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Evolution of Emissions: The Role of Clean Energy in Sustainable Development

Mohamed Khaleel[1*], Ziyodulla Yusupov[1], Nabeh Alderoubi[2], Rawad L. Abdul_jabbar[3], Monaem Elmnifi[4], Yasser Nassar[5], Hasan Shakir Majdi[6], Laith Jaafer Habeeb[7], Salah Abulifa[8]

[1] Department of Electrical-Electronics Engineering, Faculty of Engineering, Karabuk University, 78050 Karabuk, Turkey
[2] Design and Drafting Technology Department, Lincoln Campus, Southeast Community College, 68521 Nebraska Lincoln, USA
[3] College of Technical Engineering, Al-Farahidi University, 10022 Baghdad, Iraq
[4] Department of Mechanical Engineering Technology, Belgorod Technological University named after. V.G. Shukhov, 308000 Belgorod, Russia
[5] Research Center for Renewable Energy and Sustainable Development, Wadi Alshatti University, 721 Barck, Libya
[6] Department of Chemical Engineering and Petroleum Industries, Al-Mustaqbal University College, Hillah, 51001 Babylon, Iraq
[7] Training and Workshop Center, University of Technology-Iraq, 10001 Baghdad, Iraq
[8] Department of Electrical and Electronic Technologies, Higher Institute of Technical Sciences, 00218 Misrata, Libya

[*] Correspondence: Mohamed Khaleel (lykhaleel@yahoo.co.uk)

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Abstract: This paper assesses green energy technology with respect to its profound impacts, particularly photovoltaic (PV) installed capacity, wind installed capacity and hydrogen fuel cells installed capacity on sustainable development as well as mitigating greenhouse gas emissions. Additionally, the study examines recent technological improvements and empirical facts that indicate how renewable sources of energy facilitates decrease in carbon emission and further supports global sustainability goals. As a result, major findings show significant declines in CO_2 releases after extensive PV, wind and hydrogen fuel cell technologies have been deployed. The examples from China, EU countries, USA, India and Japan demonstrate these accomplishments. Cumulative CO_2 emissions from 2015 to 2023 for China were 102.0 Gt; while the United States had 43.0 Gt; EU - 25.4 Gt; India – 21.7 Gt; Japan –10.0 Gt, respectively.

Keywords: Clean energy; CO_2 emissions; PV installed capacity; Wind installed capacity; Hydrogen fuel cell installed capacity; Emissions in advanced economies

1. Introduction

The growth of clean energy (CE) has been strong due to annual acceleration in the implementation of key technologies, policy support, and cost reductions. Between 2019 and 2023, CE investments increased by nearly half resulting in a total amount of USD 1.8 trillion in 2023 with a continuous growth rate averaging about 10% p.a. for this period. As seen from the global perspective, the CE sector is a strong industrial field with substantial impact on world economy (Hassan et al., 2024). CE stands as the linchpin in mitigating the deceleration of emissions. The global augmentation of wind and solar photovoltaic (PV) capacities soared to an unprecedented approximate of 540 GW in 2023, representing a remarkable escalation of 75% compared to the antecedent year. Concurrently, worldwide sales of electric vehicles surged to approximately 14 million units, marking a notable augmentation of 35% relative to the 2022 figures. The salient impact of CE is discernible in its substantial influence on the trajectory of global CO_2 emissions (Li et al., 2024a; Sayed et al., 2024). This phenomenon is expounded in Figure 1, delineating the variance in CO_2 emissions stemming from energy combustion juxtaposed with the emissions mitigated through the deployment of major clean technologies, spanning the period from 2019 to 2023.

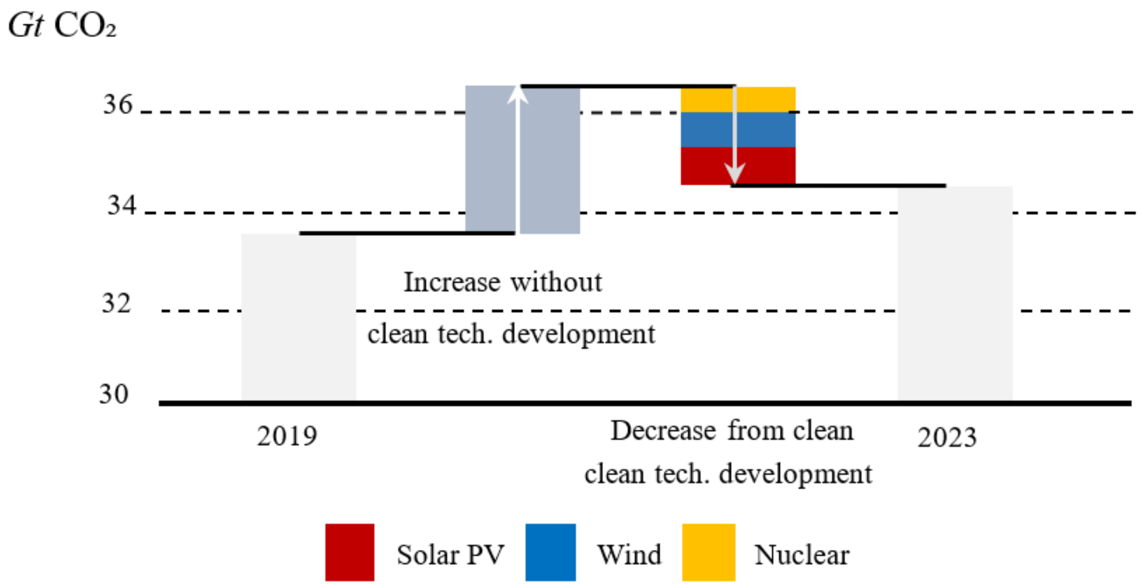

Figure 1. The variance in CO_2 emissions stemming from energy combustion juxtaposed with the emissions mitigated through the deployment of major clean technologies, spanning the period from 2019 to 2023

Riding the momentum of Covid-19 stimulus initiatives, a pronounced surge in the implementation of CE technologies has transpired since 2019. Over the period spanning from 2019 to 2023, the cumulative escalation in energy-related emissions approximated 900 million metric tons (Mt). Absent the burgeoning deployment of five pivotal CE technologies, namely solar PV systems, wind power infrastructure, nuclear energy facilities, heat pump technologies, and electric vehicles, the amplification in emissions would have been threefold greater (Adebayo & Ullah, 2023). In the year 2023, there was a notable augmentation of 1.1% observed in total energy-related CO_2 emissions. Contrary to the imperative trajectory of rapid decline mandated to align with the overarching climate objectives delineated in the Paris Agreement, CO_2 emissions ascended to an unprecedented pinnacle, registering at 37.4 Gt in 2023. This evaluation is predicated upon the meticulous and sophisticated analysis conducted by the International Energy Agency (IEA, 2023), encompassing a comprehensive assessment of regional dynamics and fuel-specific metrics, drawing from the latest authoritative national energy datasets, augmented by supplementary information concerning economic indicators and meteorological parameters. Table 1 indicates annual change in energy-related CO_2 emissions, 2015-2023. In 2023, CO_2 emissions resulting from energy combustion and industrial processes amounted to 0.41 Gt. In 2022, these emissions were 0.49 Gt, while in 2021, they reached 1.92 Gt. Clearly, in 2020, there was a significant reduction, with emissions from energy combustion and industrial processes recorded at -1.92 Gt.

Table 1. Annual change in energy-related CO_2 emissions, 2015-2023 (IEA, 2023)

Year	CO_2 Emissions	Caused by
2023	0.41 Gt CO_2	Energy combustion & industrial prosses
2022	0.49 Gt CO_2	Energy combustion & industrial prosses
2021	1.92 Gt CO_2	Energy combustion & industrial prosses
2020	-1.92 Gt CO_2	Energy combustion & industrial prosses
2019	0.01 Gt CO_2	Energy combustion & industrial prosses
2018	0.86 Gt CO_2	Energy combustion & industrial prosses
2017	0.57 Gt CO_2	Energy combustion & industrial prosses
2016	0.10 Gt CO_2	Energy combustion & industrial prosses
2015	-0.10 Gt CO_2	Energy combustion & industrial prosses

The uptick of 1.1% in emissions witnessed in 2023 equated to an augmentation of approximately 410 million metric tonnes (Mt CO_2). Notably, the rate of emissions expansion significantly lagged behind the pace of global gross domestic product (GDP) growth, which stood at approximately 3% during the same period. Consequently, the preceding year perpetuated the ongoing pattern CO_2 emissions exhibit a more subdued growth trajectory compared to the pace of global economic activity. Over the decade culminating in 2023, global CO_2 emissions manifested a marginal increment averaging slightly over 0.5% annually. This trend cannot be solely attributed to the Covid-19 pandemic; while emissions plummeted precipitously in 2020 due to pandemic-induced disruptions, they rebounded swiftly in the subsequent year, reinstating levels akin to the pre-pandemic era. Moreover, the deceleration in emissions growth cannot be attributed to sluggish global GDP expansion, as the latter sustained a robust average of 3% per annum over the course of the preceding decade, consistent with the historical annual average over the past half-century (Michael et al., 2024).

While numerous studies have examined the evolution of emissions, a comprehensive investigation specifically addressing the role of CE in contributing to sustainable development remains limited. Many existing analyses tend to focus broadly on emissions trends without delving deeply into how renewable energy sources, such as solar, wind, and hydrogen, are mitigating these emissions and fostering sustainability.

The gap in understanding has highlighted a need for more focused research to bring out the various impacts of renewable energy technology on reducing greenhouse gases and promoting environmental and economic wellbeing over the long term. The transition of world economies towards cost-effective, environmentally friendly, and efficient energy systems has increased the significance of comprehending the nexus between energy dynamics and a sustainable future (Pan et al., 2023). Saqib & Usman (2023) developed a model where they made an attempt to undertake a case study in order to find out whether there is any causal relationship exists between sustainable development, technological innovation, the strictness of energy policies, renewable energy as well as targets for achieving carbon neutrality or net-zero emissions. Yu et al. (2024) carried out their research utilizing concepts like energy utilization technique, input-output analysis technique, structural decomposition model which are based on taking China's light sector CO_2 emissions related to its use of energy into account from an input-output perspective. Results indicated that the significant individual factors constraining growth in CO_2 emissions related to energy usage were: impingement on structure of power supply; density of fuels; and aggregate inputs. Signal expansion at the supply side pertaining to light industry was responsible for this effect.

The work of Afshan et al. (2024) is characterized by a beneficial relationship amid energy consumption and carbon emissions in China, which means that the new energy direction would be faced with impediments on effectiveness. It was concluded that decision-making processes and policy development could benefit from these findings, enabling implementation of appropriate measures to foster China's greener and sustainable future. An article by Madaleno & Nogueira (2023) investigated how CO_2 emissions and the use of renewable energy affected economic growth. Fixed assets, human capital, research and development (R&D), foreign direct investment (FDI), labor force, international trade was used as control variables in this study. The study was conducted specifically for two largest polluters in the world-USA and China. Mehmood et al. (2023) have done a research work that has focused on examining emissions impact upon sustainable development. Moreover, it is worth noting that emission remains one of the biggest causes of climate change thereby posing numerous effects to environment.

The article's main focus lies in providing an in-depth discussion of how clean energy (CE) technologies contribute to the advancement of global sustainability targets. Through an exhaustive investigate of recent advancements and empirical data, the article effectively highlights the multifaceted contributions of PV, wind, and hydrogen fuel cell capacity towards mitigating greenhouse gas emissions and fostering sustainable development worldwide. Nonetheless, the article provides compelling evidence of the substantial reductions in CO_2 emissions facilitated by the widespread adoption of CE technologies, underscoring their pivotal role in combatting climate change. By presenting case studies from regions such as China, the European Union, and the United States, the article demonstrates the tangible impact of CE deployment on emissions reduction efforts, thereby informing policymakers and stakeholders about the efficacy of renewable energy solutions in addressing pressing environmental challenges.

2. Data Collection

In terms of data collection, this study primarily investigates the current state of emissions evolution and the contribution of clean energy (EC) to sustainable development, as well as the implementation and impact of relevant regulations and programs. In this direction, this article discusses the potential for decreasing CO_2 emissions based on photovoltaic, wind, and hydrogen fuel technologies in the region. Thus, the data utilized in this article were gathered and synthesized from several official reports. Below is a compilation of the main reports cited in this article:

- World Energy Transitions Outlook 2023 (Irena, 2023).
- Measuring the Emissions & Energy Footprint of the ICT Sector: Implications for Climate Action (Ayers et al., 2024).
- Global Energy and Climate Model (IEA, 2024a).
- Low-emissions Sources of Electricity (IEA, 2024b).

- CO_2 and Greenhouse Gas Emissions (Ritchie et al., 2024).
- Annual Carbon Dioxide (CO_2) Emissions Worldwide from 1940 to 2023 (Statista, 2023).

3. Clean Energy (CE)

The adoption of clean energy (CE) primarily focuses on three fundamental elements: solar photovoltaic (PV) installed capacity, wind installed capacity, and hydrogen fuel cell capacity. Together, these elements provide the fundamental structure of CE infrastructure, propelling the shift towards sustainable and renewable energy (RE) solutions.

3.1 Solar PV Installed Capacity

Despite the gradual reduction of central government subsidies for utility, commercial, and industrial-scale solar PV applications, China witnessed a significant surge in solar PV deployment. It expanded by 2.5 times and now accounts for an unprecedented 62% of global additions. According to a report from the National Renewable Energy Laboratory, the worldwide installed capacity of photovoltaic (PV) systems grew by around ten times in the past decade, going from 17 GW in 2010 to 172 GW in 2021. Solar PV played a vital role in meeting the growing global energy demands. Due to the continuous researches and development, the solar PV technology has experienced a significant change in terms of efficiency and overcoming costs constraints found in (Zhang, 2024; Ndalloka et al., 2024). in this regard the total installed solar PV capacity in the global area increases by over 80% from 2022 to 2023 to a spectacular figure of 420 GW. vital and notable to mention that, China itself, accounted for more than 80% of the solar PV capacity expansions all over the world. Thus, Figure 2 illustrates the evolution of global solar PV installed capacity additions from 2019 to 2023. By the end of 2021, the global total cumulative installed capacity of PV systems had reached at least 939 GW (Liu et al., 2024). Figure 3 presents the Solar PV installed capacity in China, the European Union, the United States, and India for the years 2019 to 2023.

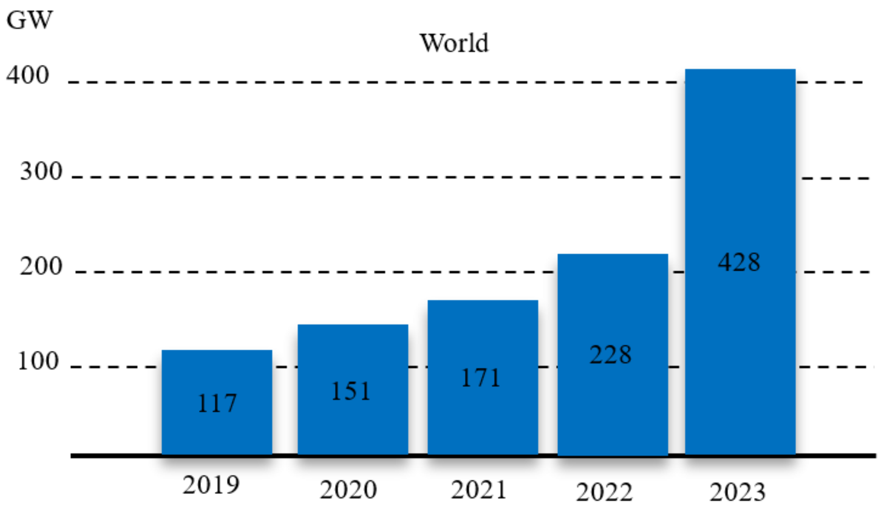

Figure 2. The global additions of solar PV installed capacity from 2019 to 2023

It is crucial to mention that, China's rapid proliferation of manufacturing capabilities precipitated a substantial 50% reduction in PV costs since December 2022, thereby enhancing the competitiveness of solar PV in comparison to provincial benchmark electricity prices predominantly reliant on coal power generation. Utilizing the Weibull distribution to anticipate the recovery potential of c-Si panels, the study quantified the significance of recycling in harmonizing the supply and demand of raw materials. The findings indicated that under the high-growth scenario, China's cumulative PV installed capacity would have reached 2125 GW by 2050, with an estimated revenue generated from recycling ranging between $400 to $700 million. Moreover, China had accumulated a remarkable 390 million kW of installed PV capacity, covering approximately 0.8 million km^2 of land by the end of 2022. With the ongoing expansion in both the quantity and magnitude of installed PV power stations in China, the requirement for land allocated to PV also increased. It was projected that by the year 2060, China's PV installed capacity would surpass 3 billion kW. Figure 3 elucidates the solar PV installed capacity trends in China, the European Union, the United States, and India for the years spanning from 2019 to 2023.

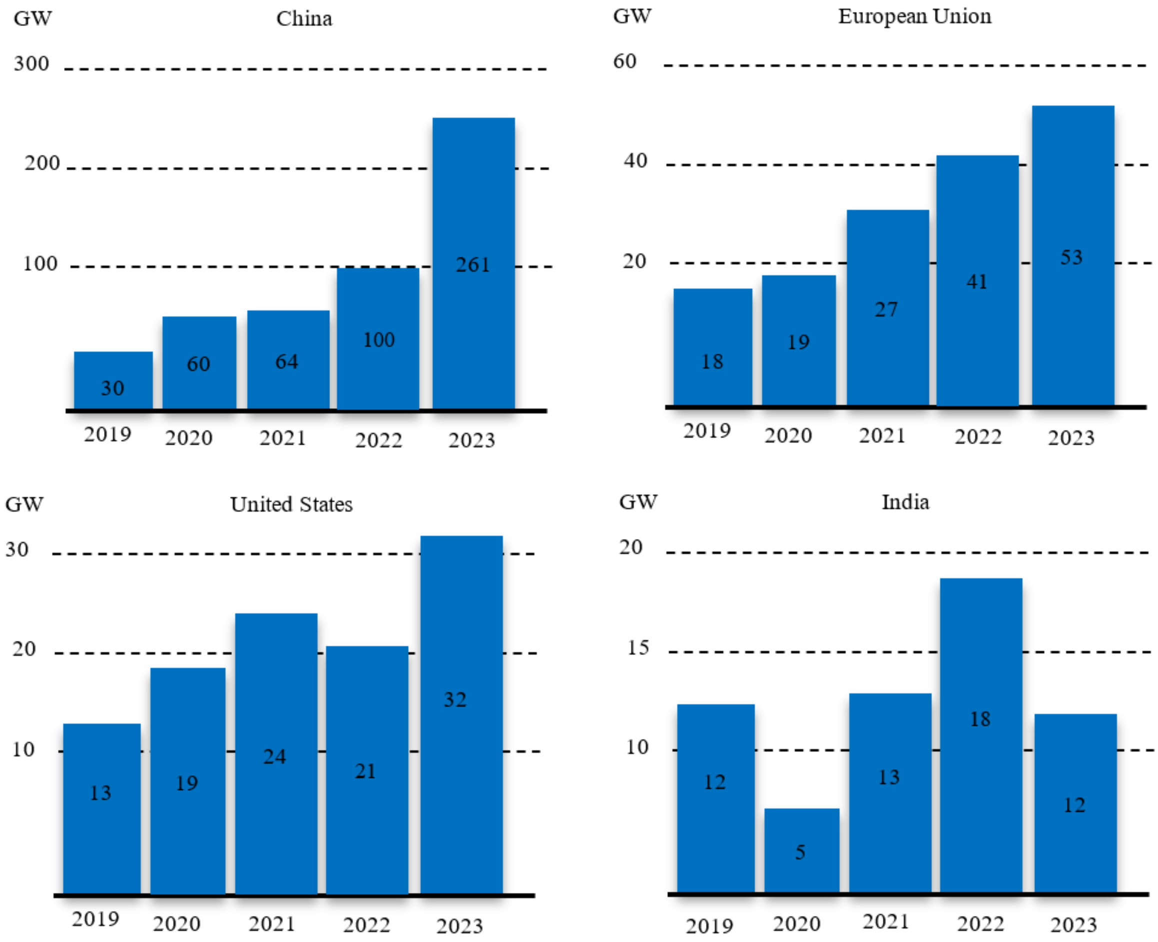

Figure 3. The Solar PV installed capacity in China, the European Union, the United States, and India for the years 2019 to 2023

Within the confines of the European Union (EU), the annual augmentation in PV installations escalated by a quarter, attaining an unprecedented pinnacle of 52 GW during the previous year. Subsequent to Russia's incursion into Ukraine, member states of the EU have undertaken measures to enhance the policy milieu aimed at expediting the deployment of renewable energy sources, with the overarching objective of mitigating reliance on natural gas. In this context, the initiative significantly increased annual solar PV installations since 2021, crucial for meeting the United Nations' 2050 carbon neutrality goal. Thus, global adoption of solar PV systems has grown in term of technological advancements and cost reductions. To clarify more, the European Union, committed to achieving carbon neutrality by 2050, has rapidly expanded its solar PV capacity, surpassing 158 GW of installed systems in 2021, highlighting its dedication to sustainable energy sources. Conversely, India witnessed a decrement in solar PV capacity additions, registering 12 GW in 2023, marking a reduction of one-third compared to the figures of 2022. This decline can be attributed to diminished competitive auction volumes for utility-scale solar projects in preceding years compounded by supply chain impediments. In Brazil, the augmentation in solar PV installations surged by over 20% year-on-year, propelled by the net metering program designed to incentivize rooftop solar PV installations. Remarkably, in 2023, the capacity expansions of solar PV in Brazil surpassed those of India.

3.2 Wind Installed Capacity

In 2023, the worldwide increment in wind capacity surged by nearly 60%, surpassing the record set in 2020. Onshore wind ventures constituted over 85% of the global wind expansion throughout the preceding year. The wind energy sector has experienced two consecutive record-setting years in terms of new capacity installations, with a combined total of 93 GW installed in 2020 and 94 GW installed in 2021. Figure 4 presents the global additions of wind installed capacity from 2019 to 2023. Figure 5 indicates the wind installed capacity in China, the European Union, the United States, and India for the years 2019 to 2023. China, being the largest power producer and consumer, had the largest installed capacity of wind turbines worldwide. Over the last two decades, China experienced a significant surge in its installed capacity of wind turbines, thereby exerting a considerable influence on its wind power industry and fostering global industry development. In this regard, China emerged as the primary driver behind the global wind proliferation, contributing to over 60% of the overall expansion, as the nation nearly doubled its additions in comparison to the figures recorded in 2022 (IEA, 2024b).

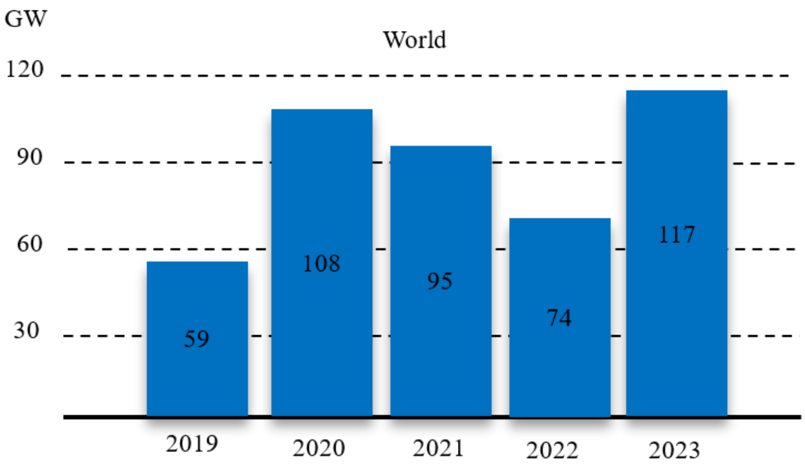

Figure 4. The global additions of wind installed capacity from 2019 to 2023

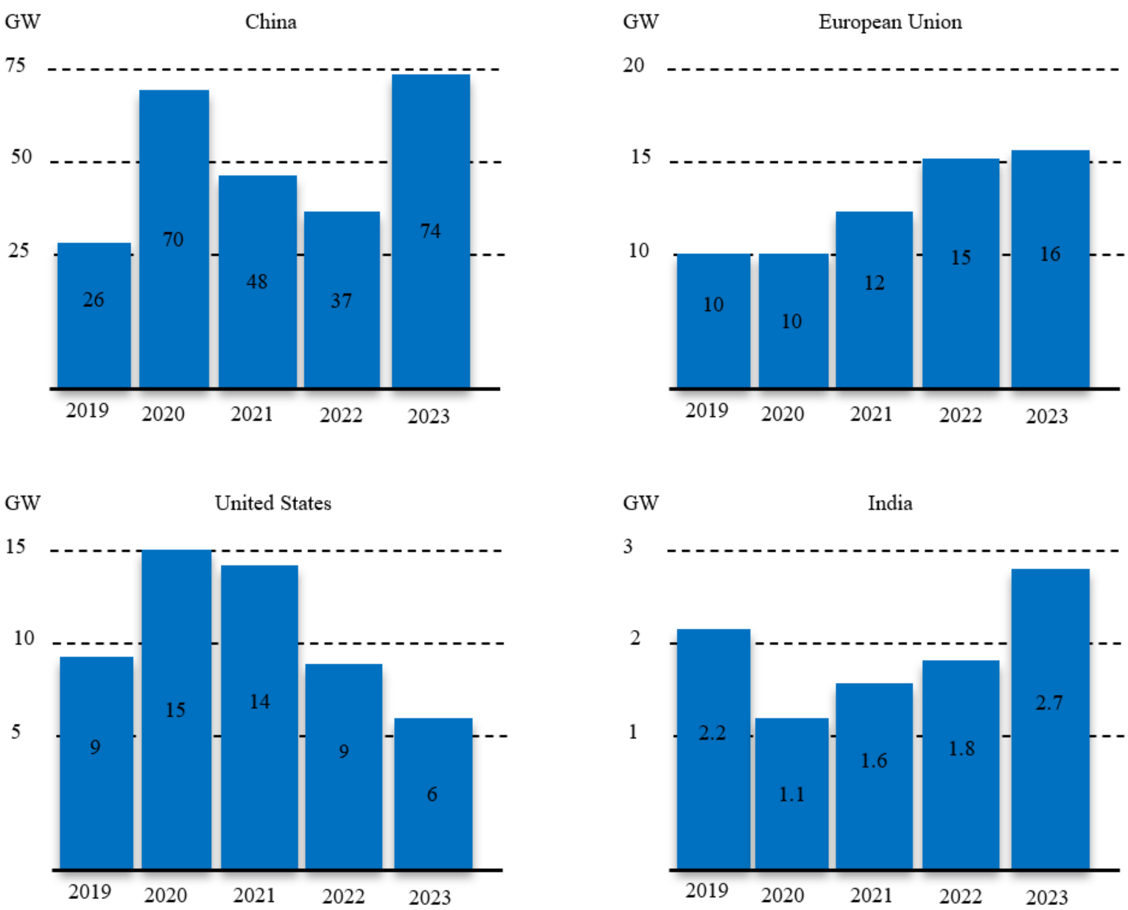

Figure 5. The wind installed capacity in China, the European Union, the United States, and India for the years 2019 to 2023

China witnessed a notable increase in investment in wind energy. By 2016, the installed wind capacity had surged to 149,000 MW, marking a 438-fold increase compared to the capacity in 2000. Moreover, China emerged as the world's foremost investor in wind energy by 2010. Nonetheless, since 2010, this swiftly expanding industry has encountered a mounting challenge in the form of wind curtailment, which refers to the relinquishment of power generation from grid-connected wind power capacity. The power grid operator, primarily the State Grid Corporation of China, opted to intermittently suspend or discontinue the grid connection of installed wind capacity during power dispatches. The magnitude of energy loss stemming from wind curtailment has been substantial and is exacerbating over time. In 2011, China experienced an average wind curtailment rate of 16%, leading to a loss of 12.3 million MWh of electrical power. These figures escalated to 19% in 2016, resulting in a loss of 49.7 million MWh, which is nearly equivalent to 75% of the total solar power generation in China during that year (Zhu et al., 2019).

Within the European Union (EU), wind capacity additions witnessed a modest uptick of slightly under 10% in 2023, chiefly attributed to the deceleration in onshore wind deployment. Developers encountered numerous obstacles, including escalating equipment expenses, inflationary pressures, and constraints within the supply chain, which have dampened their enthusiasm to engage in competitive bidding processes. In the United States, wind capacity additions experienced a decline exceeding 25% in 2023 when contrasted with the figures from 2022. European nations have served as the primary catalyst for the expansion of offshore wind farms. As of 2018, over 80% of the global installed offshore wind power capacity was situated within the European Union (EU) and the United Kingdom (UK).

In this scenario, projections suggest that installed capacity in Europe will escalate from 22 GW in 2019 to 76 GW by 2030, representing an augmentation of approximately 11,800 turbines. Biden Administration had committed to increasing Offshore Wind (OSW) capacity from 42 MW in 2022 to 30 GW by 2030—an adequate capacity to power 10 million homes. Accomplishing this target was anticipated to necessitate over $100 billion in new investments and to generate 80,000 full-time-equivalent jobs from 2023 to 2030. Policies enacted in eight East Coast states—Massachusetts, New York, New Jersey, Rhode Island, Connecticut, Maryland, Virginia, and North Carolina—aimed at developing 40 GW of OSW capacity by 2040. Furthermore, in August 2022, California adopted OSW capacity targets ranging from 3 to 5 GW by 2030 and 25 GW by 2045 (Abulifa et al., 2024; Hansen et al., 2024).

It is significant to point out that, India's expanding installed capacity for electricity generation encounters pressures stemming from escalating domestic consumption, national energy security concerns, and commitments outlined in climate change agreements. There is an urgent need to prioritize renewable energy sources, as their proportion in net electricity generated is projected to potentially reach 22% by 2030. This trajectory falls short of the target stipulated in the Paris Agreement, which aims for 40% of electricity generation to be derived from non-fossil fuel sources by 2030. Wind power potential across the Indian territory at the 100-meter altitude level was estimated utilizing data sourced from the ERA5 reanalysis spanning the period 1979–2018, employing the Weibull mixture distribution methodology. The results reveal that India's mainland and offshore regions harbor a wind power potential of approximately 7.2 TW and 18.4 TW, respectively, encompassing only 3% of the available area. Additionally, an estimated wind power potential of up to 53 TW is ascertainable over sparsely vegetated areas, which extend over 25% of India's mainland.

3.3 Hydrogen Fuel Cell Capacity

For numerous decades, hydrogen fuel cells have remained at the forefront of research endeavors undertaken by the most technologically advanced nations globally. The impetus driving this pursuit stems from the recognition that hydrogen has the potential to address escalating energy demands and mitigate the impacts of global climate change. Furthermore, the storage of hydrogen serves as a pivotal enabling technology critical for fostering sustainable hydrogen energy development, which is imperative for the future prosperity of the economy. In addition to serving as a carbon-neutral fuel source, hydrogen possesses the capability to mitigate deleterious emissions stemming from diesel engines, encompassing pollutants such as carbon monoxide, unburned hydrocarbons, particulate matter, soot, and smoke (Gayen et al., 2024; Kilic et al., 2024).

In the year 2023, the global installed capacity of water electrolyzers dedicated to hydrogen production surpassed the notable threshold of 1 GW, thereby constituting a significant landmark within the energy domain, ultimately reaching an approximate capacity of 1.3 GW. Figure 6 displays the global additions of hydrogen fuel cells from 2019 to 2023. This milestone was underpinned by a remarkable upsurge in annual augmentations, soaring to 600 MW, surpassing the previous pinnacle of 240 MW established in 2021 by two-and-a-half times. The capacity integrated in 2023 nearly equaled the cumulative global installed capacity amassed up to the preceding year of 2022. However, notwithstanding these advancements, the current pace still falls short of the requisite annual multi-gigawatt augmentations essential for the realization of climate objectives. Figure 7 illustrates the hydrogen fuel cell capacity in China, the European Union, the United States, and India for the years 2019 to 2023.

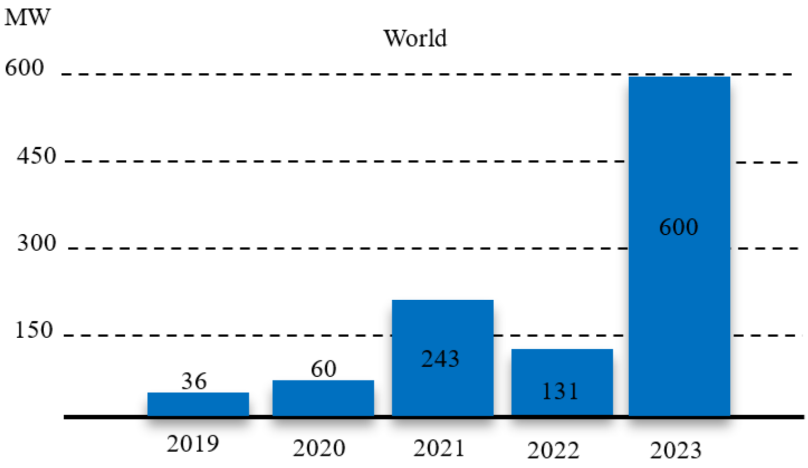

Figure 6. The global additions of hydrogen fuel cells from 2019 to 2023

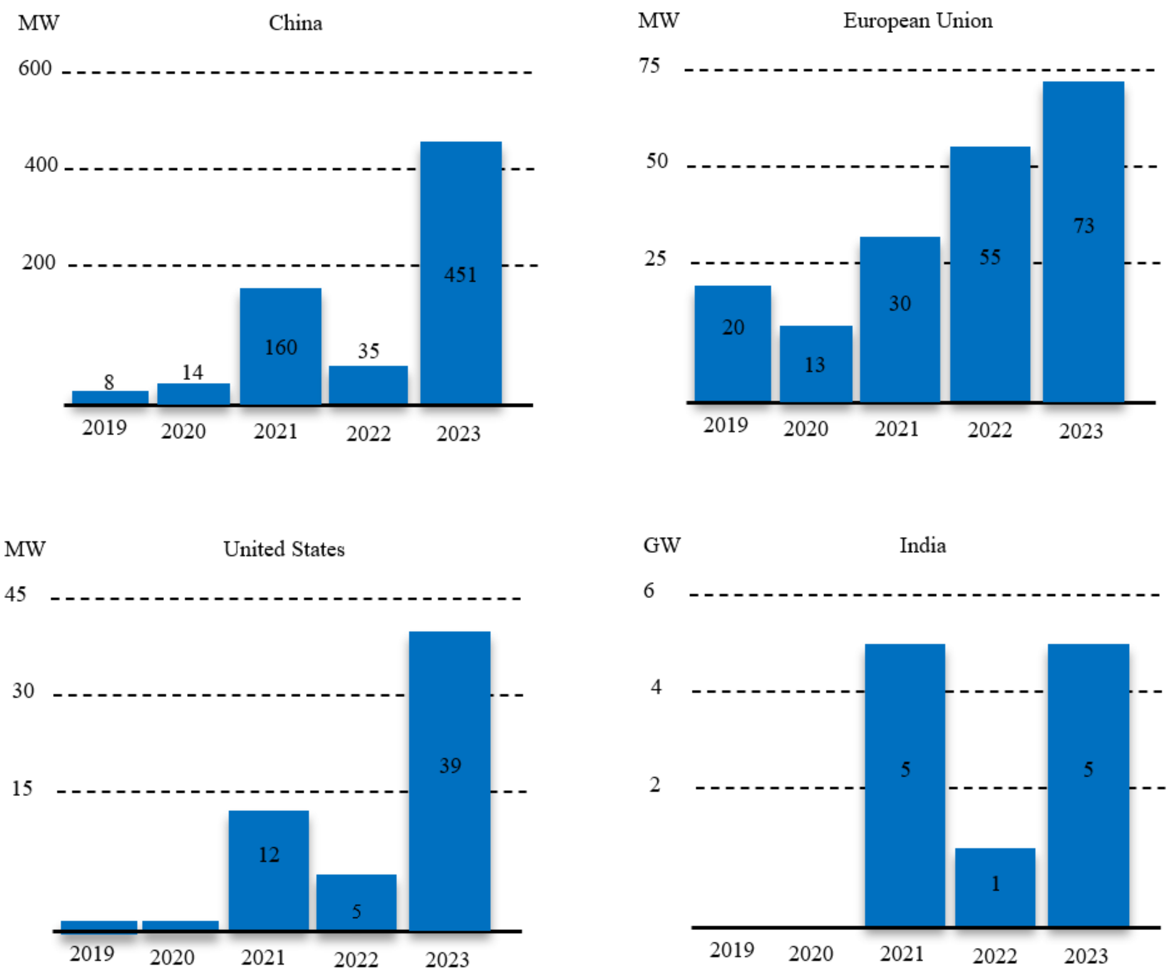

Figure 7. The hydrogen fuel cell capacity in China, the European union, the United States, and India for the years 2019 to 2023

It should be observed that, transitioning from a status of contributing less than 10% to the global installed capacity in 2020, China has ascended to a position of pronounced influence since 2021, culminating in an installed capacity surpassing 650 megawatts (MW) by the culmination of 2023, thereby encompassing close to half of the global installed capacity. In this sense, this paradigm shift has been propelled by the amplification of project magnitudes by Chinese stakeholders, evidenced by numerous ventures exceeding 100 MW in capacity.

Consequently, China presently hosts six of the largest operational electrolysis projects globally, inclusive of the 260 MW facility situated in Kuqa, orchestrated by Sinopec for the dual purpose of hydrogen production and its utilization in refining operations. Even though, it is anticipated that this project will not attain full operational capacity until the year 2025 (Iyke, 2024; Ren et al., 2023).

In 2020, the European Union commanded approximately one-third of the global installed capacity; however, it has since relinquished its preeminent status, as evidenced by marginal augmentations barely exceeding 70 megawatts (MW) in 2023 (Li et al., 2024b; Yan et al., 2024). Concurrently, the United States has ascended to the position of the third-largest market subsequent to the European Union, characterized by additions surpassing 30 MW. In this trend, the lion's share of this augmentation can be attributed to a singular project, namely the Cavendish NextGen Hydrogen Hub situated in Florida. Moreover, the largest operational electrolysis facility outside of China, boasting a capacity of 40 MW, commenced operations in the United States in January 2024.

4. Emissions in Advanced Economies

Following a reduction of approximately 4.5% in 2023, emissions within advanced economies have dwindled to levels lower than those recorded fifty years ago in 1973. While emissions within this cohort of nations had reached comparable nadirs in 2020, 1974-75, and 1982-83, two salient disparities distinguish the contemporary context. Firstly, unlike the transitory declines observed in 1974-75 and 1982-83, emissions within advanced economies (referred to as AEE) have been undergoing a sustained structural decline since 2007. Secondly, the gross domestic product (GDP) of advanced economies expanded by approximately 1.7% in 2023, in stark contrast to the stagnation or outright economic recession characterizing the aforementioned periods. It should be highlighted that, the downturn experienced in 2023 epitomizes the most substantial percentage reduction in AEE outside of recessional phases. Demonstrated in Table 2 are the CO_2 emissions stemming from combustion within advanced economies, spanning the years 2015-2023.

Table 2. The CO_2 emissions stemming from combustion within advanced economies, spanning the years 2015-2023

Year	CO_2 Emissions	From
2023	10.4 Gt CO_2	AEE
2022	11.0 Gt CO_2	AEE
2021	11.0 Gt CO_2	AEE
2020	10.4 Gt CO_2	AEE
2019	11.4 Gt CO_2	AEE
2018	11.8 Gt CO_2	AEE
2017	11.8 Gt CO_2	AEE
2016	11.8 Gt CO_2	AEE
2015	11.9 Gt CO_2	AEE

In the year 2023, the cumulative carbon dioxide (CO_2) emissions stemming from energy combustion activities within the confines of the European Union (EU) demonstrated a marked reduction, nearly reaching 9% or approximately 220 million metric tons (Mt). While this decline mirrors the scale observed during the Covid-19 pandemic in 2020, the contextual framework in 2023 diverges significantly, characterized by the EU's experience of modest economic expansion, approximating 0.7%. Particularly noteworthy is the substantial contribution of burgeoning CE endeavors, which accounted for half of the observed emissions abatement in 2023, representing the principal driver of this trajectory. Concerning this topic, foremost among these initiatives was the proliferation of renewable energy sources within the electricity sector, signifying a watershed moment wherein wind power, for the first time, eclipsed both natural gas and coal in electricity generation, emblematic of a seminal juncture in the region's energy transition. Concurrently, the generation of electricity from coal witnessed a precipitous decline of 27% in 2023, while natural gas-based electricity production receded by 15%. Furthermore, the resurgence of hydroelectric power subsequent to the droughts of 2022, coupled with a partial resurgence in nuclear power, also contributed significantly to the mitigation of reliance on fossil fuels within the power sector.

It is essential to emphasize that, the aggregate carbon dioxide (CO_2) emissions resultant from energy combustion within the United States underwent a notable decline of 4.1%, equivalent to a reduction of approximately 190 million metric tons (Mt), notwithstanding an economic growth rate of 2.5%. Predominantly, two-thirds of this reduction in emissions emanated from the electricity sector. Concurrently, the United States encountered a significant deficit in hydropower generation in 2023, which declined by approximately 6% or 15 terawatt-hours (TWh). Additionally, there was also a shortfall observed in wind power generation within the same period. In the year 2022, propitious wind conditions prevailed in crucial regions conducive to wind power generation throughout the United States. Even though, in 2023, owing in part to the influence of El Niño, average daily wind velocities in these regions precipitously declined to the lowest levels observed in the decade. Had wind conditions mirrored those of 2022, an estimated reduction of 16 million metric tons (Mt) of carbon dioxide emissions would have been realized in the United States in 2023.

Despite the deficiencies in hydro and wind resources that affected the United States, the integration of renewables within the electricity sector resulted in a reduction of emissions by approximately 20 million Mt. If adverse wind and hydrological conditions had not transpired, the adoption of renewable energy sources would have contributed to an emissions reduction of approximately 40 Mt. In this connection, the predominant impetus behind emissions abatement in the US electricity sector was the transition from coal to natural gas. Within this framework, this transition was propelled by favorable natural gas prices relative to coal since 2022, coupled with the continued decommissioning of coal-fired power plants. Consequently, while electricity generation from coal declined by nearly 20% in 2023, electricity generation from natural gas experienced a growth of 6%.

In 2023, China's carbon dioxide (CO_2) emissions surged by 565 million metric tons (Mt), culminating in a total of 12.6 Gt. This accounts for a growth rate of 4.7%, with emissions stemming from energy combustion increasing by 5.2%, while those emanating from industrial processes remained relatively stable. In this respect, this escalation persisted despite China's dominant position within the global CE sector. In the same year, China contributed approximately 60% of the worldwide additions in solar photovoltaic (PV), wind power, and electric vehicles (EVs). The combined share of solar PV and wind power in total electricity generation surged from 4% in 2015 to 15% in 2023, approaching the level observed in advanced economies (17%). Additionally, China's proportion of EVs in total vehicle sales surpassed that of advanced economies by more than twofold in 2023.

In 2023, India experienced a significant surge in economic activity, with the economy expanding by 6.7%. Concurrently, the country's emissions exhibited a more rapid escalation compared to its Gross Domestic Product (GDP), increasing by slightly over 7%, representing a rise of approximately 190 million metric tons (Mt) to reach a total of 2.8 Gt. Nonetheless, India's per capita emissions persist at notably low levels, hovering around 2 metric tonnes, which is less than half of the global average of 4.6 metric tonnes. Concerning this topic, the substantial uptick in India's overall emissions was propelled by the sustained swift rebound in economic performance from the nadirs experienced during the Covid-19 pandemic.

5. Factors in Emissions Calculations

Several factors necessitate consideration for computing emissions displacement stemming from distributed energy projects, encompassing accounting protocol, marginal emissions, and capacity factor. Each of these components is delineated comprehensively below.

5.1 Emissions Accounting Protocol

Enterprises aiming to assess potential reductions in emissions and the displacement of marginal emitters may utilize the prescribed guidelines advocated by the World Resources Institute (WRI) Greenhouse Gas Protocol. This protocol stands as the most extensively employed methodology for accounting greenhouse gas (GHG) emissions, serving as the cornerstone for practically all GHG standards and programs. The GHG Protocol encompasses project-level emissions accounting and offers sector-specific directives tailored for on-site electric generation initiatives.

5.2 Marginal Emissions

Marginal emissions depict the emissions generated when additional distributed generation resources are incorporated into the system. While average grid emissions provide a calculation, they do not accurately portray how a marginal generation unit is displaced by the distributed asset. The United States Environmental Protection Agency (EPA) disseminates the Emissions & Generation Resource Integrated Database (eGRID), which encompasses marginal (non-baseload) emission rates. These rates are advocated for estimating emission reductions resulting from renewable energy or energy efficiency projects aimed at curbing the consumption of grid-supplied electricity.

5.3 Capacity Factor

The system capacity factor delineates the proportion of actual electrical energy output over a specific timeframe relative to the maximum attainable electrical energy output within the corresponding period. The utmost feasible output aligns with the full nameplate capacity under the assumption of continuous system operation. Within this scope, Intermittent technologies typically exhibit a diminished capacity factor in comparison to their always-on counterparts. This metric serves as a pivotal distinguishing factor between consistently available and intermittent energy sources. Emissions displacement analysis can be conducted by considering various inputs, including:

- The recommended marginal emission rate for comparative purposes.

- The magnitude of the project.
- The emissions associated with distributed technology.
- The capacity factor.

The fundamental equations pertinent to the computation are delineated as follows:

CO_2 Reduction per Megawatt-hour (MWh) = Emissions from Non-baseload Sources in the eGRID Subregion - Carbon Dioxide (CO_2) Emissions from the Project.

Annual CO_2 Reduction = Size of the Project (in Megawatts, MW) × Capacity Factor × Total Annual Hours × CO_2 Reduction per MWh.

6. The Changing Landscape of Global Emissions

The dynamic milieu of emissions is undergoing continual evolution. China's cumulative carbon dioxide (CO_2) emissions surpassed the collective emissions of advanced economies in 2020, further amplifying to a margin of 15% higher in 2023. Concurrently, India outstripped the European Union to ascend as the third-largest contributor to global emissions in 2023. With respect to this, nations within developing Asia collectively account for approximately half of the global emissions share, marking a substantial surge from approximately two-fifths in 2015 and around one quarter in 2000. It is relevant to highlight that, China stands as the foremost emitter, singularly contributing to 35% of the global CO_2 emissions output. Table 3 displays the total CO_2 emissions of China from 2015 to 2023. Table 4 displays the total CO_2 emissions of United States from 2015 to 2023. Table 5 illustrates the total CO_2 emissions of European Union from 2015 to 2023. Table 6 shows the total CO_2 emissions of India from 2015 to 2023. Table 7 displays the total CO_2 emissions of Japan from 2015 to 2023.

Table 3. The total CO_2 emissions of China from 2015 to 2023

Year	Regin	CO_2 Emissions
2023	China	12.6 Gt CO_2
2022	China	12.1 Gt CO_2
2021	China	12.1 Gt CO_2
2020	China	11.5 Gt CO_2
2019	China	11.3 Gt CO_2
2018	China	11.1 Gt CO_2
2017	China	10.6 Gt CO_2
2016	China	10.4 Gt CO_2
2015	China	10.3 Gt CO_2
	Total:	102.0 Gt CO_2

Table 4. The total CO_2 emissions of United States from 2015 to 2023

Year	Regin	CO_2 Emissions
2023	United States	4.5 Gt CO_2
2022	United States	4.7 Gt CO_2
2021	United States	4.7 Gt CO_2
2020	United States	4.4 Gt CO_2
2019	United States	4.9 Gt CO_2
2018	United States	5.0 Gt CO_2
2017	United States	4.9 Gt CO_2
2016	United States	4.9 Gt CO_2
2015	United States	5.0 Gt CO_2
	Total:	43.0 Gt CO_2

Table 5. The total CO_2 emissions of European Union from 2015 to 2023

Year	Regin	CO_2 Emissions
2023	European Union	2.5 Gt CO_2
2022	European Union	2.7 Gt CO_2
2021	European Union	2.7 Gt CO_2
2020	European Union	2.6 Gt CO_2
2019	European Union	2.8 Gt CO_2
2018	European Union	3.0 Gt CO_2
2017	European Union	3.0 Gt CO_2
2016	European Union	3.0 Gt CO_2
2015	European Union	3.0 Gt CO_2
	Total:	25.4 Gt CO_2

Table 6. The total CO_2 emissions of India from 2015 to 2023

Year	Regin	CO_2 Emissions
2023	India	2.8 Gt CO_2
2022	India	2.7 Gt CO_2
2021	India	2.4 Gt CO_2
2020	India	2.2 Gt CO_2
2019	India	2.4 Gt CO_2
2018	India	2.5 Gt CO_2
2017	India	2.3 Gt CO_2
2016	India	2.2 Gt CO_2
2015	India	2.2 Gt CO_2
	Total:	21.7 Gt CO_2

Table 7. The total CO_2 emissions of Japan from 2015 to 2023

Year	Regin	CO_2 Emissions
2023	Japan	1.0 Gt CO_2
2022	Japan	1.1 Gt CO_2
2021	Japan	1.1 Gt CO_2
2020	Japan	1.0 Gt CO_2
2019	Japan	1.1 Gt CO_2
2018	Japan	1.1 Gt CO_2
2017	Japan	1.2 Gt CO_2
2016	Japan	1.2 Gt CO_2
2015	Japan	1.2 Gt CO_2
	Total:	10.0 Gt CO_2

In 2023, advanced economies persisted with relatively elevated per capita emissions, approximately 70% greater than the global mean. Conversely, India's per capita emissions remain substantially below the global average, standing at approximately 2 metric tonnes. Within the European Union, per capita emissions have undergone a robust decline, currently hovering only around 15% higher than the global average and approximately 40% lower than those of China. China's per capita emissions surpassed those of the aggregate advanced economies in 2020, further escalating to a margin of 15% higher by 2023. It is appropriate to highlight that, 2023 marked the initial instance wherein China's per capita emissions exceeded those of Japan, albeit remaining one-third lower than those of the United States.

7. Conclusion

Renewable energy including PV, wind and Hydrogen Fuel cell technologies remain key to the on-going achievement of sustainable development and the emerging imperative for dealing with the increasing effects of climate change. For the year 2023, a record addition in the global solar PV capacity was observed, which crossed the 420 GW mark, that is fairly 80% extra than the solar capacity of the prior year. Further, a global wind capacity addition saw nearly 60% growth compared to 2020 and thus, a new record was achieved. It is rather evident that onshore wind projects were chiefly responsible for about 85/ of the world's increment in wind energy the same year. Therefore, the global capacity of water electrolyzers, intended for hydrogen production, resulted in the achievement of the 1 GW mark in 2023, with approximately 1.3 GW. It is therefore can be said that this achievement goes a long way in enhancing the development of the energy sector. Thus, the subject of this article has raised concern within the importance of renewable energy sources in the fight against greenhouse gas emissions and the achievement of international sustainable development goals. Meanwhile, the scenarios by country indicate that between the years 2015 and 2023 China emitted a total of 102 Gt.

Thus, the changes in policy and regulations play a very significant role in the creation of transition that has taken place in the energy sector especially in the use of renewable energy sources where policy support and international collaboration should be sustained and enhanced. Based on the findings of this analysis, it is crucial for policymakers, stakeholders, and researchers to appreciate the kind of information presented herein and increase attempts to harness CE technologies for a better future for the next generations. A methodological limitation that is always apparent in this type of study is the unoriginal use of self-generated data collected from selected government reports, while these may not be fully accurate and compatible. Also, much more emphasis is given to the numerical information from the previous periods and it might be completely blinded for non-numerical factors, such as policy efficacy and, for example, the evolution of technologies that may have an impact on the emissions.

The assessment focuses only on the most influential countries while the less influential but still capable of causing shifts in the global emission are excluded. The analysis of the strategies that could be more effective in decreasing the emission levels depending on the regions would give a more precise idea of the effectiveness of certain measures in controlling CO_2 emissions. Besides, extending the investigation to the small countries as well as dividing research by regions can provide a more comprehensive picture of the emissions' tendencies. There is potential for the study to extend the understanding of the socio-economic effects of employing measures that affect overall emission reduction to foster sustainable and just transitions towards the development of green economies. For this reason, this article summarizes the desperate call for concerted global cooperation in curing carbon emissions.

Data Availability

Not applicable.

Conflicts of Interest

The authors declare no conflict of interest.

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