

According to IRENA's reports [22,23], Asia led global renewable

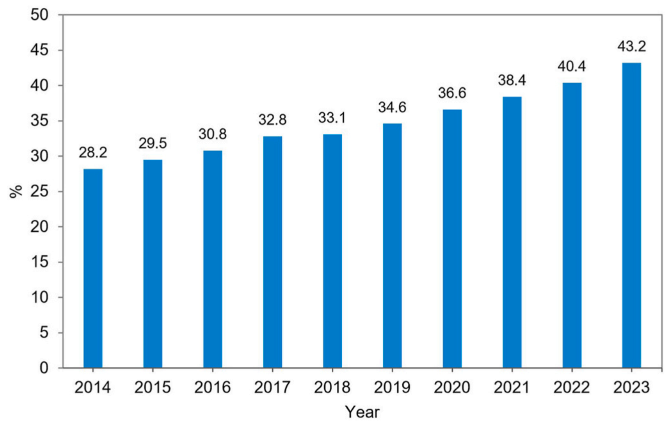

Fig. 6. Renewable energy share of electricity capacity.

energy capacity growth in 2023, with China making the largest contribution. Europe, North America, the Middle East, and other regions also recorded notable growth. The Middle East recorded its highest renewable energy expansion to date. Tables 2 and 3 summarize the regional capacity contributions and growth rates. Table 2 presents the total renewable energy capacity by region, while Table 3 presents the renewable energy share in electricity capacity from 2014 to 2023 across all regions.

4.1. Solar energy

Global renewable power capacity reached 3870 GW by the end of 2023. Solar energy represented the largest share of global renewable power capacity in 2023 and reached 1419 GW, accounting for 36.67% of the total capacity. This represented an increase of 346 GW or 32.25% compared with 2022. Solar PV accounted for almost all of this growth, with additions of 347 GW, while concentrated solar power (CSP) increased by only 0.3 GW. Fig. 8 shows the growth of global solar power capacity from 2014 to 2023. Fig. 9 shows the trends in PV and CSP installations over the same period. The figure indicates a rapid increase in PV deployment during 2022 and 2023, while CSP growth remained gradual [22,23].

According to the IEA's Solar Heat Worldwide report [25], global operational solar thermal capacity reached 560 GW_{th} by the end of 2023, which was equivalent to approximately 800 million square meters of collector area. This represented an increase of 18 GW_{th}, or 3%, compared with 2022. New solar thermal installations added 21 GW_{th} of capacity in 2023. However, this value was 7% lower than the amount installed in 2022. Fig. 10 presents the annual installed collector capacity and net capacity additions.

In 2023, solar energy capacity remained highly concentrated in a small number of countries, with China dominating the global market. China reached 609,921 MW of installed solar capacity, which accounted for 43.01% of the global total, and contributed 62.71% of all new capacity additions during the year. The United States ranked second with 139,205 MW of installed capacity, while Japan, Germany, and India

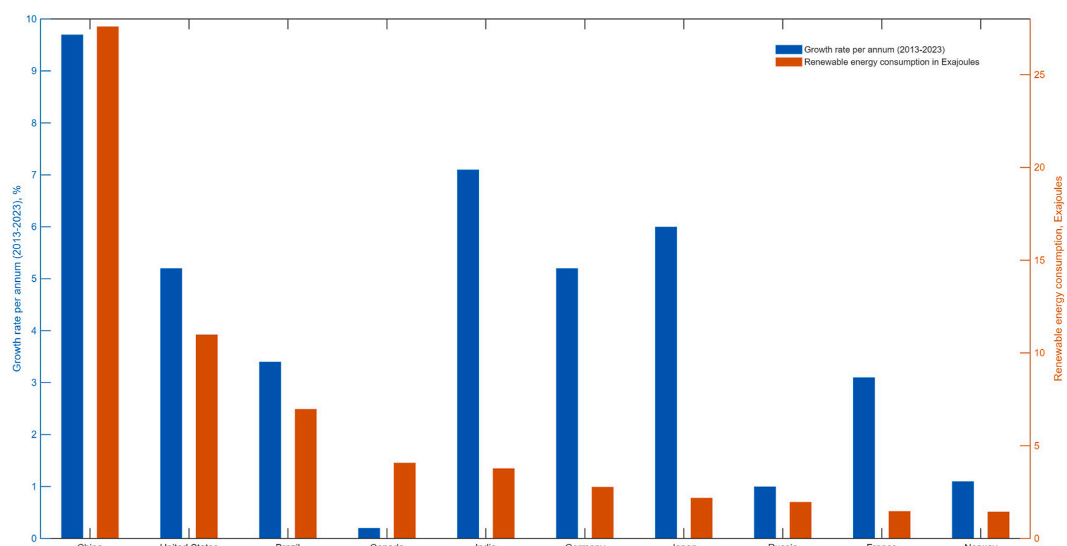

Fig. 7. Leading countries by renewable energy consumption worldwide in 2023.

Table 2
Renewable Energy Capacity Contributions of each Region in 2023.

Region	Renewable Energy Capacity in 2023 (GW)	Global Share in 2023 (%)	Change/Difference (2023-2022) (GW)	Growth (from 2022 to 2023) (%)	Growth in new capacity (%)
Global	3870	-	473.4	13.94	-
Africa	62	1.60	2.7	4.56	0.57
Asia	1961	50.67	327.8	20.07	69.24
Central America & Caribbean	19	0.49	0.84	4.63	0.18
Eurasia	122	3.15	3	2.51	0.63
Europe	787	20.34	71.2	9.96	15.04
Middle East	36	0.93	5.1	16.59	1.08
North America	530	13.69	34.9	7.05	7.37
Oceania	64	1.65	5.5	9.38	1.16
South America	289	7.47	22.4	8.41	4.73

Table 3
Renewable energy share of electricity capacity of each Region from 2014 to 2023.

Region	Year										Countries with highest RE share of the electricity capacity
	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	
Global	28.2	29.5	30.8	32.1	33.1	34.6	36.6	38.4	40.3	43	-
Africa	19.3	19.8	19.8	20.9	21.3	21.6	22.3	22.6	23.6	24.3	• Lesotho 99.4% • Ethiopia 98.2%
Asia	25.7	27.2	28.6	30.3	31.7	33.1	35.7	37.7	39.7	43.4	• Bhutan 99.6% • Nepal 98.1%
Central America & Caribbean	27.7	30.6	32.6	34.2	35	35.6	35.8	37.2	38.2	38.7	• Costa Rica 89.4% • Guatemala 70.7%
Eurasia	24.6	26	25.5	26.2	27	27.5	28.7	29.7	30.1	30.8	• Georgia 74.8% • Turkey 55%
Europe	39.3	41.3	42.9	44.5	45.5	47.9	49.8	51.9	54.4	56.9	• Norway 98.2% • Andorra 97%
Middle East	5.9	5.6	5.7	5.7	6.2	6.9	7.3	7.8	8.9	9.9	• Palestine 90.6% • Jordan 37.1%
North America	22.5	24.1	25.5	26.4	27.2	28.7	30.6	32.3	33.7	35.2	• Canada 69.8% • Greenland 49.1%
Oceania	30.2	29.7	31.6	34.3	37.9	41.7	44.9	47.4	50.2	53.3	• Tokelau 100% • New Zealand 80.7%
South America	63.1	64.3	65.1	65.6	66.3	67.2	67.5	68.3	69.9	71.4	• Paraguay 99.7% • Brazil 85.7%

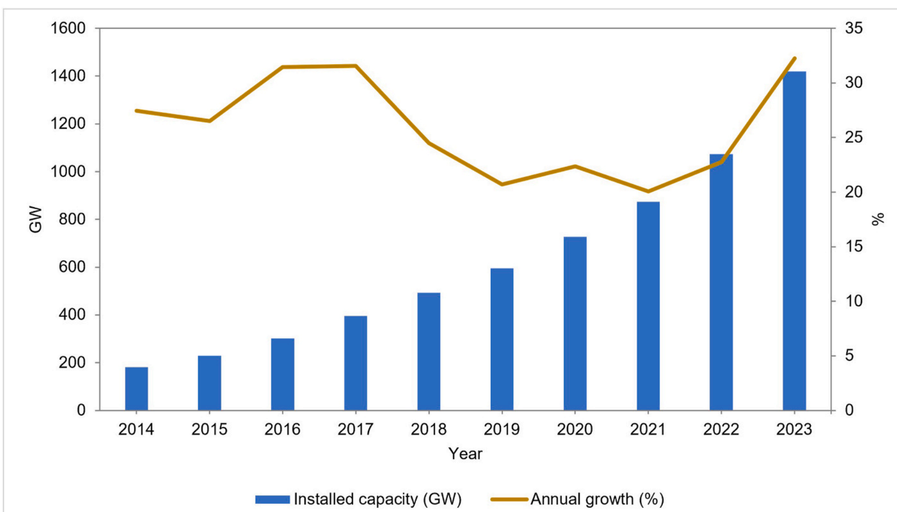

Fig. 8. Global solar power capacity from 2014 to 2023.

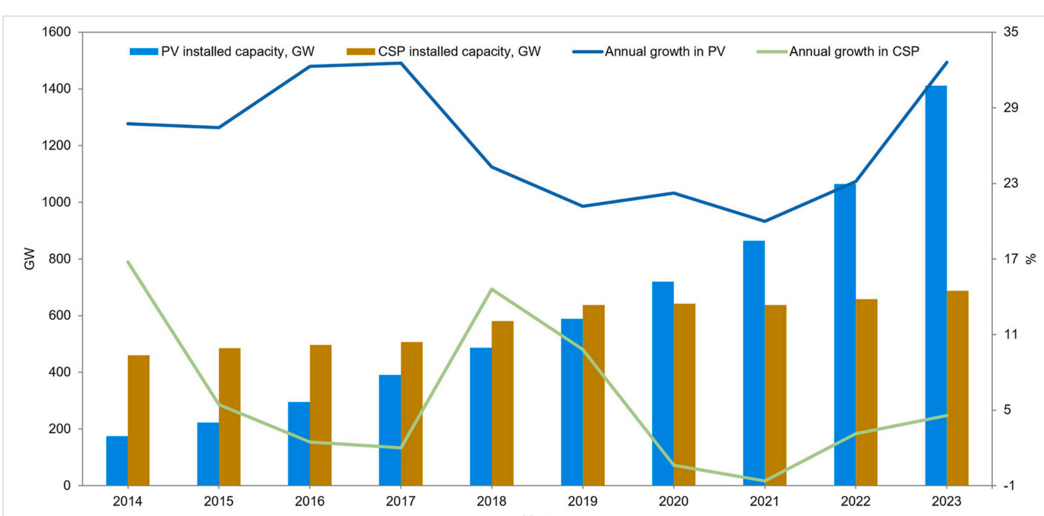

Fig. 9. Trends in PV and CSP capacity.

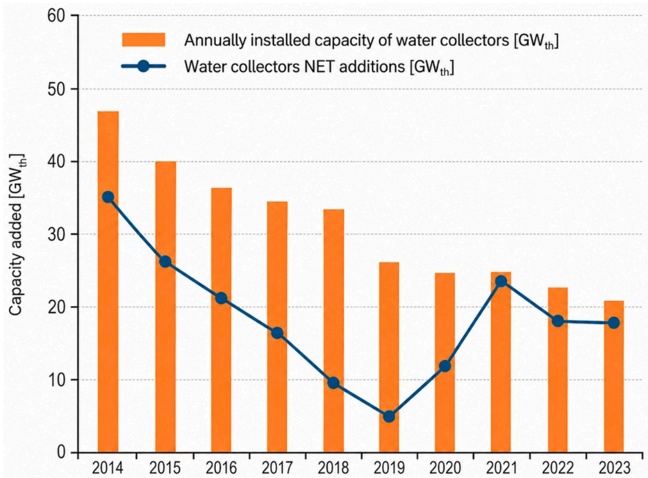

Fig. 10. Trends in annual installed collector capacity and net additions [25].

were also among the leading countries in global solar deployment. Table 4 summarizes solar energy capacity by country and region in 2022 and 2023, including growth rates and regional shares. Table 5 lists the ten leading countries based on total installed capacity and annual additions. Figs. 11 and 12 present the top ten countries by photovoltaic and concentrated solar power capacity share, respectively. Fig. 13 shows the countries that recorded the highest growth in the solar thermal market during 2023.

4.2. Wind energy

Wind energy was the second largest source of global renewable energy capacity in 2023. Total installed wind capacity reached 1017 GW and accounted for 26.28% of total renewable energy capacity [22,23]. Wind capacity increased by 116 GW compared with 2022, which corresponded to a growth rate of 12.87%. This increase was the largest annual addition recorded during the past decade. Onshore wind remained the dominant technology. It accounted for 92.86% of total wind capacity and 24.41% of total renewable energy capacity. Offshore wind continued to expand and represented 7.18% of total wind capacity and 1.9% of total renewable energy capacity. Fig. 14 shows the growth of global wind power capacity from 2014 to 2023.

Table 5
global solar energy capacity and growth in 2023: Top 10 countries.

Country	Solar Energy Capacity in 2023 (MW)	Percent contribution to the total capacity in the world (2023)	Added Solar Energy Capacity in 2023 (2023-2022) (MW)	Percent contribution to the added total capacity in the world (2023)
China	609921	42.98%	216889	62.71%
USA	139205	9.81%	24844	7.18%
Japan	87068	6.14%	4011	1.16%
Germany	81739	5.76%	14260	4.12%
India	73109	5.15%	9719	2.81%
Brazil	37449	2.64%	11929	3.45%
Australia	33683	2.37%	3725	1.08%
Spain	31016	2.19%	5401	1.56%
Italy	29795	2.10%	5234	1.51%
South Korea	27046	1.91%	2968	0.86%

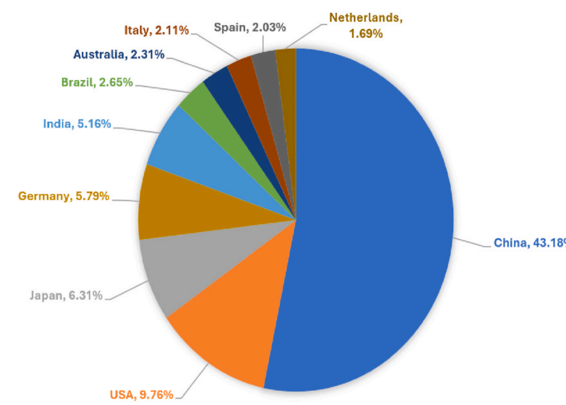

Fig. 11. Top 10 nations with the most PV power capacity in 2023.

Onshore wind capacity increased from 340.91 GW in 2014 to 944.34 GW in 2023, with an annual growth rate of 12.54% in 2023. Offshore wind capacity increased from 8.5 GW in 2014 to 72.66 GW in 2023. The offshore growth rate reached its highest value of 57.89% in 2021 and decreased to 17.26% in 2023. Fig. 15 shows the trends in onshore and offshore wind installations from 2014 to 2023.

China led the global wind energy market in both onshore and

Table 4
global solar energy capacity by country and region in 2023.

Region	Country	Solar Energy Capacity in 2022 (MW)	Solar Energy Capacity in 2023 (MW)	Growth in 2023	Percent contribution to the total capacity in the region (2023)	Percent contribution to the total capacity in the world (2023)
Africa	South Africa	6326	6164	−2.56%	45.87%	0.435%
	Egypt	1724	1856	7.66%	13.81%	0.131%
Asia	China	393032	609921	55.18%	72.67%	43.01%
	Japan	85066	89077	4.72%	10.61%	6.28%
Central America & Caribbean	Dominican Republic	735	1077	46.54%	22.59%	0.076%
	Puerto Rico	639	955	49.45%	20.03%	0.067%
Eurasia	Turkey	9426	11293	19.81%	79.51%	0.796%
	Russia	1816	2170	19.49%	15.28%	0.153%
Europe	Germany	67479	81739	21.13%	28.32%	5.76%
	Spain	25615	31016	21.08%	10.75%	2.19%
Middle East	United Arab Emirates	3596	5907	64.27%	31.38%	0.417%
	Israel	4411	4525	2.58%	24.03%	0.319%
North America	USA	114361	139205	21.72%	89.23%	9.82%
	Mexico	9356	10910	16.61%	6.99%	0.769%
Oceania	Australia	28887	32612	12.90%	97.59%	2.30%
	New Zealand	260	363	39.12%	1.09%	0.026%
South America	Brazil	25520	37449	46.74%	75.82%	2.64%
	Chile	6687	8898	33.06%	18.02%	0.627%

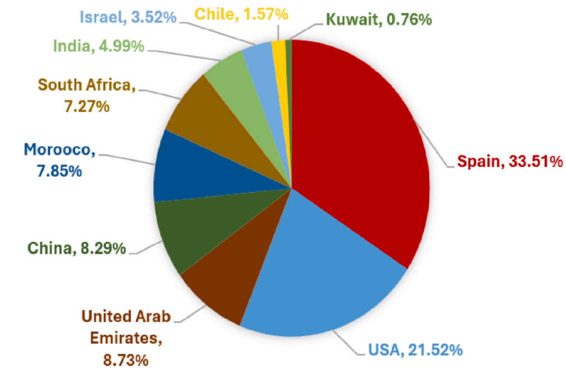

Fig. 12. Top 10 nations with the most concentrated solar power capacity in 2023.

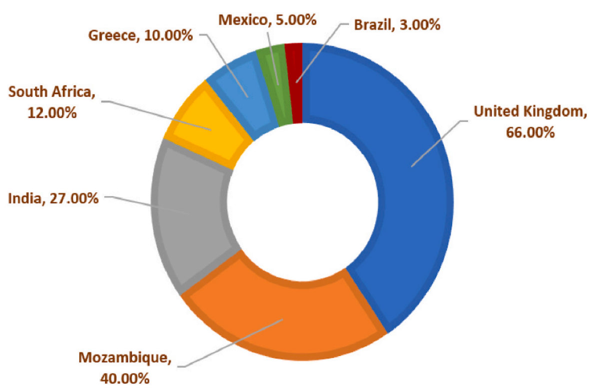

Fig. 13. Countries with largest solar thermal market growth in 2023.

offshore installations. The United States, Germany, India, and Brazil also ranked among the leading countries in their respective regions. Table 6 presents the distribution of wind energy capacity by country and region in 2023. Table 7 lists the ten leading countries based on total installed capacity and annual additions. Figs. 16 and 17 compare the capacity shares of the top ten countries in onshore and offshore wind energy, respectively.

4.3. Hydropower energy

Hydropower remained a major component of global renewable energy capacity in 2023, with an installed capacity of 1268 GW, which accounted for 32.76% of the total capacity [22,23]. However, capacity expansion slowed significantly, with net additions of only 7.2 GW. Fig. 18 shows the growth of global hydropower capacity from 2014 to 2023 and indicates the slower expansion of this technology in established markets.

China remained the global leader and recorded the largest capacity addition of 2890 MW. Australia, Nigeria, and Colombia also recorded notable growth. Table 8 presents hydropower capacity by country and region for 2023. Table 9 presents the top ten countries by total installed capacity and annual additions. Fig. 19 shows their share of global hydropower capacity.

4.4. Bioenergy

Bioenergy contributed 150.3 GW to global renewable energy capacity in 2023, which accounted for 3.88% of the total capacity [22,23]. Capacity growth slowed in 2023, with additions of 4.365 GW compared with 6.385 GW in 2022. Bioenergy power generation reached 697 TWh in 2023 and accounted for 2.4% of global electricity generation [21]. Most bioelectricity was generated from the combustion of solid biomass sources, including wood pellets, wood chips, and sugarcane bagasse. Municipal and industrial waste, as well as biogas, also contributed to bioelectricity generation [30].

Table 10 presents bioenergy capacity by country and region for 2022 and 2023. The data show considerable variation across markets, with expansion concentrated in a limited number of countries. China recorded the largest capacity addition in 2023, while Japan also made a significant contribution. The United States recorded a decline in capacity. Table 11 presents the top ten countries by total capacity and annual additions. Fig. 20 shows the growth of global bioenergy capacity, while Fig. 21 shows the distribution of solid biofuel and renewable waste capacity among the leading countries.

4.5. Geothermal energy

Geothermal energy reached a total installed capacity of 14.85 GW in 2023, which accounted for 0.384% of global renewable energy capacity [22,23]. The growth rate continued to decline, with increases of 2 0.41% in 2021, 1.94% in 2022, and 1.53% in 2023. Fig. 22 shows the global

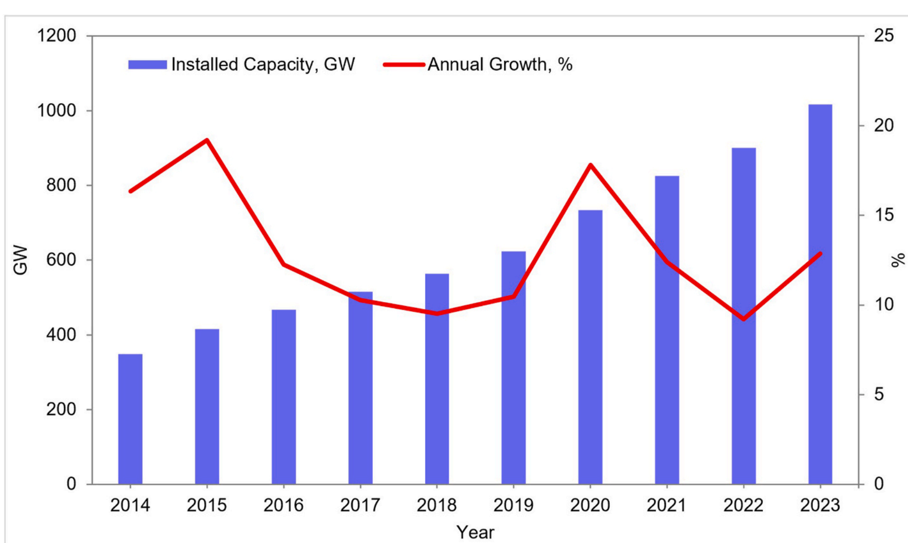

Fig. 14. Global wind power capacity.

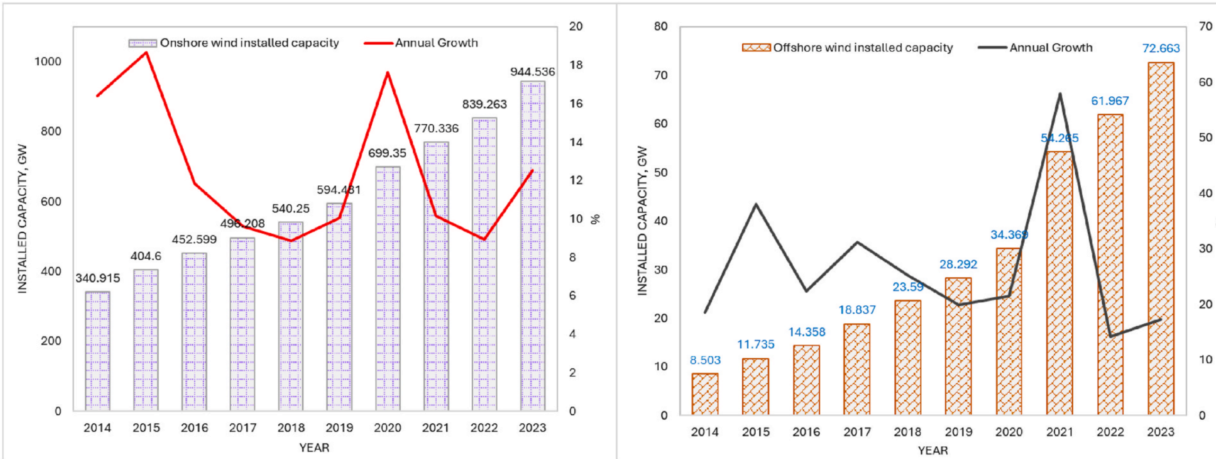

Fig. 15. Trends in onshore and offshore power capacity.

Table 6
global wind energy capacity by country and region in 2023.

Region	Country	Wind Energy Capacity in 2022 (MW)	Wind Energy Capacity in 2023 (MW)	Growth in 2023	Percent contribution to the total capacity in the region (2023)	Percent contribution to the total capacity in the world (2023)
Africa	South Africa	3163	3442	8.82%	39.77%	0.34%
	Egypt	1643	1890	15.03%	21.84%	0.19%
Asia	China	365964	441895	20.75%	86.91%	43.44%
	India	41930	44736	6.69%	10.49%	4.40%
Central America & Caribbean	Dominican Republic	417	417	0%	19.18%	0.04%
	Costa Rica	390	408	4.62%	18.77%	0.04%
Eurasia	Turkey	11396	11697	2.64%	81.77%	1.15%
	Russia	2218	2518	13.53%	17.60%	0.25%
Europe	Germany	66163	69459	4.98%	27.02%	6.83%
	Spain	30114	31028	3.04%	12.07%	3.05%
Middle East	Jordan	614	614	0%	32.82%	0.06%
	Saudi Arabia	403	403	0%	21.54%	0.04%
North America	USA	141674	148020	4.48%	85.89%	14.55%
	Canada	15265	16989	11.29%	9.86%	1.67%
Oceania	Australia	10555	11327	7.31%	90.89%	1.11%
	New Zealand	994	1059	6.54%	8.50%	0.10%
South America	Brazil	24163	29135	20.58%	73.12%	2.86%
	Chile	3830	4510	17.75%	11.32%	0.44%

Table 7
global wind energy capacity and growth in 2023: Top 10 countries.

Country	Wind Energy Capacity in 2023 (MW)	Percent contribution to the total capacity in the world (2023)	Added Wind Energy Capacity in 2023 (2023-2022) (MW)	Percent contribution to the added total capacity in the world (2023)
China	441895	43.44%	75931	65.48%
USA	148020	14.55%	6346	5.47%
Germany	69459	6.83%	3296	2.84%
India	44736	4.40%	2806	2.42%
Spain	31028	3.05%	914	0.79%
United Kingdom	30215	2.97%	1453	1.25%
Brazil	29135	2.86%	4972	4.29%
France	22196	2.18%	1385	1.19%
Canada	16989	1.67%	1724	1.49%
Italy	12308	1.21%	487	0.42%

trend in geothermal installed capacity from 2014 to 2023.

The United States remained the leading country in total geothermal capacity, while Indonesia recorded the largest capacity addition in 2023. Table 12 presents the top ten countries by total capacity and annual additions, including each country's contribution to global growth during the period.

4.6. Marine energy

Marine energy remained the smallest contributor to global renewable energy capacity in 2023 and accounted for only 0.014% of the total capacity [22,23]. In 2023, 2 MW of new capacity was installed, increasing the cumulative capacity to 527 MW. South Korea was the

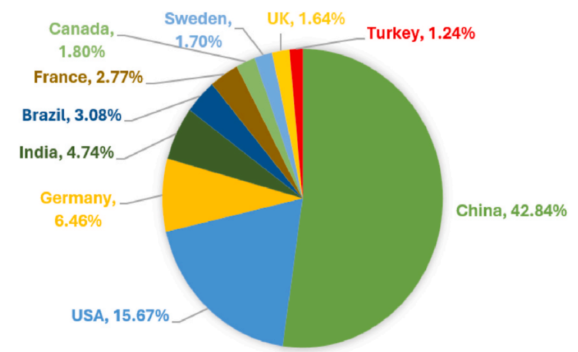

Fig. 16. Top 10 nations with the most onshore wind power capacity in 2023.

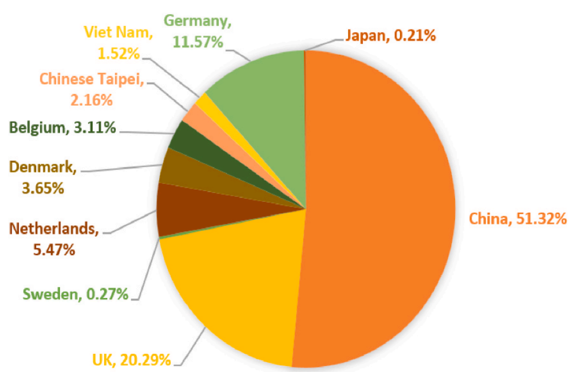

Fig. 17. Top 10 nations with the most offshore wind power capacity in 2023.

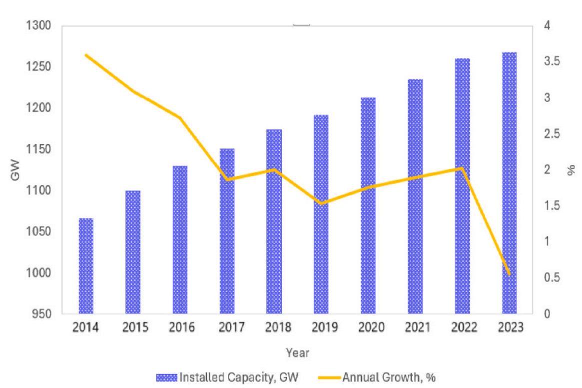

Fig. 18. Global renewable hydropower capacity.

leading country and accounted for 48.57% of global installed marine energy capacity. France followed with 212 MW, representing 40.23% of the total capacity. Fig. 23 shows the growth of marine energy capacity from 2014 to 2023 and reflects the early stage of commercialization of these technologies.

4.7. Hydrogen energy

Both green and blue hydrogen have the potential to serve as clean energy carriers for transportation, heating, and electricity generation [31]. Blue hydrogen production remained relatively stable in 2023. In contrast, green hydrogen production increased rapidly after 2020 and accounted for 96.6% of the total increase in hydrogen production of 62 Mt between 2022 and 2023 [10]. However, the growth rate was lower than the peak level recorded in 2022. Fig. 24 shows the production trends of blue and green hydrogen. Fig. 25 compares regional green hydrogen production for 2022 and 2023. Asia Pacific recorded the highest production at 93.6 Mt and the highest growth rate at 133.3%, followed by Europe and North America.

According to the IEA's Global Hydrogen Review 2024 [17], global hydrogen demand reached 97 Mt in 2023, which represented an increase of 2.5% compared with 2022. Hydrogen demand remained concentrated in the refining and chemical sectors and was mainly supplied by fossil-fuel-based hydrogen. Low emission hydrogen accounted for less than 1 Mt of total demand. China recorded the highest demand at 28 Mt, followed by the United States at 13 Mt. The Middle East and India recorded growth rates above 5%, mainly driven by refining, methanol, and steel production. Fig. 26 shows the regional distribution of hydrogen demand. At the project level, 2023 marked an important stage in the expansion of green hydrogen infrastructure. Xinjiang Sinopec's plant became the world's largest green hydrogen facility, with a capacity of 260 MW and annual production of 20,000 tons. The facility was supported by 300 MW of on-site solar and wind power generation [32].

4.8. OFF-GRID technologies

Off-grid renewable technologies, including solar PV, hydropower, bioenergy, wind, and biogas, are used for households, water pumping, street lighting, telecommunications, rural schools and clinics, and remote industrial facilities. Total installed capacity reached 12,754.6 MW by the end of 2023, which represented an increase of 585 MW compared with 2022. However, the annual growth rate declined compared with the peak level recorded in 2022. Fig. 27 shows the overall growth trend in off-grid renewable capacity from 2014 to 2023.

Solar PV was the dominant off-grid technology and accounted for 38.9% of total capacity, equivalent to 4961 MW. Between 2022 and 2023, solar PV contributed 405 MW, which represented 69.23% of total new off-grid capacity additions. Fig. 28 shows the distribution of off-grid renewable technologies by capacity share. Off-grid capacity and annual additions were concentrated in a limited number of countries, led by Indonesia and India, as presented in Table 13. India recorded the largest solar PV addition with 230 MW out of the global increase of 405 MW, reaching a total of 2197 MW. Indonesia led other off-grid renewable technologies with 2989.9 MW of installed capacity and contributed 96.49 MW out of the global increase of 179.28 MW in this category.

5. Greenhouse gases

A GHG is any gas that absorbs infrared radiation or heat emitted by the Earth, trapping it in the atmosphere and preventing it from escaping into space. Even small changes in the concentration of these gases over time can have a significant impact on global temperatures and weather changes [33]. Common GHGs in the atmosphere include water vapor, CO_2, CH_4, N_2O, ozone (O_3), sulfur dioxide (SO_2), and F-gases [34]. However, researchers have identified the three primary GHGs of greatest global concern today as CO_2, CH_4, and N_2O [35].

The greenhouse effect occurs when solar radiation passes through the atmosphere and is absorbed by the Earth's surface, which then re-emits the energy as infrared radiation. GHGs trap part of this heat and warm the planet through a process similar to the effect of glass in a greenhouse [1]. Natural concentrations of GHG are necessary for regulating the Earth's temperature and supporting life. However, the increase in GHG concentrations caused by human activities is a major driver of climate change [36].

According to the GHG Emissions of All World Countries 2024 report [26], global GHG emissions reached 53.0 $GtCO_{2eq}$ in 2023, which was 1.9% higher than in 2022. China, the United States, India, the EU27, Russia, Brazil, Indonesia, and Japan were the largest emitters and together accounted for 66.98% of global emissions, as shown in Fig. 29. China recorded the largest increase in emissions at 784 $MtCO_{2eq}$, while India recorded the highest growth rate at 6.1%. In contrast, emissions in the EU27 decreased by 7.5%, while Japan recorded a decrease of 6%.

Table 8
global hydropower energy capacity by country and region in 2023.

Region	Country	Hydropower Energy Capacity in 2022 (MW)	Hydropower Energy Capacity in 2023 (MW)	Growth in 2023	Percent contribution to the total capacity in the region (2023)	Percent contribution to the total capacity in the world (2023)
Africa	Ethiopia	4821	4883	1.29%	13.17%	0.39%
	Angola	3729	3729	0%	10.06%	0.29%
Asia	China	367710	370600	0.79%	68.11%	29.23%
	India	47220	47331	0.24%	8.70%	3.73%
Central America & Caribbean	Costa Rica	2331	2372	1.76%	28.18%	0.19%
	Panama	1845	1845	0%	21.92%	0.15%
Eurasia	Russia	51398	50571	−1.61%	57.17%	3.99%
	Turkey	31571	31779	0.66%	35.93%	2.51%
Europe	Norway	34269	34401	0.39%	17.48%	2.71%
	France	24236	24139	−0.40%	12.26%	1.90%
Middle East	Iran	11503	11679	1.53%	77.77%	0.92%
	Iraq	1557	1557	0%	10.37%	0.12%
North America	USA	86628	86660	0.037%	47.26%	6.83%
	Canada	83307	83307	0%	45.43%	6.57%
Oceania	Australia	7713	8440	9.43%	57.27%	0.67%
	New Zealand	5680	5680	0%	38.54%	0.45%
South America	Brazil	109802	109903	0.092%	61.10%	8.67%
	Venezuela	16811	16811	0%	9.35%	1.33%

Table 9
global hydropower energy capacity and growth in 2023: Top 10 countries.

Country	Hydropower Energy Capacity in 2023 (MW)	Percent contribution to the total capacity in the world (2023)	Added Hydropower Energy Capacity in 2023 (2023-2022) (MW)	Percent contribution to the added total capacity in the world (2023)
China	370600	29.23%	2890	41.17%
Brazil	109903	8.67%	101	1.44%
USA	86660	6.84%	32	0.46%
Canada	83307	6.57%	0	0%
Russia	50571	3.99%	−827	−11.78%
India	47331	3.73%	111	1.58%
Norway	34401	2.71%	132	1.88%
Turkey	31779	2.51%	208	2.96%
Japan	28216	2.23%	18	0.26%
France	24139	1.90%	−97	−1.38%

5.1. Sources of greenhouse gases

Human activities (anthropogenic) and natural systems are the two main sources of GHGs. Natural sources include forest fires, oceans, wetlands, permafrost thaw, volcanic activity, and respiration from living organisms. These processes emit CO_2, CH_4, and N_2O through combustion, decomposition, and biological activity [37].

According to the Intergovernmental Panel on Climate Change (IPCC) [27], human activities are responsible for nearly all of the increase in GHGs in the atmosphere over the past 150 years. Key contributing sectors include the power industry, industrial combustion and processes, buildings, transport, fuel exploitation, agriculture, and waste. The GHG Emissions of All World Countries 2024 data [26] provides sector-specific emissions figures, as shown in Figs. 30 and 31.

Fig. 30 shows the sector share of total GHG emissions in 2023 and the contribution to the annual increase from 2022. The power industry is the largest emitter, followed by industrial combustion and processes and transport. Transport contributes the largest share of the 2023 increase, followed by industrial combustion and the power industry, while other sectors contribute smaller shares.

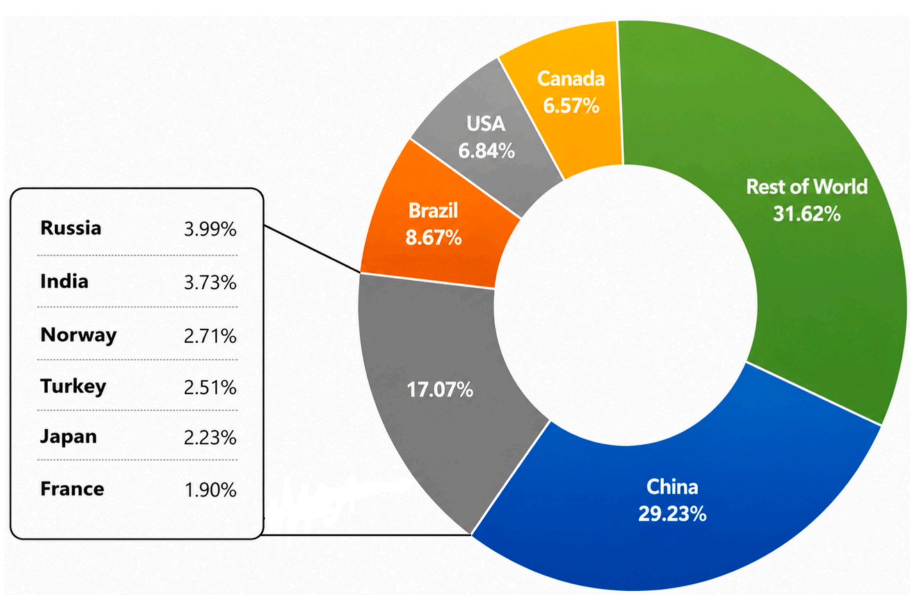

Fig. 19. Shares of the top ten countries in global hydropower capacity and the rest of the world.

Table 10
Global bioenergy capacity by country and region in 2023.

Region	Country	Bioenergy Capacity in 2022 (MW)	Bioenergy Capacity in 2023 (MW)	Growth in 2023	Percent contribution to the total capacity in the region (2023)	Percent contribution to the total capacity in the world (2023)
Africa	Ethiopia	335	310	−7.46%	16.31%	0.21%
	South Africa	265	265	0%	13.94%	0.18%
Asia	China	29390	31225	6.24%	49.72%	20.78%
	India	10669	10752	0.78%	17.12%	7.16%
Central America & Caribbean	Cuba	966	966	0%	32.33%	0.64%
	Guatemala	870	870	0%	29.12%	0.58%
Eurasia	Turkey	1861	2001	7.52%	58.66%	1.33%
	Russia	1373	1373	0%	40.25%	0.91%
Europe	Germany	9830	9950	1.22%	23.23%	6.62%
	UK	7438	7477	0.52%	17.46%	4.98%
Middle East	Israel	26	26	0%	23.42%	0.02%
	United Arab Emirates	9	24	166.67%	21.62%	0.02%
North America	USA	11102	10990	−1.01%	74.97%	7.31%
	Canada	2682	2682	0%	18.29%	1.78%
Oceania	Australia	878	878	0%	78.96%	0.58%
	New Zealand	144	145	0.69%	13.04%	0.10%
South America	Brazil	17224	17597	2.17%	86.03%	11.71%
	Venezuela	423	737	74.23%	3.60%	0.49%

Table 11
global bioenergy capacity and growth in 2023: Top 10 countries.

Country	Bioenergy Capacity in 2023 (MW)	Percent contribution to the total capacity in the world (2023)	Added Bioenergy Capacity in 2023 (2023-2022) (MW)	Percent contribution to the added total capacity in the world (2023)
China	31255	20.80%	1865	42.72%
Brazil	17597	11.71%	373	8.54%
USA	10990	7.314%	−344	−7.88%
India	10752	7.16%	83	1.90%
Germany	9950	6.62%	120	2.75%
UK	7477	4.98%	39	0.89%
Japan	6384	4.24%	980	22.45%
Thailand	4705	3.13%	102	2.34%
Sweden	4507	3.00%	0	0%
Italy	3434	2.29%	42	0.96%

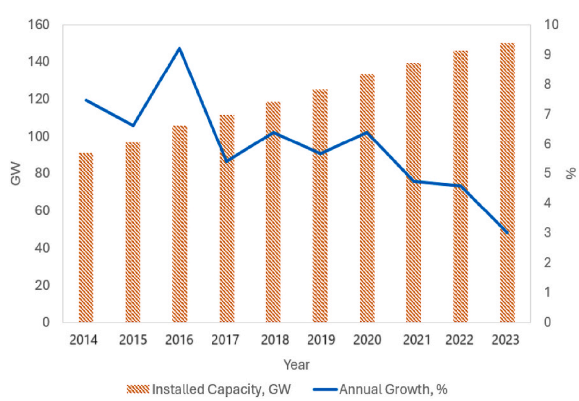

Fig. 20. Global renewable bioenergy capacity.

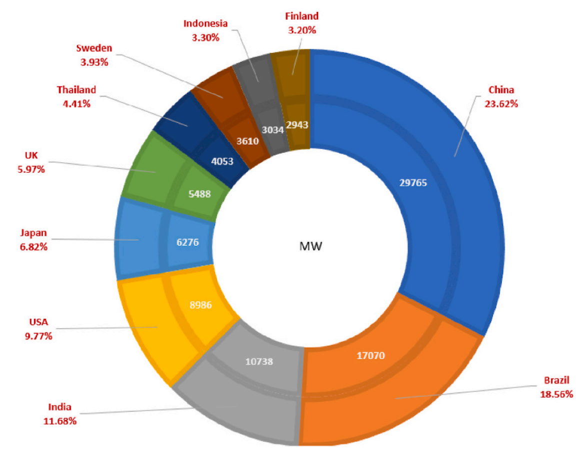

Fig. 21. Shares of the top ten countries in bioenergy capacity derived from solid biofuels and renewable waste capacity.

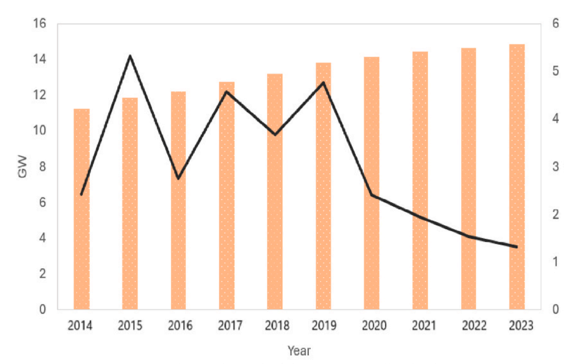

Fig. 22. Geothermal energy installed capacity.

Fig. 31 shows sectoral GHG emissions for 2022 and 2023. Total emissions increased by 994.43 $MtCO_{2eq}$ in 2023. Transport contributed 300.46 $MtCO_{2eq}$ of this increase, followed by the industrial combustion and processes at 237.81 $MtCO_{2eq}$ and the power industry at 234.46 $MtCO_{2eq}$. Fuel exploitation contributed 13.35%, while waste, buildings, and agriculture contributed 35.07 $MtCO_{2eq}$, 29.73 $MtCO_{2eq}$, and 24 $MtCO_{2eq}$ respectively. Transport recorded the highest growth rate at 3.72%, followed by fuel exploitation at 2.31%, industrial combustion and processes at 2.13%, waste at 1.80%, power industry at 1.58%, and lower growth in buildings and agriculture.

5.1.1. Power industry

The power industry refers to the sector responsible for electricity generation, transmission, and distribution. Based on EI data [10], global electricity generation increased by 2.46% in 2023 and reached a record 29,925 TWh. Fig. 32 shows that fossil fuels remained the dominant

Table 12
global geothermal capacity and growth in 2023: Top 10 countries.

Country	Geothermal Energy Capacity in 2023 (MW)	Percent contribution to the total capacity in the world (2023)	Added Geothermal Energy Capacity in 2023 (2023-2022) (MW)	Percent contribution to the added total capacity in the world (2023)
USA	2674	18.01%	25	12.95%
Indonesia	2418	16.29%	58	30.05%
Philippines	1952	13.15%	20	10.36%
Turkey	1691	11.39%	0	0%
New Zealand	1050	7.07%	0	0%
Mexico	999	6.73%	0	0%
Kenya	984	6.63%	35	18.13%
Italy	772	5.20%	0	0%
Iceland	756	5.09%	0	0%
Japan	428	2.88%	−9	−4.66%

Fig. 23. Marine energy installed capacity.

source, with coal as the largest contributor at 10,513 TWh, up from 10, 324 TWh in 2022, and natural gas as the second largest at 6746 TWh, up from 6669 TWh. Oil accounted for a small share. Non fossil sources, including hydropower, nuclear energy, and renewables, contributed less than fossil fuels. China's power sector emitted 6540 $MtCO_{2eq}$, which accounted for 43.4% of global power industry emissions. CO_2 accounted for 99.02% of emissions from the power sector, while N_2O accounted for 0.88% and CH_4 for 0.11%.

5.1.2. Industrial combustion and processes

Heavy industries, including chemical, paper, steel, aluminum, cement, and critical minerals, are highly energy intensive, while light industries include food and beverage, textiles, assembly, and fabrication sectors [38]. Industrial energy consumption remained heavily dependent on fossil fuels, particularly coal [39]. Industrial combustion accounted for 6452 $MtCO_{2eq}$ in 2023, while industrial processes, including cement and chemical production, contributed 4956 $MtCO_{2eq}$. China emitted 4869 $MtCO_{2eq}$ from the industrial sector, which represented 42.67% of global industrial emissions and an increase of 3.29% from 2022. CO_2 represented 84.32% of industrial emissions, followed by F-gases at 12.72%, N_2O at 2.66%, and CH_4 at 0.30%.

5.1.3. Transportation

The transportation sector includes aviation, international shipping, electric vehicles, trucks and buses, cars and vans, and railways. According to the IPCC Sixth Assessment Report [40], the sector accounted for 15% of total anthropogenic emissions. Road transportation accounted for 69% of sectoral emissions, followed by international shipping at 9% and international aviation at 7%. In 2023, the transport sector emitted 8382 $MtCO_{2eq}$ and recorded the highest annual growth rate among all sectors at 3.72%. The United States was the largest contributor at 1736 $MtCO_{2eq}$, representing 20.71% of total transport emissions. Private passenger vehicles accounted for 90% of mileage in the United States and 58% of transport emissions, while public transit contributed 27% and aviation 13% [41]. CO_2 represented 98.29% of transport emissions, followed by N_2O at 1.34% and CH_4 at 0.37%.

5.1.4. Agriculture

GHG emissions from agriculture arise from enteric fermentation, manure management, rice cultivation, fertilization, liming, agricultural residue burning, and soil management [42]. Global agricultural emissions reached 6488 $MtCO_{2eq}$ in 2023, an increase of 24 $MtCO_{2eq}$ from 2022 and more than 20% above 1990 levels. CH_4 accounted for 71.06% of agricultural emissions, followed by N_2O at 26.72% and CO_2 at 2.21%. Regionally, Asia led global agricultural emissions in 2023, with China contributing 885 $MtCO_{2eq}$, India 791 $MtCO_{2eq}$, and Brazil 631 $MtCO_{2eq}$ as the three largest national sources.

5.1.5. Buildings

The building sector includes energy use for construction, heating, cooling, lighting, and appliances. The sector emitted 3761 $MtCO_{2eq}$ in 2023, an increase of 0.8% from 2022. CO_2 accounted for 90.76% of emissions, followed by CH_4 at 7.40% and N_2O at 1.84%. According to the IEA's Tracking Clean Energy Progress 2023 report [18], residential buildings accounted for 5.52% of direct global energy emissions and 11.06% of indirect emissions, while nonresidential buildings contributed 2.74% directly and 7.38% indirectly. Building construction and

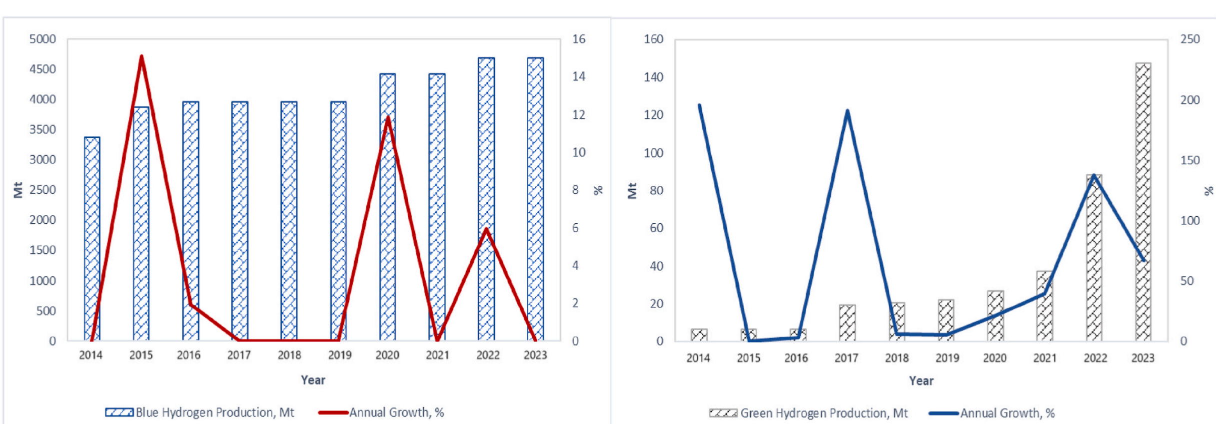

Fig. 24. Trends in blue and green hydrogen production. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

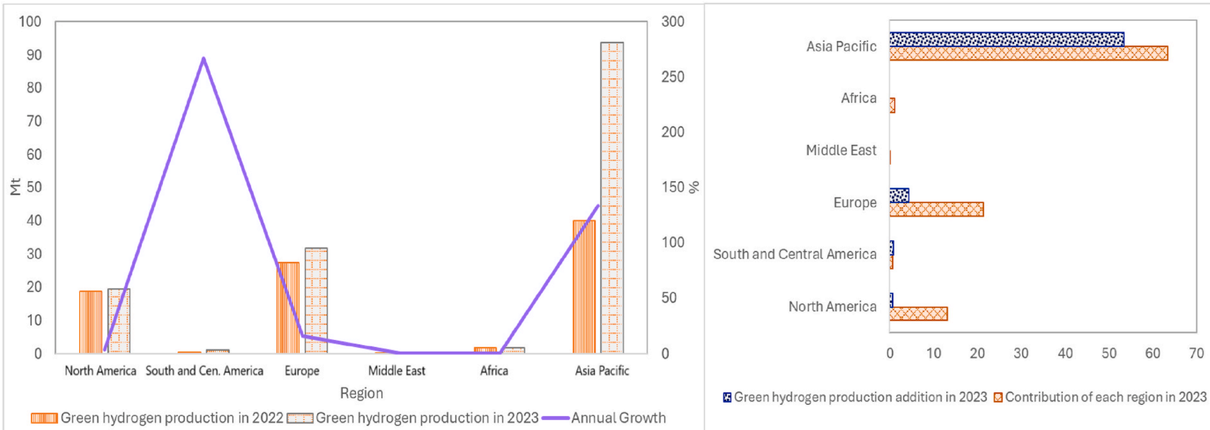

Fig. 25. Trends in blue and green hydrogen production. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

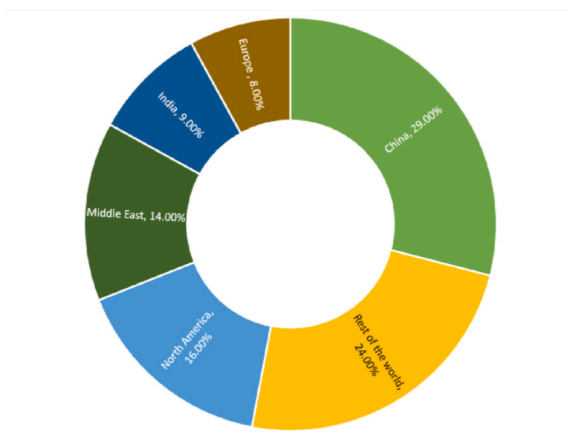

Fig. 26. Regional distribution of hydrogen demand in 2023.

production of bricks and glass contributed 6.79% and 6.16% of emissions, respectively, as shown in Fig. 33. China recorded the highest building sector emissions at 703 $MtCO_{2eq}$, followed by the United States at 608 $MtCO_{2eq}$ and India at 269 $MtCO_{2eq}$. These three countries accounted for more than 42% of global building sector emissions.

5.1.6. Fuel exploitation

Fuel exploitation includes the extraction, production, and refining of fossil fuels. The sector emitted 5872 $MtCO_{2eq}$ in 2023, an increase of 133 $MtCO_{2eq}$ from 2022. CH_4 accounted for 54.45% of emissions, followed by CO_2 at 45.41% and N_2O at 0.14%. China and the United States were the largest contributors globally. China accounted for approximately 25% of total fuel exploitation emissions and added 43.6 $MtCO_{2eq}$ in 2023.

5.1.7. Waste

Waste sector emissions mainly result from landfill decomposition, wastewater treatment, and solid waste management processes. The sector emitted 1979 $MtCO_{2eq}$ in 2023, representing 3.74% of global emissions. CH_4 accounted for 92.65% of waste sector emissions, followed by N_2O at 6.44% and CO_2 at 0.91%. China was the largest contributor at 387 $MtCO_{2eq}$, followed by the United States at 147 $MtCO_{2eq}$, India at 141 $MtCO_{2eq}$, and Brazil at 130 $MtCO_{2eq}$.

5.2. Major greenhouse gases

In 2023, fossil CO_2 was the dominant contributor, accounting for 73.7% of total emissions, followed by CH_4 at 18.9%, N_2O at 4.7%, and F-gases at 2.7% [26]. The following sections provide a detailed overview of the sources of each GHG and their respective emission trends over

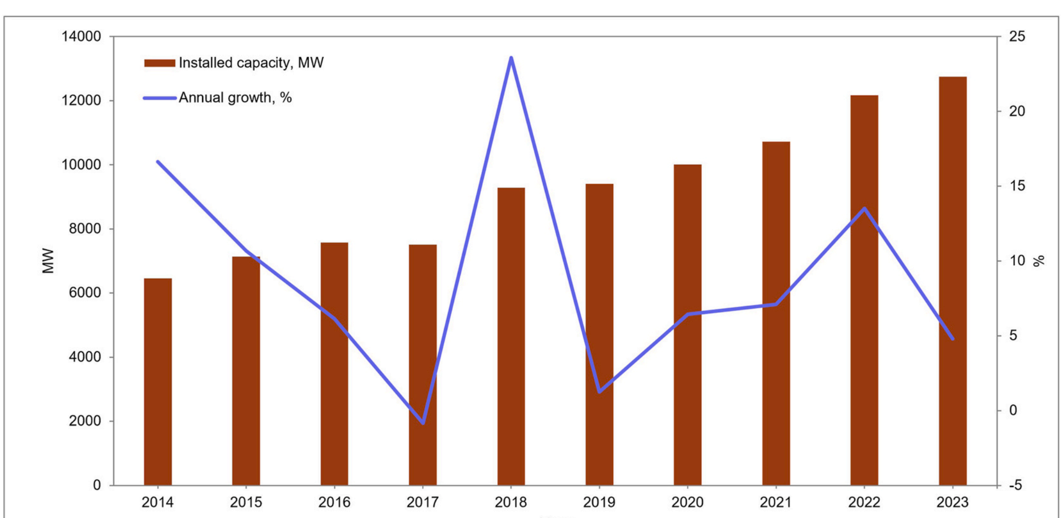

Fig. 27. Off-grid technologies installed capacity from 2014 to 2023.

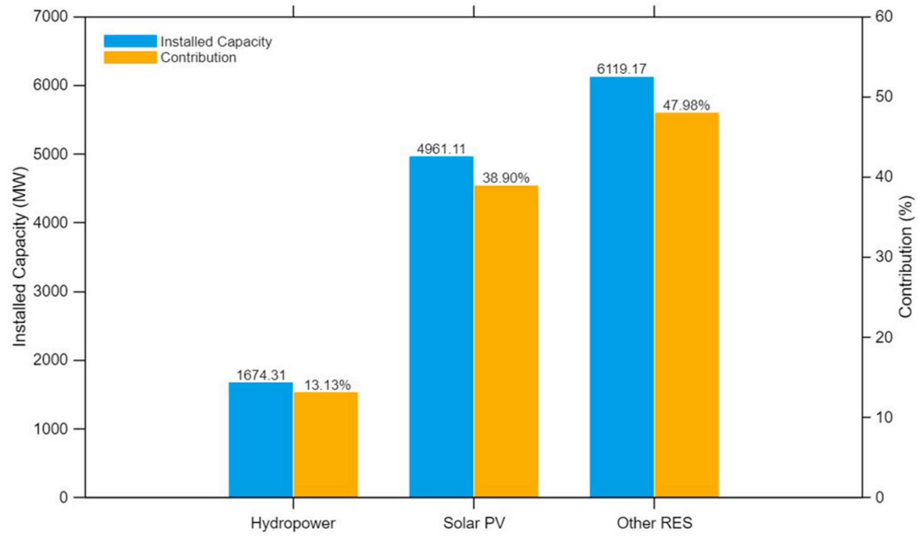

Fig. 28. Contribution of the off-grid technologies to the total installed capacity.

Table 13
Global off-grid technologies Capacity and Growth in 2023: Top 10 Countries.

Country	Off-grid technologies capacity in 2023 (MW)	Percent contribution to the total capacity in the world (2023)	Added off-grid technologies capacity in 2023 (2023-2022) (MW)	Percent contribution to the added total capacity in the world (2023)
Indonesia	4137	32.43%	157	26.79%
India	3302	25.89%	283	48.29%
China	986	7.73%	40	6.835
Malaysia	540	4.23%	0	0%
Yemen	290	2.27%	26	4.44%
Peru	221	1.73%	0	0%
Venezuela	201	1.58%	0	0%
Bangladesh	181	1.42%	6	1.02%
Papua N Guin	148	1.16%	0	0%
Sudan	135.57	1.06%	0	0%

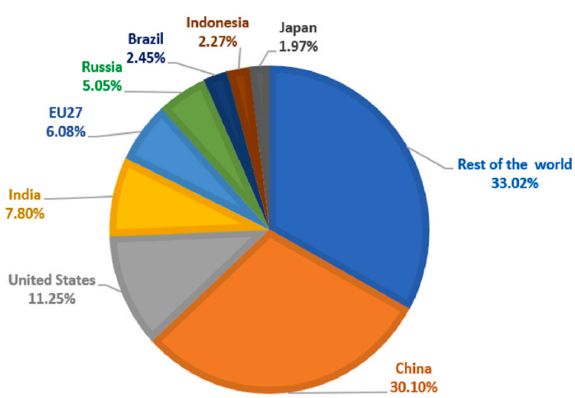

Fig. 29. Largest GHG emitters in 2023.

time.

5.2.1. *Carbon dioxide (CO_2)*

According to NOAA's Global Monitoring Lab [12], the average global atmospheric CO_2 concentration reached a record 419.3 ppm in 2023, an increase of 2.8 ppm from 2022. Based on the GHG Emissions of All World Countries 2024 Report [26], the total emissions of CO_2 in 2023

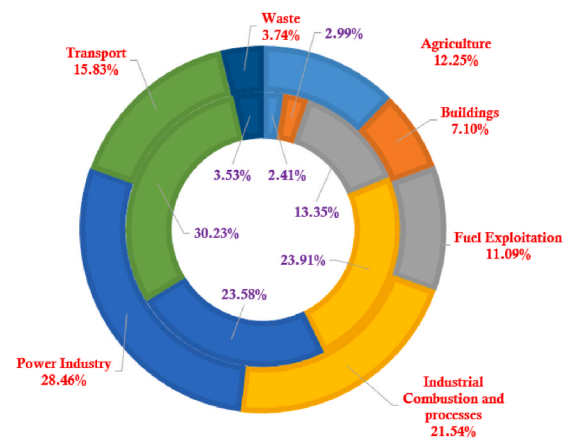

Fig. 30. Contribution of each sector to the total and the addition of GHG emissions in 2023.

was 39,024 $MtCO_{2eq}$. Fig. 34 shows the sectoral distribution of CO_2 emissions, with the power industry as the largest source, followed by industrial combustion and transport. Fig. 35 shows the trend from 2014 to 2023, during which emissions increased from 36,427 to 39,024 $MtCO_2$, except for a temporary decline in 2020 during the COVID 19 pandemic. The power sector recorded the largest increase over the decade, rising from 13,701 $MtCO_2$ in 2014 to 14,924 $MtCO_2$ in 2023. Table 14 identifies the largest country sector contributors above 500 $MtCO_{2eq}$, led by China's power industry at 6473 $MtCO_{2eq}$ and industrial combustion at 2874 $MtCO_{2eq}$, followed by the United States transport sector at 1711 $MtCO_{2eq}$ and power industry at 1463 $MtCO_{2eq}$.

5.2.2. *Methane (CH_4)*

Livestock, rice production, oil and gas supply chains, coal mining, landfills, and wastewater treatment were the main sources of CH_4 emissions [43]. These sources accounted for 90% of global CH_4 emissions. Global CH_4 emissions increased from 9076 $MtCO_{2eq}$ in 2014 to 10, 001 $MtCO_{2eq}$ in 2023. Fig. 36 shows that agriculture was the largest source at 46.10%, followed by fuel exploitation at 31.97% and waste at 18.34%. Buildings, transport, industrial combustion, and the power industry each contributed less than 1%. Fig. 37 shows the sectoral trend from 2014 to 2023. Agricultural emissions increased from 4369 to 4611 $MtCO_{2eq}$, fuel exploitation increased from 2881 to 3197 $MtCO_{2eq}$, and waste increased from 1532 to 1834 $MtCO_{2eq}$. Buildings declined slightly

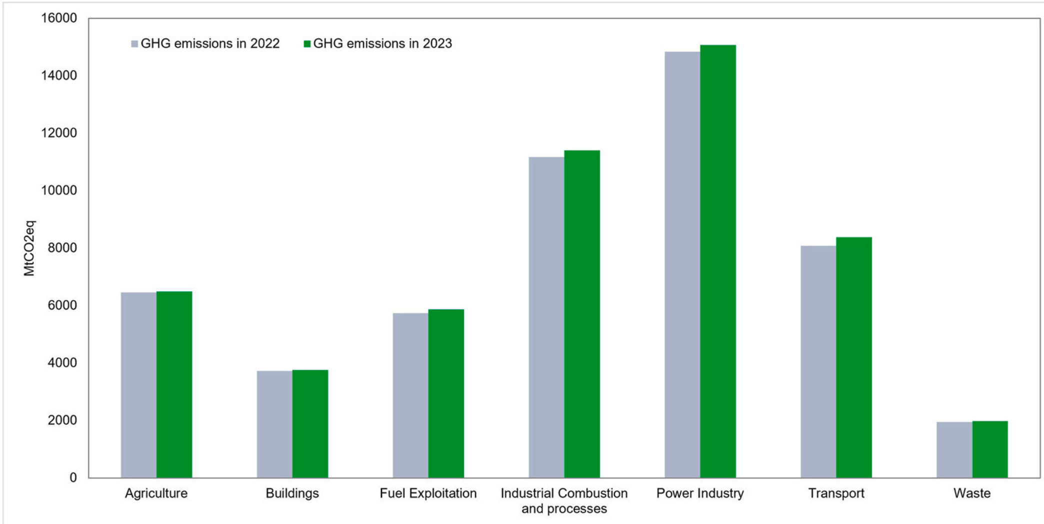

Fig. 31. GHG emissions by sector for the period 2022-2023.

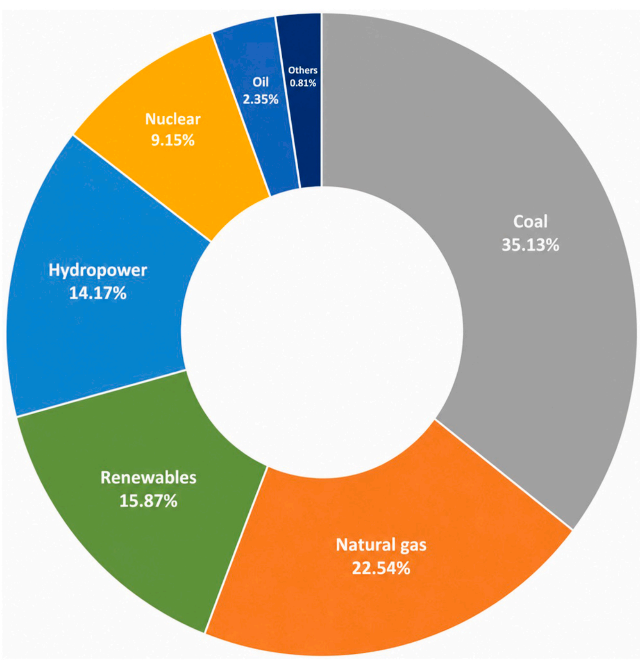

Fig. 32. Global distribution of electricity generation by various energy sources in 2023.

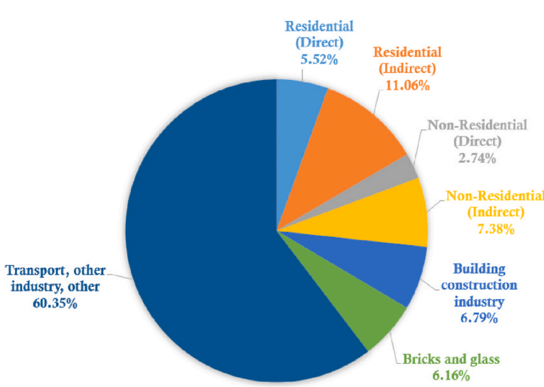

Fig. 33. The share of buildings in global energy and process emissions in 2022.

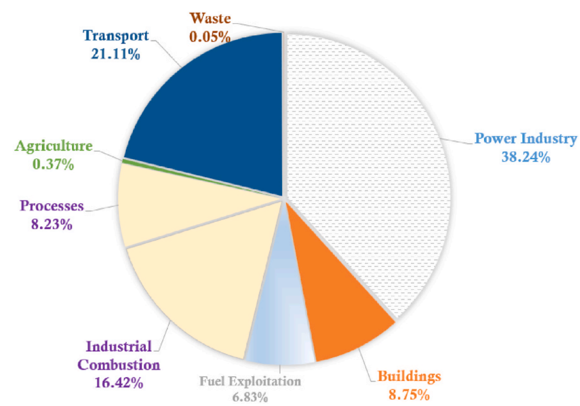

Fig. 34. Distribution of CO_2 emissions worldwide in 2023, by sector.

from 294 to 278 $MtCO_{2eq}$, while transport remained close to 30 $MtCO_{2eq}$. Most sectors recorded a sharp increase between 2020 and 2021 following the post pandemic economic recovery. Table 15 identifies the major country sector contributors, mainly concentrated in agriculture and fuel exploitation in China, India, Brazil, the United States, and Russia.

5.2.3. Nitrous oxide (N_2O)

Global N_2O emissions increased from 2312 $MtCO_{2eq}$ in 2014 to 2487 $MtCO_{2eq}$ in 2023. Fig. 38 shows that agriculture was the largest source at 69.71%, followed by industrial processes at 11.17%, the power industry at 5.33%, waste at 5.13%, and transport at 4.52%. Buildings, industrial combustion, and fuel exploitation contributed smaller shares. Fig. 39 shows the sectoral trend from 2014 to 2023. Agricultural emissions increased by 6.78% over the period, transport increased from 99 to 112 $MtCO_{2eq}$, and waste increased from 110 to 127 $MtCO_{2eq}$. The power industry recorded a moderate increase of 31 $MtCO_{2eq}$, while industrial combustion remained nearly stable between 25 and 26 $MtCO_{2eq}$. Table 16 identifies the major country sector contributors, led by the agricultural sectors of China and India.

5.2.4. Fluorinated gases (F-GASES)

F-gases, including hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF_6), are highly potent GHGs with strong climate warming effects [44]. HFCs are mainly used in refrigeration, air conditioning, foam production, and fire extinguishers [45].

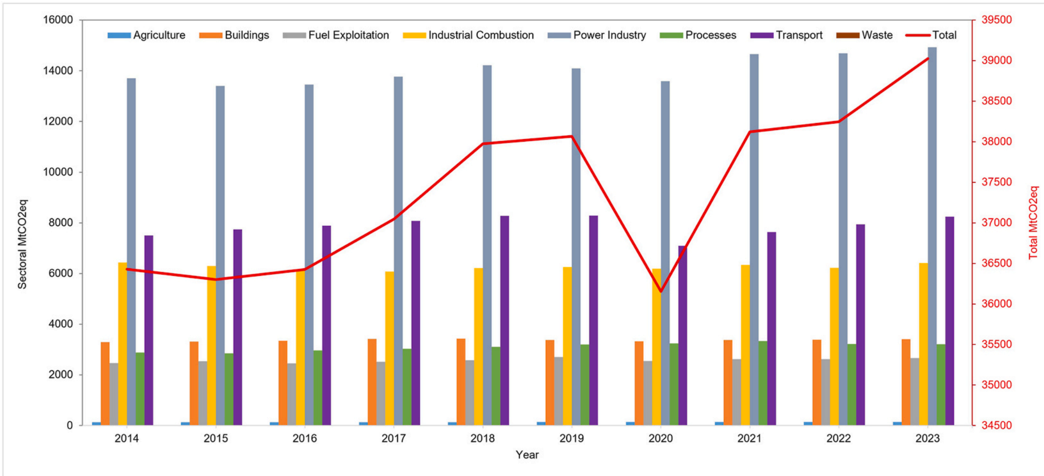

Fig. 35. Distribution of CO_2 emissions worldwide from 2014 to 2023, by sector.

Table 14
Highest contributors to the CO_2 emissions (More than 500 $MtCO_{2eq}$).

Country	Sector	Emissions $MtCO_{2eq}$	Percentage of the total
China	Power Industry	6472.95	16.59%
China	Industrial Combustion	2874.02	7.36%
United States	Transport	1710.65	4.38%
United States	Power Industry	1463.28	3.75%
China	Processes	1454.07	3.73%
India	Power Industry	1377.00	3.53%
China	Transport	1077.76	2.76%
Russia	Power Industry	881.85	2.26%
China	Fuel Exploitation	713.51	1.83%
China	Buildings	648.63	1.66%
India	Industrial Combustion	619.02	1.59%
United States	Buildings	593.49	1.52%

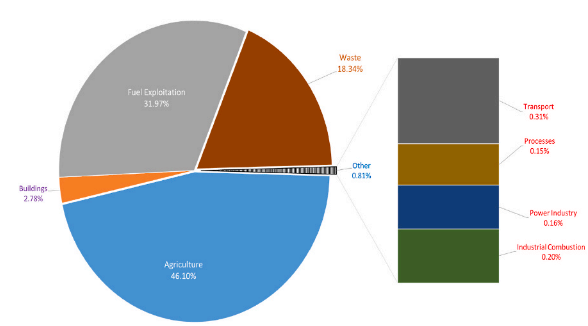

Fig. 36. Distribution of CH_4 emissions worldwide in 2023, by sector.

PFCs are mainly associated with electronics manufacturing and aluminum production, while SF_6 is widely used in electrical switchgear and electronics manufacturing. Fig. 40 shows that F-gas emissions increased from 1040 $MtCO_{2eq}$ in 2014 to 1451 $MtCO_{2eq}$ in 2023. Industrial processes were the main emission source. China, the United States, India, Saudi Arabia, and Russia were the largest contributors, as shown in Table 17.

6. Climate change scenario

Climate change refers to long-term changes in average weather patterns caused by both natural processes and human activities. Major impacts include sea level rise, ocean acidification, changes in the water cycle, loss of marine ecosystems, spread of climate sensitive diseases, and adverse effects on human health [46].

6.1. Global climate indicators

Global climate indicators provide a quantitative assessment of changes in the Earth's climate system. The following subsections present the main climate indicators recorded in 2023.

6.1.1. Global warming

According to the WMO [13], the global mean near surface temperature in 2023 was 1.45 ± 0.12°C above the 1850-1900 average, making 2023 the warmest year in the 174-year observational record. It exceeded the previous records set in 2016 and 2020. Based on NASA data [47], the Earth's surface temperature in 2023 was approximately 1.36°C above the late nineteenth century average. Fig. 41 shows the global surface temperature trend from 1880 to 2023.

6.1.2. Ice sheets

The Greenland and Antarctic ice sheets account for 97% of global glacier area. Complete melting of the Greenland ice sheet would raise global sea levels by approximately 7 m, while complete melting of the Antarctic ice sheet would raise sea levels by about 54 m [48]. NASA GRACE satellite data show continuous ice mass loss in both regions since 2002. Antarctica lost approximately 150 Gt of ice annually, as shown in Fig. 42, while Greenland lost around 270 Gt annually, as shown in Fig. 43 [49]. This continued ice loss is a major contributor to global sea level rise.

6.1.3. Oceans warming and acidification

The ocean absorbs approximately 25% of annual anthropogenic CO2 emissions. Dissolved CO_2 alters ocean carbonate chemistry and reduces ocean pH, a process known as ocean acidification [50]. According to NOAA [51], global average sea surface temperature in July 2024 was 1.21°C above the twentieth century average and exceeded the previous July record by 0.03°C. This marked the fourteenth consecutive month of record high global temperatures. Fig. 44, based on data from the Copernicus Marine Environment Monitoring Service [52] and a report from WMO [14], shows the global annual mean ocean surface pH from 1985 to 2022, indicating a gradual decline with regional and temporal

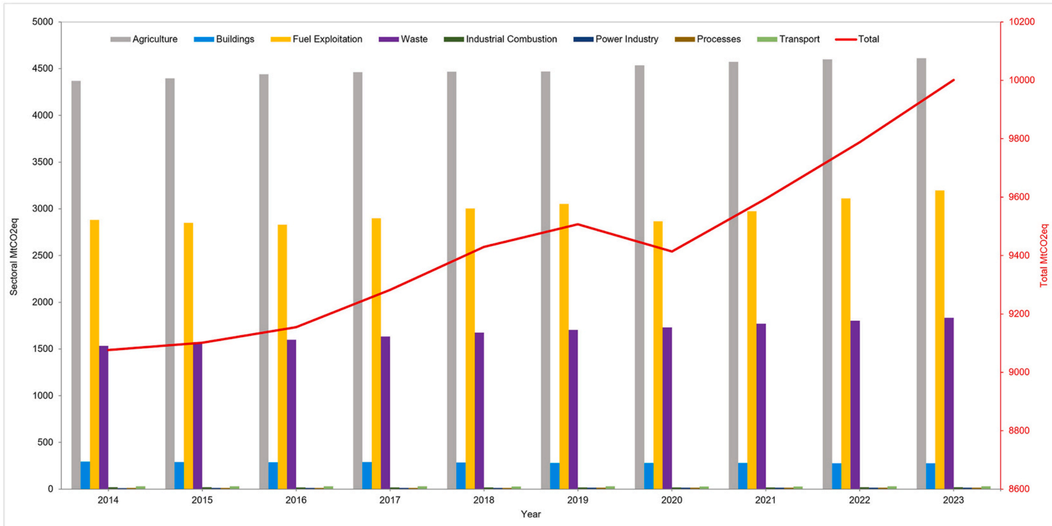

Fig. 37. Distribution of CH_4 emissions worldwide from 2014 to 2023, by sector.

Table 15
Greatest contributors to the CH_4 emissions (More than 150 $MtCO_{2eq}$).

Country	Sector	Emissions $MtCO_{2eq}$	Percentage of the total
China	Fuel Exploitation	734.81	7.35%
China	Agriculture	631.26	6.31%
India	Agriculture	567.56	5.67%
Brazil	Agriculture	471.23	4.71%
United States	Fuel Exploitation	442.04	4.42%
China	Waste	356.36	3.56%
Russia	Fuel Exploitation	269.61	2.70%
Indonesia	Fuel Exploitation	261.87	2.62%
United States	Agriculture	254.97	2.55%
Pakistan	Agriculture	209.70	2.10%

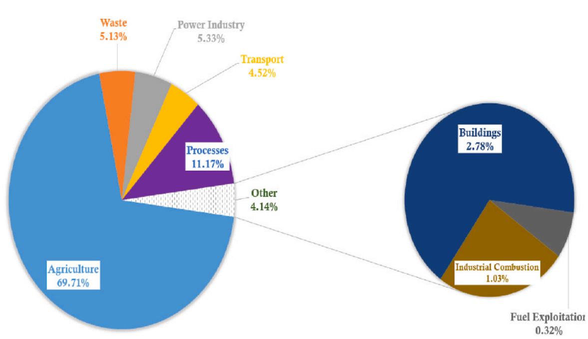

Fig. 38. Distribution of N_2O emissions worldwide in 2023, by sector.

variations.

6.1.4. Mountain glaciers

According to preliminary data from the World Glacier Monitoring Service, reference glaciers recorded a net ice loss equivalent to nearly 26 m of liquid water in 2023, corresponding to approximately 28.6 m of ice thickness [53]. Fig. 45 shows the cumulative mass change of reference glaciers from 1950 to 2023. Global reference glaciers have lost more than 30 m water equivalent since 1950, with glacier mass loss accelerating over recent decades despite the reduction in glacier area.

6.1.5. Sea level

Global warming increases sea levels through glacier and ice sheet melting and the thermal expansion of seawater, while groundwater and reservoir depletion contribute smaller effects [54]. Fig. 46 shows NASA satellite observations of global sea level change from 1993 to 2023. Global sea level increased by approximately 101.9 mm over the period, with the rate of rise accelerating in recent years [55].

6.1.6. Extreme weather and climate events

Extreme weather and climate events, including heat waves, cold waves, heavy rainfall, droughts, tornadoes, and tropical cyclones, are increasing in frequency and intensity due to climate change. According to the WMO [56], the number of recorded climate disasters increased fivefold over the past 50 years. Improved early warning systems and disaster management contributed to a nearly threefold reduction in fatalities over the same period.

6.2. Climate predictions for 2024-2028

According to the WMO [13], there is an 86% probability that at least one year between 2024 and 2028 will be warmer than 2023, and an 80% probability that global temperature will temporarily exceed 1.5°C above pre-industrial levels. Average temperatures during 2024-2028 are projected to remain above the 2019-2023 average, with Arctic warming expected to exceed the global average. These projections suggest that emission trends observed in 2023 are not consistent with long-term climate stabilization goals.

6.3. Climate change agreements/conferences

The United Nations Framework Convention on Climate Change (UNFCCC), established in 1994, provides the foundation for international efforts to stabilize GHG concentrations [57]. The Kyoto Protocol, adopted in 1997, introduced legally binding emission reduction targets for developed countries and established market based mechanisms, including the Clean Development Mechanism [58]. In 2009, the 15th Conference of the Parties (COP15) in Copenhagen aimed to strengthen global climate commitments. However, it did not result in a universally binding agreement [59].

The Paris Agreement established a framework based on nationally determined contributions that applies to all Parties [60]. Under this framework, countries set their own mitigation and adaptation targets and report progress through periodic reviews and global stocktakes. The Agreement seeks to limit global warming to well below 2°C above pre-industrial levels and pursue efforts to limit warming to 1.5°C. These objectives require effective national climate policies, strong regulatory

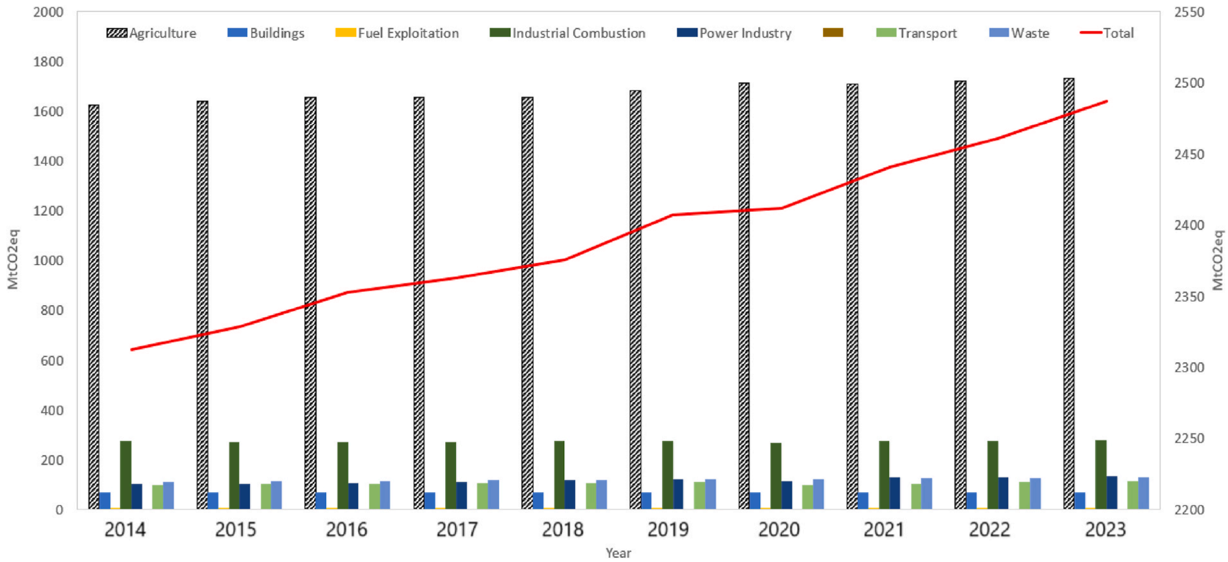

Fig. 39. Distribution of N_2O emissions worldwide from 2014 to 2023, by sector.

Table 16
Greatest contributors to the N_2O emissions (More than 50 $MtCO_{2eq}$).

Country	Sector	Emissions $MtCO_{2eq}$	Percentage of the total
China	Agriculture	238.70	9.60%
India	Agriculture	192.54	7.74%
Brazil	Agriculture	147.17	5.92%
United States	Agriculture	131.54	5.29%
Indonesia	Agriculture	66.053	2.66%
China	Power Industry	63.51	2.55%
Pakistan	Agriculture	52.11	2.10%

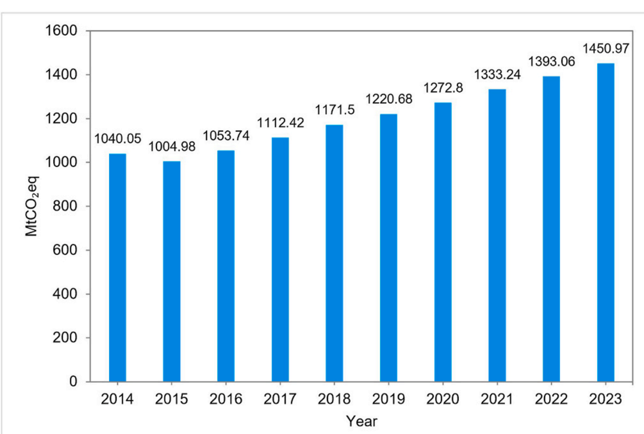

Fig. 40. Emissions from F-gases for the period 2014 to 2023.

Table 17
Greatest contributors to the F-gases emissions (More than 50 $MtCO_{2eq}$).

Sector	Country	Emissions $MtCO_2$	Percentage of the total
Industrial Processes	China	481.61	33.2%
	United States	216.01	14.89%
	India	68.75	4.74%
	Saudi Arabia	59.06	4.07%
	Russia	59.01	4.07%

frameworks, and sustained investment in low-carbon development.

6.4. Net zero emissions (NZE) scenario

The net zero emissions scenario refers to a pathway where GHG emissions are balanced by an equivalent amount of emissions removed from the atmosphere, which leads to net zero emissions [61]. Net zero emissions are essential for limiting global warming to 1.5°C or 2°C above pre-industrial levels. Without substantial reductions in global GHG emissions, global temperatures could exceed the 2°C threshold before 2050 [62]. This transition requires coordinated action across the energy, transport, industry, and agriculture sectors. As of 2023, 44 countries and the European Union had adopted net zero targets. These targets cover about 70% of global CO_2 emissions and global GDP. Fig. 47 presents the IEA net zero pathway, which projects global CO_2 emissions to decline to 21.1 Gt by 2030. Industry, electricity generation, and transport remain the largest emitting sectors. The pathway targets annual solar and wind capacity additions of 1020 GW, electric vehicles reaching 60% of global car sales, and low carbon hydrogen production increasing to 150 Mt from 850 GW of electrolyser capacity by 2030. By 2050, renewable energy is expected to supply nearly 90% of global electricity generation, while carbon capture technologies remove about 7.6 $GtCO_2$ per year [19].

IRENA's 1.5°C scenario projects that renewable energy will account for 77% of the global energy mix by 2050 [24]. The scenario requires average annual renewable capacity additions of 1066 GW between 2023 and 2050. Electricity is expected to supply more than 50% of final energy consumption, while modern biomass and green hydrogen contribute 16% and 14% of total energy demand, respectively. IRENA also estimates that renewable energy investment must increase significantly above 2023 levels to maintain progress toward the 1.5°C pathway.

7. Role of renewable energy sources in environmental protection

According to the UNEP Emissions Gap Report [28], exceeding the 2030 emissions levels implied by Nationally Determined Contributions as of 2023 would make limiting warming to 1.5°C extremely difficult and increase the risk of exceeding 2°C. Mitigation and adaptation are complementary approaches for addressing climate change risks [63]. Key mitigation strategies include renewable energy deployment, industrial energy efficiency, sustainable agriculture, reforestation, and

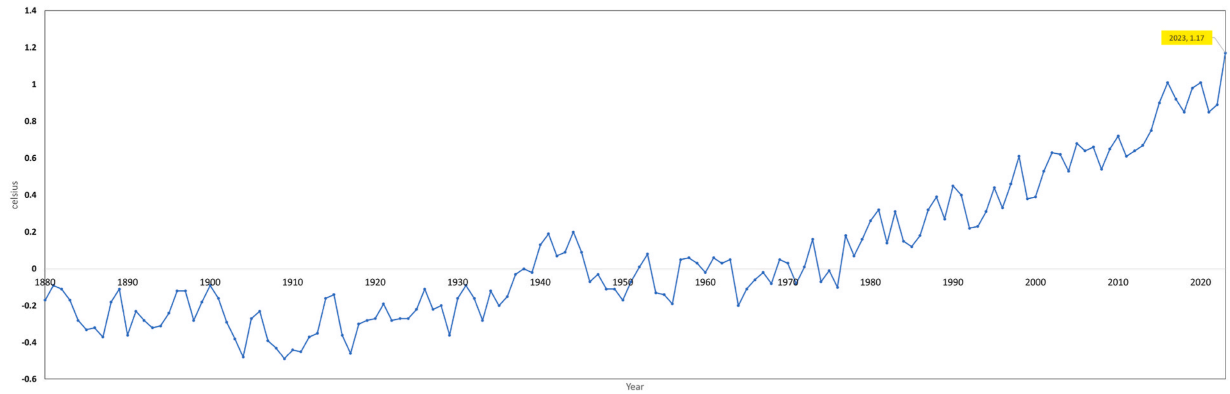

Fig. 41. The change in global surface temperature from 1880 to 2023 compared to the long-term average from 1951 to 1980.

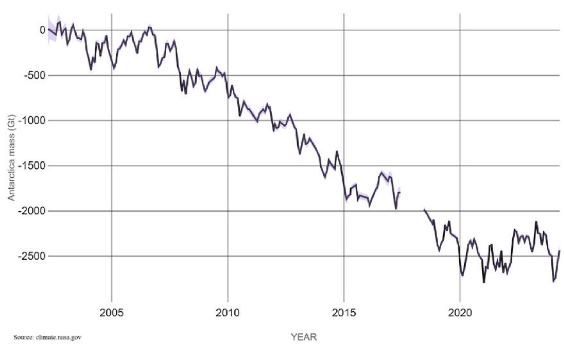

Fig. 42. Land ice sheets mass in Antarctica [49].

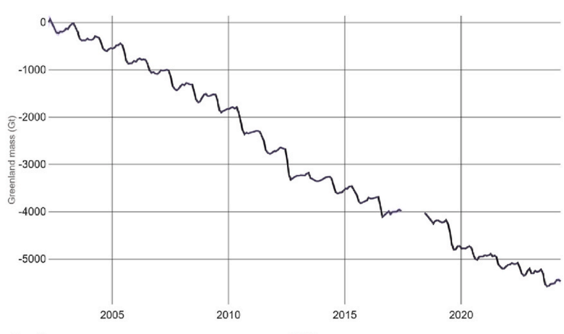

Fig. 43. Land ice sheets mass in Greenland [49].

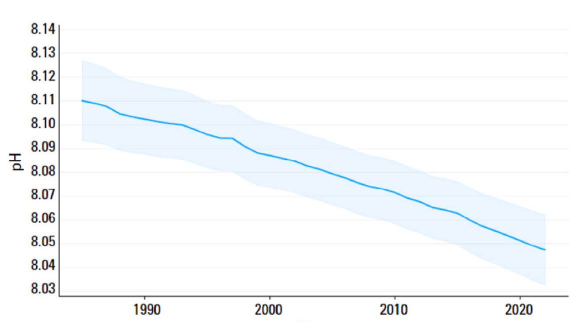

Fig. 44. Global annual mean ocean surface pH (blue) covering the period 1985–2022. The shaded area indicates the estimated uncertainty in the values [14,52]. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

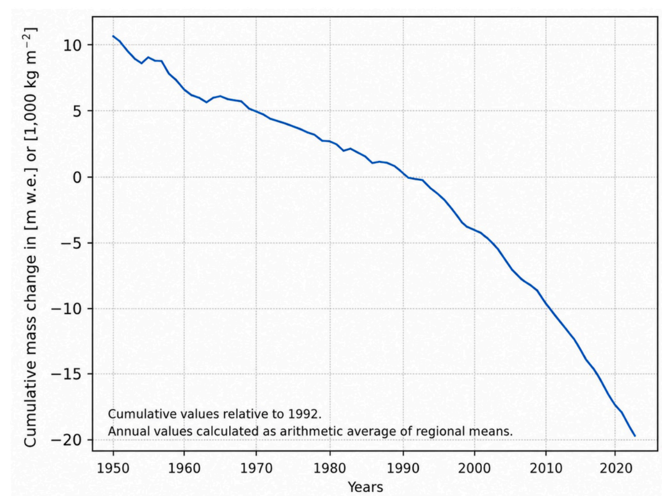

Fig. 45. Cumulative mass change of reference glaciers [53].

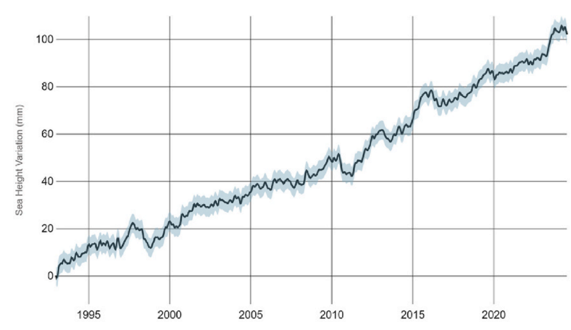

Fig. 46. Change in global sea level from 1995 to 2023 [55].

transport electrification [64].

Renewable energy consumption reduces environmental pollution and climate risk [65]. Table 18 shows that coal fired electricity has a median carbon footprint of 1001 gCO_{2eq}/kWh and natural gas 486 gCO_{2eq}/kWh, while renewable sources have substantially lower values. Wind power ranges from 13 to 20 gCO_{2eq}/kWh, hydropower averages 25.8 gCO_{2eq}/kWh, and solar PV can be as low as 12 gCO_{2eq}/kWh [66–76]. Table 19 shows that fossil fuels contribute to resource depletion, air pollution, acidification, eutrophication, and climate change, while wind and solar mainly involve land use impacts [77]. Previous studies also showed that renewable energy deployment reduces CO_2 emissions while supporting economic growth [78], [79].

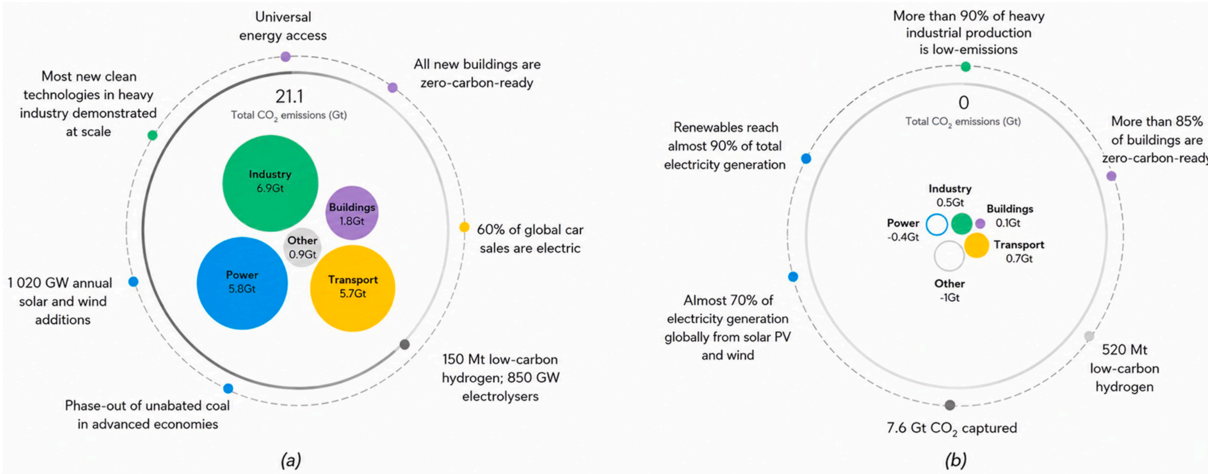

Fig. 47. IEA's net zero emissions pathway by: (a): 2030, (b): 2050 [19].

Table 18
CO_2 footprint for energy sources.

Generation type	GHG emission factor (gCO_{2eq}/kWh)			Causes	Reference
	Max	Min	Median		
Coal-fired	1689	675	1001	Coal mining, transportation, combustion, power plant operation and maintenance, and waste disposal.	[66]
Gas-fired	988	307	486	Gas extraction, processing, transportation, combustion, and plant efficiency.	[67]
Nuclear	122	5.4		Ore grade, extraction technique, enrichment technique, and power plant construction requirements and others.	[68]
Wind onshore	44	8	20	Turbine manufacturing, mining of raw materials, shipping, construction, and maintenance.	[69]
Wind offshore	24	5.3	13.0 ± 5.2	Similar to onshore but with more raw material usage and larger turbine bases.	[70]
Hydropower	237.0	0.04	25.8 ± 3.0	Dam construction, reservoir impoundment, land use, and maintenance.	[71]
Marine technologies - Wave	39	12	22.8	Recycling and disposal operations.	[72]
Marine technologies - Tidal	20	10	15		
Geothermal Double flash configuration for power generation only	23	15	23	Material extraction and transportation, drilling fluids, and wastewater management.	[73]
Photovoltaic – Rooftop (pc-Si)	66	26	12	Silicon production, material components, installation, and lifetime.	[74]
Photovoltaic - For a-Si cell	50	15.6	30.5	Silicon production, equipment, and lifetime.	[74]
Solar thermal - CSP with storage	9.8			Steel and concrete, and land use.	[75]
Biomass	200.078			Feedstock use, land use, waste products, and energy conversion.	[76]

Table 19
Most significant environmental impacts of energy production forms [77].

Impact	Coal	oil	Gas	Biomass	Nuclear	Hydropower	Wind	Solar
Resource depletion	X	X	X		X			
Land use	X			X		X	X	X
Water source regulation						X		
Thermal releases	X	X	X	X	X			
Noise						X		
Air quality	X	X	X	X				
Acidification	X	X	X	X				
Eutrophication	X	X	X	X				
Greenhouse effect	X	X	X	X				

7.1. The role of RES in mitigating ghg emissions for each GHG emissions sector

In this section, the authors explored the role and contribution of RES in mitigating GHG emissions in various sectors. These sectors include power industry, industrial combustion and processes, buildings, transportation, agriculture, and waste management.

7.1.1. Power industry

The power sector is easier to decarbonize and requires lower mitigation costs than many other sectors. Therefore, it plays a central role in reducing GHG emissions. Hybrid systems that integrate multiple low-carbon technologies provide a flexible and cost-effective pathway for power system decarbonization [80]. Optimization studies show that a reduction in thermal generation and an increase in the renewable energy share to 20% can reduce emissions by 77.6 million tons and decrease environmental costs by $1894.5 million by 2030. Demand-side management further improves system efficiency [81]. Life cycle assessment studies show that most emissions associated with nuclear and renewable energy technologies occur during manufacturing, construction, and installation rather than during electricity generation. Renewable and nuclear energy can jointly support net-zero electricity systems when planners adapt deployment strategies to regional resource availability [82]. Empirical evidence from 26 countries shows a statistically significant negative relationship between solar energy consumption and CO_2 emissions [83]. A 1% increase in wind energy consumption reduces carbon emissions by 0.018% [84]. The Gökçekaya Dam generates 597.85 GWh annually and avoids approximately 408,534 tCO_2 per year when it displaces fossil-fuel generation [85]. Geothermal power generation avoids about 380 tCO2 per GWh of electricity produced [86]. A biomass co-firing system displaces 36,321 tons of coal per year and avoids 93,279 tons of CO_2 and 1046 tons of SO_2 annually [87].

7.1.2. Industrial combustion and processes

Heavy industry is more difficult to decarbonize than the power sector because industrial processes require high temperature heat and produce process related emissions. Renewable energy technologies, including PV, wind, hydropower, biomass, concentrating solar power, heat pumps, and geothermal energy, can reduce fossil fuel consumption in energy intensive industries [88]. Biomass can replace 20% of industrial coal consumption in California's Central Valley and reduce emissions by 0.5 $MtCO_{2eq}$ [89]. In steel production, hydrogen-based direct reduced iron processes require approximately 3200 MW of PV capacity for each million tons of annual steel output [90]. Replacing 1100 GWh of natural gas with 1310 GWh of renewable electricity in reheating furnaces reduces emissions from 247,500 to 86,152 tCO_{2eq} per year. Hydrogen substitution can further reduce CO_2 emissions by more than 89% per ton of steel produced [91]. The glass industry can reduce emissions through electrical melting and hydrogen combustion technologies [92]. In polymer production, a 100% renewable energy scenario increases heat recovery by a factor of four, reduces energy costs by 41%, and decreases CO_2 emissions by 512,778 tons [93].

7.1.3. Transportation

Road transport decarbonization mainly depends on electrification through battery and hydrogen technologies. EVs provide zero tailpipe emissions, higher efficiency, lower maintenance, and reduced urban air pollution compared with internal combustion engine vehicles [94]. The global EV fleet is projected to increase from less than 45 million in 2023 to 250 million in 2030 and 525 million in 2035, while global FCEV stock reached 87,600 units in 2023 after a 20% annual increase [20]. A 90% reduction in transport CO_2 emissions, equivalent to 1.3 $MtCO_{2eq}$ annually, can be achieved with high EV penetration at a 12% higher cost compared with fossil-fuel-based transport [95]. However, the effectiveness of transport electrification depends strongly on electricity generation sources. Spain could achieve an 82% reduction in transport emissions by 2040 when electricity generation is largely supplied by RES [96]. Similarly, Italian regions with lower grid carbon intensity achieve greater emission reductions from EV adoption than fossil-fuel-dependent regions [97]. Therefore, RES integration is essential for achieving effective transport decarbonization [98].

7.1.4. Agriculture

Energy plays an important role in agricultural activities through electricity-intensive operations such as water pumping, machinery operation, greenhouse heating, food transport, and processing [99]. Analyses across agricultural economies showed that a 1% increase in renewable energy consumption reduces carbon emissions by 0.16% in the short-term and 0.22% in the long-term. In contrast, a 1% increase in fertilizer use raises emissions by 0.01% and 0.04%, while a 1% increase in livestock production increases emissions by 0.20% and 0.56% in the short and long-term, respectively [100]. In Uzbekistan, renewable energy implementation in agriculture reduced approximately 1.34 $MtCO_{2eq}$ and provided an electricity generation potential of 10,424 MWh/year from biogas and solar PV systems [101]. In Romania, supplying a tomato farm using offshore wind energy reduced emissions by about 1208.66 tCO_{2eq} annually, with a projected payback period of 9.33 years [102].

7.1.5. Buildings

Building decarbonization requires both the electrification of end use systems and the decarbonization of electricity generation [103]. An analysis of 108 scenarios for the United States residential sector showed that rapid grid decarbonization, building retrofits, improved thermal insulation, heat pump deployment, and smaller new home floor areas can reduce emissions by 91% between 2020 and 2050 [104]. Zero carbon thermal energy systems and advanced building technologies can reduce building energy consumption by approximately 5.0 quads and lower projected carbon emissions by 67%. Achieving carbon neutrality by 2050 requires additional carbon capture and energy conservation measures [105]. Integrating PV systems with heat pumps achieves energy savings greater than 50% and reduces CO_2 emissions by up to 73% in heating and cooling applications [106]. The global 1.5°C pathway requires an annual building renovation rate of 2.4%, increases in building electrification of 4% to 14%, and increases in renewable energy shares of 3% to 30%. It also requires electricity carbon intensity to decrease by a factor of four to six compared with the values assumed in the decarbonization scenarios and to fall below 40 gCO_2/kWh globally [107]. Demand response programs combined with renewable energy integration further reduce CO_2 emissions across different building types [108]. Passive house electrification scenarios in a Northern Ireland case study reduce global warming potential by 58%, 66%, and 70%, while the most ambitious scenario reduces carbon emissions by 83% [109]. In the United States building sector, aggressive energy efficiency measures, electrification, and high renewable energy penetration reduce CO_2 emissions by 72% to 78% compared with 2005 levels [110].

7.1.6. Waste

Waste-to-Energy (WtE) technologies, including incineration, gasification, anaerobic digestion, and biogas recovery, reduce waste volumes and GHG emissions by replacing fossil-fuel-based energy generation [111–113]. In Iran, diverting all municipal solid waste to WtE systems could achieve 54% of the national emission reduction target through incineration, 40% through anaerobic digestion, and 30% through landfill gas recovery [114]. Converting municipal solid waste to methanol using gasification and electrolytic hydrogen achieved net GHG emissions of 183 kg CO_{2eq}/t methanol over a 100-year global warming potential and −1222 kg CO_{2eq}/t methanol over a 20-year global warming potential [115]. In wastewater treatment plants, integrating biogas systems and solar PV achieved annual GHG reductions of 3.31685 $MtCO_{2eq}$ for anaerobic sludge blanket reactors and 5.09269 $MtCO_{2eq}$ for activated sludge systems, while PV integration further reduced emissions by 10-40% [116]. Smaller wastewater treatment plants achieved a 45% reduction in CO_2 emissions between 2014 and 2021, reduced external electricity demand by 18.7%, and lowered emissions from 1.2 to 0.8-0.9 kg CO_2/m^3 of wastewater [117]. Across 3444 wastewater treatment plants in China, renewable energy utilization reduced indirect GHG emissions by approximately 17%, including 10% from thermal energy, 3% from solar energy, and 4% from biogas utilization [118].

7.2. Tracking res progress for NZE by 2050

The IEA Tracking Clean Energy Progress 2023 report [18] evaluates more than 50 energy-system components against the NZE by 2050 pathway, classifying them as on track, more effort needed, or not on track, as summarized in Table 20. Solar PV and electric vehicles are the only components classified as on track. Coal-fired electricity remains the main challenge, requiring a 55% reduction in unabated generation by

Table 20
Tracking clean energy progress.

Component/Sector/Technology	Assessment	Aim	Needed action to get on track	Progressed Countries
Coal-fired Electricity Generation	Not on track	• Global coal use falls by 90% by 2050. • Full decarbonization of the global power sector by 2040.	• Immediate reductions and 55% decline in unabated coal-fired generation by 2030. • Complete phase-out by 2040.	• China • Indonesia • Viet Nam • Group of 7 • Portugal • Germany • Slovakia
Natural Gas-fired Electricity Generation	More efforts needed	• Gas demand decreases to 3400 bcm by 2030 and 920 bcm by 2050.	• Emissions from gas plants must fall by 2% annually through to 2030.	• United States • United Kingdom • Nigeria • Colombia
Solar PV Electricity	On track	• Generation reaches 8255 TWh by 2030.	• 26% average annual growth (2023-2030). • Focus on both distributed and utility-scale PV. • Strengthen supply chain resilience and diversification.	• China • European Union • United States • India • Brazil
Wind Electricity	More efforts needed	• Generation level of 7400 TWh by 2030.	• Annual growth rate of 17% needed. • Increase capacity additions to 350 GW by 2030. • Enhance permitting and reduce development timelines for onshore and offshore installations.	• China • European Union • United States • United Kingdom
Hydroelectricity	More efforts needed	• Annual generation reaches 5500 TWh by 2030.	• 4% annual growth required until 2030. • 50 GW of new hydropower plants needed each year through 2030.	• China • India • Europe • United States
Nuclear Power	More efforts needed	• Global capacity reaches 916 GWe by 2050. • COP28 signatories aim to triple nuclear power capacity by 2050.	• Expand capacity by 15 GW annually (3% growth) to 2030. • Nuclear investment of USD 125 billion per year required in late 2020s.	• Belgium • Canada • China • Finland • France • Japan • Korea • Poland • United Kingdom • United States
Electric Vehicles	On track	• EV sales reach 65% of total car sales by 2030.	• Annual sales increase by 23% until 2030. • 17 million public charging points needed by 2030, with 23% annual growth.	• Norway • China • Canada • United States • European Union
Industry	Not on track	• Industrial emissions fall to 7 Gt CO2 by 2030. • Industrial energy productivity grows by 3% per year.	• Industry emissions must decline by 3% annually until 2030. • Accelerated policy action is required.	• China • European Union • United States
Buildings	More efforts needed	• All new buildings and 20% of existing stock must be zero-carbon-ready by 2030. • Energy consumption in buildings drops by around 25% and fossil fuel use decreases by more than 40% by 2030.	• Emissions must fall by 9% per year until 2030. • Energy consumption per square meter must decrease by 35% by 2030.	• China • Japan • European Union • United States

2030 and complete phase-out by 2040. Emissions from natural gas-fired generation must decline by 2% annually through 2030. Wind power requires 17% annual growth and 350 GW of new capacity by 2030, while hydropower requires 4% annual growth and 50 GW of annual additions. Nuclear capacity must expand by 15 GW annually with investments reaching $125 billion per year by the late 2020s. Industrial emissions must decline by 3% annually, while building emissions must decrease by 9% annually with a 35% reduction in energy use per square meter by 2030. These results show that the progress in 2023 remained insufficient to meet the NZE pathway.

8. Challenges and barriers for renewable energy spread implementation

Renewable energy deployment advanced considerably in 2023, but several barriers still restricted growth and limited expansion into many regions. According to the IEA Renewables 2023 report, global renewable capacity reaches 7300 GW by 2028 under 2023 policies. This level remains below the target of more than 11,000 GW by 2030. The report estimates that removing existing barriers increases renewable growth by nearly 21% [15]. In addition, the IEA Renewables 2024 report [16] states that renewable fuel adoption must nearly double by 2030 to align with the NZE pathway, with high costs remaining a major challenge. The following subsections classify these barriers into economic and financial, technical and infrastructure, policy and regulatory, and social and cultural categories.

8.1. *Economic and financial barriers*

High upfront capital cost remains a major barrier to renewable energy deployment across all regions [119–121]. These costs often result in long payback periods, which increase investment uncertainty and reduce the competitiveness of renewable energy projects relative to fossil fuel alternatives, particularly in countries that maintain fossil fuel subsidies [119,122,123]. The challenge is more pronounced in developing economies, where high perceived investment risk increases the cost of capital and restricts access to foreign financing [119,123]. As a result, countries such as Ecuador and several African nations continue to face slow renewable energy adoption due to high investment costs, limited financing opportunities, and persistent fossil fuel subsidies [122,123].

Market structures continue to disadvantage renewable energy sources because fossil fuels benefit from environmental and health externalities that are rarely reflected in market prices, while renewable technologies do not receive comparable support [120,121]. The renewable energy policy paradox described in Ref. [124] further limits investment. Solar and wind generation have near-zero marginal costs, but their variable output can lower electricity prices in liberalized markets. This effect reduces revenue certainty and weakens private investment incentives. Power systems therefore continue to depend on fossil fuel generation to provide reliability and balancing services. Policymakers can address these barriers by reducing fossil fuel subsidies, expanding concessional financing in developing economies, and reforming electricity markets to reward flexibility, energy storage, and grid support services from renewable resources [15,16,124].

8.2. Technical and infrastructure barriers

Grid integration and energy storage remain major technical barriers to renewable energy deployment [119,121]. The variable output of solar and wind generation requires flexible generation resources, demand response programs, and energy storage systems. Many electricity networks, particularly in developing regions, lack these capabilities [120,121]. In Ecuador, limited grid connectivity and restricted access to advanced technologies further constrain renewable energy expansion [122]. In the European Union, inadequate transmission infrastructure, high grid connection costs, and limited market flexibility reduce the competitiveness of variable renewable energy (VRE) technologies [125,126]. Expanding auction mechanisms, increasing trading time resolution, and removing price caps can improve investment conditions for VRE technologies [126]. High balancing and grid costs also reduce the economic competitiveness of VRE technologies. Skilled labor shortages further limit renewable project development, construction, and maintenance [119,120]. In developing countries, unclear regulatory frameworks and unstable government support increase investment risks and discourage both domestic and foreign investors from financing renewable energy projects [120,123].

8.3. Policy and regulatory barriers

Uncertain policies, inconsistent regulations, administrative requirements, and delays in permitting increase project costs and slow the deployment of renewable energy technologies [119,125]. In the European Union, long approval processes and limited regulatory transparency create obstacles for project development. Evidence shows that countries with more efficient permitting systems achieve higher levels of renewable energy deployment [125]. Political instability and changing policy commitments also reduce investor confidence and make long-term planning more difficult. Weak carbon pricing policies and poor coordination among energy policies allow fossil fuels to remain competitive in many markets [121]. Centralized electricity systems and monopoly market structures further hinder the shift toward decentralized renewable energy systems [120]. Unclear regulations and inconsistent government support discourage both domestic and foreign investment by increasing uncertainty, particularly in developing economies [122,123].

8.4. Social and cultural barriers

Low public awareness of renewable energy benefits and local opposition to project siting remain common challenges [119,120,122,123]. Land use disputes, concerns about visual impacts, and cultural resistance often delay project development in both developed and developing countries. In Africa, cultural resistance adds to existing economic, technical, and regulatory barriers [123]. Similar issues have been reported in Ecuador, where limited public awareness and local opposition have slowed the adoption of renewable energy technologies [122]. Many households, communities, and small businesses do not have adequate information about the costs, benefits, and long-term value of renewable energy systems. This lack of information can reduce interest in renewable energy investments, even when favorable financial and technical conditions exist [121]. Public engagement initiatives, clear communication of project benefits, and inclusive planning processes can help overcome these challenges. In addition, the early participation of local communities can increase public acceptance and facilitate project development.

8.5. Implications for policy and investment

Renewable energy deployment requires coordinated action across economic, technical, regulatory, and social dimensions. Governments can support this transition through policy reforms that simplify permitting procedures, strengthen carbon pricing mechanisms, and gradually remove fossil fuel subsidies. Investments in grid infrastructure, energy storage systems, and financing mechanisms are also necessary, particularly in developing countries. In addition, countries need stronger technical expertise, more resilient supply chains, and greater public awareness to support the expansion of renewable energy technologies [16]. Renewable energy investment increased in 2023, but most funding remained concentrated in a limited number of regions and technologies [24]. More investment is needed in Africa, South and Southeast Asia, and Latin America to support a balanced energy transition and help achieve the targets of the NZE pathway.

9. Conclusion and recommendations

This paper presented an integrated analysis of the global renewable energy landscape in 2023. It combined international energy and climate datasets to examine deployment trends, environmental impacts, and progress toward the NZE pathway. The results show that 2023 was a significant year for renewable energy growth. However, the findings also highlight major structural and regional challenges that continue to slow the global energy transition. The main findings and recommendations are summarized below.

9.1. Main findings

- Energy landscape in 2023: Fossil fuels remained dominant in global primary energy consumption, at 81.47% of the total, with oil, coal, and natural gas contributing 31.7%, 26.47%, and 23.3%, respectively. Renewable energy sources contributed 14.56%. The energy sector remained the largest source of global GHG emissions.
- Renewable Energy Growth: Global renewable energy consumption reached 50.58 EJ in 2023, which represented an increase of 11.95% compared with the previous year. Renewable capacity additions reached 510 GW, the fastest expansion in two decades and almost 50% higher than in 2022. Solar PV and wind energy accounted for 96% of all new capacity additions. The share of renewables in global electricity generation increased to 30%, compared with 19% in 2000. Solar and wind technologies were the main contributors to this growth and together produced 13.4% of global electricity.
- Technology Performance: Solar power capacity increased by 346 GW in 2023 and reached 1419 GW. Solar represented 36.67% of global

renewable power capacity, and PV technology accounted for almost all new additions. Wind power added 116 GW and reached a total capacity of 1017 GW, which represented 26.28% of global renewable capacity. Onshore wind remained dominant with 92.86% of total wind capacity, while offshore wind reached 7.18% and continued to expand. Hydropower capacity reached 1268 GW, but annual additions were limited to 7.2 GW because the technology has already matured in many established markets. Bioenergy reached 150.3 GW, although its growth rate slowed. Geothermal capacity increased to 14.85 GW, while marine energy remained at an early stage of development with 527 MW installed. Green hydrogen recorded its largest annual increase between 2022 and 2023 and accounted for 96.6% of total growth in hydrogen production.

- Regional Distribution: Asia led global renewable energy growth in 2023 with 327.8 GW of new capacity. China accounted for the largest share of total renewable capacity and annual additions across solar, wind, hydropower, and bioenergy technologies. Europe added 71.2 GW, while North America added 34.9 GW. The Middle East recorded its highest annual expansion with 5.1 GW of new renewable capacity, which represented a 16.59% increase compared with 2022. Africa added 2.7 GW. This result demonstrates both the continent's strong renewable potential and the financial barriers that continue to limit deployment.
- Climate indicators: Global temperature reached $1.45 \pm 0.12^{\circ}$C above pre-industrial levels. Atmospheric CO_2 concentration reached 419.3 ppm. Climate impacts such as sea level rise, glacier retreat, and extreme weather became more severe in 2023.
- GHG emissions: Global GHG emissions increased to 53.0 $GtCO_{2eq}$ in 2023. China remained the largest emitter and produced approximately 30% of global emissions. The United States followed with 11.25%. EU27 emissions declined by 7.5%. The power sector, industry, and transport generated the largest shares of global emissions. Global emissions remained inconsistent with the NZE pathway.
- NZE Progress: Solar PV and electric vehicles were the only technologies identified as being on track to meet NZE targets for 2050. Coal-fired electricity generation, industry, wind power, hydropower, and nuclear energy all require much faster progress. Global coal consumption must decline by 55% before 2030 and reach complete phase-out by 2040. Industrial emissions must decrease by 3% each year. This goal requires stronger policies and greater investment in technologies such as green hydrogen.
- Challenges and barriers: Renewable energy deployment faces economic, technical, regulatory, and social barriers. In many developing economies, high financing costs, weak infrastructure, and policy uncertainty create additional constraints.

9.2. Recommendations

The transition to a renewable energy system depends on more than the deployment of new generation capacity because policy frameworks, infrastructure, financing conditions, and institutional factors all influence the speed and scale of adoption. Policy and market design remain central to the energy transition because renewable energy tends to face weaker investment signals in many electricity markets, especially when prices fall during periods of high generation. Reforms around market structure, permitting, subsidy removal, and carbon pricing are therefore often discussed together since they all affect investment conditions in different ways. Infrastructure is another major issue. Many power systems were not built for high shares of variable renewable energy, so transmission limits, distribution constraints, and a lack of storage slow down integration. Without upgrades in these areas, even strong renewable capacity growth does not translate smoothly into system-wide change. Financing also remains uneven. Some regions continue to attract most of the investment, while others with high renewable potential struggle to access affordable capital. This gap is especially visible in parts of Africa, South and Southeast Asia, and Latin America, where financial risk remains a major barrier even when resources are available. Public acceptance, early community involvement, and institutional capacity should not be treated as secondary factors because they influence whether projects move forward or face delays. These issues also connect to newer technologies such as green hydrogen, which continue to depend on policy support and infrastructure development.

The 2023 baseline presented in this paper demonstrates that the technological infrastructures for a global energy transition already exist. Future progress will depend on how quickly governments, industries, and financial institutions address the structural barriers identified in this study. The success of the NZE pathway will depend not on technology availability, but on effective policy implementation, adequate investment, and coordinated international action.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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