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Decarbonization Strategies in the United States of America and the European Union (EU): A Comparative Analysis

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Abstract

Recent developments in climate change and growing global carbon dioxide (CO_2) emissions requires all countries to significantly intensify their efforts to reduce emissions in the energy sector. Considering this assertion, this study conducts a comparative analysis of some decarbonization strategies adopted by the United States and the European Union to reduce carbon greenhouse gas emissions. Thus, this study derived data from various online data sources to analyze carbon emissions and decarbonization strategies in the U.S. and the European Union. Using curve-fitting models in Microsoft Excel, the study also modeled the average carbon emissions per state and country from 2005 to 2030 for U.S. states and EU countries. Results from the models show a decline in average carbon emissions in the U.S. (from 116 units in 2005 to 83 units by 2030), while emissions in EU countries are projected to increase (from 104.5 to 129.9 metric tons). The focus on these two regions is due to their significant contributions to global greenhouse gas emissions and their advanced decarbonization strategies. That is, the United States has historically relied on coal, petroleum, natural gas, nuclear energy, and renewables for electricity generation with natural gas and renewables becoming the dominant energy sources in recent years. Additionally, the U.S. has also adopted key technologies such as Energy efficiency, industrial electrification, low-carbon fuels, feedstocks, and energy sources (LCFFES), and carbon capture, utilization, and storage (CCUS) to reduce carbon emissions. Comparatively, the EU has seen better performance from nuclear and geothermal energy, while biomass, oil, and large-scale hydropower lag. Also, the EU's primary decarbonization strategies focus on electrification and carbon-neutral power, energy efficiency, demand-side measures, and circular economy principles. Hence, the study concludes that decarbonizing the energy system is essential for addressing climate change and mitigating the effects of increasing emissions worldwide.

Keywords

United States, European Union, Decarbonization, RAF Sensitivity, Climate Change, Carbon Emissions

1. Introduction

According to IPCC (2018), the earth's climate has changed. Mean global temperatures have increased 1˚C above pre-industrial peaks and are expected to reach 1.5˚C within twenty years at present levels of warming. Jackson et al. (2018) explain that recent studies have emphasized the difficulty of maintaining global mean temperatures below 2˚C, and even less than 1.5˚C (IPCC, 2018). Nearly 90% of all CO_2 emissions generated by human activities are caused by the use of fossil fuels and the production of cement. Climate change is frequently described as one of the most complicated issues confronting humanity, affecting the whole planet and all facets of contemporary society (Dupont & Oberthür, 2015). According to the Anthropocene discourse, humanity has had a powerful impact on the Earth system since the beginning of industrialization, and in the process, so many planetary limits have been crossed (Crutzen, 2006). Studies show that people are concerned about climate change because of the increased frequency and severity of occurrences such as sea-level rise, floods, fires, storms, droughts, and sea-level rise. Furthermore, climate change is projected to exacerbate a wide range of diseases. Climate change is caused by humans, and the primary cause is the increased use of fossil fuels to meet the world's growing energy demand (Papadis & Tsatsaronis, 2020).

Dupont & Oberthür (2015) highlight that human-caused climate change is caused by the increased emission of powerful and effective long-lived greenhouse gases (GHGs) from before the industrial times. Simultaneously, many authors criticized the concept by renaming it the Capitalocene. This term emphasizes that the conflict of society-nature relations is caused by a particular form of social development under capitalist production relations. The obligations and dangers of events such as climate change are very unevenly distributed in connection to the complexities of disparities within capitalism (Moore, 2016). Recent advancements in climate change and rising carbon dioxide (CO_2) emissions worldwide demonstrate that, while the share of renewable energy in the primary energy supply is increasing, all countries must massively improve their efforts in the coming years to cut emissions in the energy sector (Papadis & Tsatsaronis, 2020). Papadis &

Tsatsaronis (2020) further explain that to mitigate the effects of climate change, emissions of carbon dioxide from the energy sector must be lowered. Substantial reductions may be obtained by applying suitable technologies and policies. Furthermore, in the absence of possible solutions, society must strive for a rapid increase in CO_2 removal technically from 0 to 0.5 per year by 2030, and 2.5 5 by 2040 and 2050, respectively (Rockström et al., 2017).

De Blas et al. (2020) argue that despite more fuel-efficient vehicles and the implementation of better policies, emissions of greenhouse gases from transportation continue to rise in most countries. According to the IPCC (2018), if current trends continue, GHG emissions from transportation could increase more drastically than emissions from other tertiary sectors that use energy. With transportation accounting for roughly 25% of greenhouse gas emissions, decarbonization of this sector will be essential for achieving the Paris Agreement goals (Lefèvre et al., 2021). Decarbonizing transportation will be required to keep global warming below 2 degrees Celsius. With its continued dependence on fossil fuels, transportation is thought to be more challenging to decarbonize than in other areas (Pietzcker et al., 2014).

Global energy consumption is moving away from fossil fuels and toward renewable sources. There are multiple instances of public and private organizations working diligently to decarbonize the economy. As the energy transformation gains traction, new ecosystems and technologies emerge. As part of a progressively sustainable society, these developments are assisting in the growth of renewables, the emergence of new power sources, the improvement of energy efficiency, the reduction of emissions, and the creation of new markets for carbon and other residues. Simultaneously, many of the frequently sought decarbonization pathways, such as increased electricity generation, widespread use of clean energy, and strengthening measures for energy efficiency present specific challenges (Porters, 2020).

Many energy industry players have openly stated their willingness to become carbon neutral by 2050. While their long-term goals are explicit, these industries face a more troubling threat in the near future. Many businesses are having difficulty understanding the material implications of their set objectives for their pricing, operational processes, workers, and markets in the coming years (Porters, 2020). Cho (2022) points out that one of the challenges of decarbonization is that, while it will be beneficial in the long run, it will necessitate large investments in the near term. Between 2021 and 2050, it will most probably take $275 trillion to reduce carbon emissions in the sectors, with power generation, transportation, and buildings accounting for 75 percent of asset spending. The most significant challenge to cutting emissions is the amount of money spent on power systems and fossil fuel facilities. The average individual has also made significant investments in fossil fuels through heaters and gasoline-powered vehicles. Hence, the issue will be met only when renewable energy becomes less costly and efficient that it drives fossil fuels out of the market (ibid). The oil and gas industry's involvement in tackling long-term emissions is exacerbated by the International Energy Agency's (IEA) projection that global energy consumption will be 30% higher in 2040 than it is presently. The sector must strike a balance between having to meet energy demand and evolving to lower-carbon, more renewable sources of energy (Meyer, 2018).

The aim of the study is to make a comparative analysis of some decarbonization strategies adopted by the United States and the European Union (EU) in their quest to reduce carbon emissions in the atmosphere. By utilizing online data sources, the study obtained carbon emissions data for the U.S. from scholarly articles, the World Bank, the U.S. Energy Information Administration. Also, data for EU was gathered from the Climate Policy Info Hub, other scholarly articles as well as decarbonization strategies from the Office of Energy Efficiency & Renewable Energy. Additionally, the study employed GIS and ArcGIS software to create maps and charts visualizing per capita carbon dioxide emissions in the U.S. and EU (2000-2021), including sector-based emissions, greenhouse gas reductions, and resource availability sensitivity. The study focused on the United States because it has the fastest-growing economy and the highest GHG emissions. Additionally, it has a number of fully developed decarbonization strategies (Hsu et al., 2022). Also, the study concentrates on the European Union because according to the history of international climate change negotiations, the EU may take the lead in decarbonization development. Internationally, the EU is still one of the largest emitters, EU member states bear a high level of historical duty, and the EU prides itself on international climate leadership (Geden et al., 2019). There has been a rise in the published literature on rising carbon emissions in the US and EU and some initiatives undertaken to combat climate change. However, very few scholarly documents have made a comparative analysis between the two, which will be a gap in this research. Therefore, this paper seeks to provide a bridge to the current knowledge gap that exists in the subject area.

2. Decarbonizing Society

One of the climate change solutions is the shift toward sustainable and low-carbon cities. It appears to fit into the smart city idea through a number of practical activities. This concept is given a lot of weight, drawing attention to smart cities becoming the hub of creative solutions and economic growth, and thus necessitate careful analysis and recognition (Strielkowski et al., 2020). According to the International Renewable Energy Agency (2020), the decarbonization of the energy sector has been a focus of recent research for so many years. The use of renewable energy is universally recognized to be the most evident approach to achieving decarbonization. As a result, many countries are already generating electricity with a growing share of renewable energy sources. For instance, in 2019, China and the United States had the most deployed wind energy and solar photovoltaics capabilities globally.

Kanoh (1992) defines decarbonization as the lowering of CO_2 emissions from fuel production and consumption. Sun (2005) explains that decarbonization is an unavoidable phenomenon as a result of advances in technology and social progress. Technological advancement creates resources and factories that decrease the amount of CO_2 released into the atmosphere. Social development also reduces the emissions generated by human activity. Countries and regional groups around the world have described decarbonization as an energy and ecological policy goal and have seen substantial progress. The necessity to cut carbon emissions (GHGs) and prevent terrible climate change cases, along with predicting the exhaustion of fossil fuels, drives decarbonization efforts. Transportation is typically cited as one of the most daunting sectors to decarbonize from this perspective. This is due to prevailing cultural travel demand, the assertion that transportation is the least variable renewable end-use sector, the ongoing expansion of global transport demand, and technical constraints in substituting oil-based fuels (IPCC, 2018).

Ahman & Nilson (2015) explain that the manufacturing industry faces both challenges and opportunities as society decarbonizes. Decarbonization offers a chance for the industry that produces finished products to develop higher added-value clean technological products and establish new eco-friendly markets. The opportunities are less apparent, and the struggles are significantly larger for the energy-intensive industry (EII), which manufactures primarily raw materials. In regard to financial issues, the demand for significant low-carbon assets in the energy sector is considered to be the main barrier, both in advanced and developing economies. Deep-rooted and long-term investments and initiatives to ensure decarbonization while facilitating economic development are considered necessary (Fay et al., 2015).

Papadis & Tsatsaronis (2020) claim that amidst a slew of increased publications acknowledging the need for decarbonization and the problems associated with it, both national and international politics are falling far short of the mark. Many scholars and scientists advocate for tighter restrictions on carbon emissions, such as a carbon tax, in order to promote quick action in the short to medium term. There is an urgent need for immediate action because the development and execution of internationally accepted strategies take time. They argue that a multilateral carbon tax is the most promising technique for hastening the decarbonization process. Nonetheless, due to high capital needs, competition among energy firms for decarbonization choices available, irregular environmental laws, and general awareness of shifts in use, this process will be extremely difficult for humanity (Papadis & Tsatsaronis, 2020).

3. Decarbonization in the EU

The transportation sector is a major contributor to the European Union's climate change (EU). While the EU's overall carbon emissions are decreasing, transport-related emission levels seem to be higher than they were in 1990. Car traffic accounts for approximately 12% of total emissions of greenhouse gases in the EU. By publicizing the European Green Deal (EGD) communication, EU Commission President Ursula von der Leye emphasized the EU's initiatives to boost decarbonization before 2020 (Haas & Sander, 2020). Emissions of greenhouse gases (GHG) have been steadily decreasing since 1990, while other energy sectors have attained consistent declines over the same time period. Considering the small number of choices available, air transport is perhaps the most critical area to decarbonize in this setting. The major opportunity for air transport is thus to transition to renewable fuels (Chiaramonti, 2019). Similarly, Siskos et al. (2022) suggest that to achieve net-zero emissions by mid-century, the EU's transportation sector must be decarbonized.

Lenschow & Sprung (2010) highlight that the EU is frequently referred to as a leader in environmental and climate policy because the union has made significant advancements in decarbonizing its economy, minimizing the total emissions by over 20% from 1990 levels to 2018 (Pavlenko, 2021). According to Dupont & Oberthür (2015), the EU's climate change policy changed as a result of global developments. In the1980s, EU institutions started actively considering climate change as a potential field for internal policymaking, owing mainly to multilateral agreements that resulted in a memorandum of understanding on the United Nations Framework Convention on Climate Change (UNFCCC) in 1992.

Perissi & Jones (2022) also accentuate that the National Energy and Climate Plans (NECPs) and Long-Term Strategy (LTS) plans of European Union (EU27) Member States assess national commitments to the European Union's (EU) energy-climate goals. They are currently the primary "tools" for promoting decarbonization in the EU. The European Commission is in charge of mandating and reviewing these plans (EC). NECPs and LTS are policy instruments and investment programs providing policy instruments and strategic initiatives that provide a forward-thinking structure for both investors and businesses. The European Union's Emissions Trading System (EU ETS) is the most audacious attempt to cut carbon emissions presently. The EU ETS has been the EU's direct reflection for meeting its Kyoto Protocol climate targets. It is a framework in which government agencies established a maximum permissible amount of emissions over a defined period of time and request tradable emission authorizations. In carbon markets, these licences, which are generally good for one tonne of CO2, are the medium of exchange (Bayer & Aklin, 2020).

Under the impetus of the European Union's (EU) climate-neutral aspiration, Bigerna & Polinori (2022) explain that the decarbonization goal by 2050 has emerged as a crucial focus globally. The EU set a good example during the United Nations—UNFCCC-, 202 by directing other countries involved in setting their own specific goals for net-zero carbon emissions. It is presently challenging to determine the financial impact of the decarbonization goal, and thus whether meeting the 2050 objective would harm or profit economic growth. Similarly, Ahman & Nilsson (2015) write that Europe's industry is gradually recognizing the importance of a low-carbon transformation. Sector frameworks have started to look into the barriers. However, there is still substantial doubt about how targets can be met and a transition managed. Due to its emissions, the industry contributes significantly to the climate issue. It is also an essential element of the remedy because it will generate the low-carbon technologies required to decarbonize all areas of the economy.

Decarbonizing the EU necessitates the elimination of carbon output in several sectors of society as well as significant reductions in emissions in other areas. Setting things up, in particular, necessitates a phase-out of emissions of carbon dioxide caused by the consumption of fossil fuels (DuPont & Oberthür, 2015). In regard to environmental policy, the decarbonization goal is consistent with the EU's dedication to global climate action under the Paris Agreement, which has been in place since 2015 and serves as the foundation of the European Green Deal (Bigerna & Polinori, 2022). According to Haas & Sander (2020), several European countries began setting up environmental departments, regulatory bodies, and laws in the 1970s, against the backdrop of worsening destruction of the environment and social movements demanding a secure environment. The power sector, especially, began a transition away from fossil and nuclear technological innovations, as demonstrated by the EU's renewable energy percentage increasing from 9.6% in 2004 to 18.9% in 2018. The EU garnered great self-confidence in emerging as an environmental leader as a result of adventurous initiatives in environmental policy in some member countries.

All through 2015, Oberthür (2016) explains that EU member states and the Commission are involved actively in global climate politics, with statements from Brazil and Germany, along with France and China, highlighting notable achievements. The EU also helped ensure the transition toward national carbon reduction plans and consulted the US to try to discover a mutual ground. Nevertheless, from a perspective standpoint, all EU Member States have difficulty with execution. As all countries have well-structured but poorly functioning retail markets, this encompasses the legacy obstacle of making competition beneficial (Boscán, 2020).

4. Decarbonization in the United States of America

According to Hsu et al. (2022), the Paris Agreement of 2016 was a ground-breaking international agreement aimed at limiting global warming to "ideally 1.5 degrees Celsius". To meet this goal and avoid the most severe consequences of climate change, the US must transition to zero-carbon energy sources by 2030 and achieve zero greenhouse gas (GHG) emissions by 2050. Many states, industries, and organizations have pledged to reduce greenhouse gas emissions to zero by 2050, a target referred to as decarbonization. In order to achieve this goal in the United States, a transition in energy use in some sectors is required. Examples include housing, transportation, manufacturing, and the energy sectors. Given that all of these sectors connect with the built environment and urban planning, planning academics and practitioners have numerous chances to engage decision-makers working on decarbonization initiatives at the national level (ibid).

Zhu et al. (2022) point out that the United States (U.S.) produces approximately 15% of GHG emissions globally from burning fossil fuels and other industrial activities (Boden et al., 2017). As a result, developing viable decarbonization mechanisms for the United States is critical for the global climate. The International

Energy Agency (2021) also highlights that when it comes to renewable capacity and power generation, the United States is among the world's greatest countries. Renewable power generation in the United States increased between 2008 and 2018, with wind and solar power contributing the majority of the rise (Energy Information Administration, 2019).

As a consequence of rapid economic expansion, Shen et al. (2021) explain that the percentage of non-hydro renewable generation in US energy production increased from 3% in 2008 to 10% in 2018. Renewable generation is anticipated to increase further in order to attain state-level renewable energy targets as well as climate objectives. Bistline et al. (2022) also explain that wind and solar energy generation technologies have seen rapid cost reductions in the past few years. Solar and wind power are now among the cheapest options for generating power in many areas, thanks to advances in technology and industry growth and development. However, uncertainties about prospective changes in technology and emissions regulations raise concerns about the speed and intensity, and applicability of renewable adoption in the future. According to Shen et al. (2021), state-level renewable energy targets are responsible for roughly half of the increase in renewable energy use in the United States. Before the end of 2019, thirteen states, along with Washington, DC, and Puerto Rico, had passed laws committing to 100% renewable energy goals.

Berrill et al. (2021) also write that the United States has one of the world's highest per capita residential energy consumption rates. Recent declines in residential emissions related to energy in the United States have mainly resulted from decarbonizing electricity production, with relatively small cuts resulting from improved energy efficiency and the use of electricity for heating. This problem can be alleviated by reducing residential energy demand through efficiency and adequacy. Renovation of existing buildings and replacement of existing stock with new houses are two techniques for improving building stock energy consumption. Evaluating these techniques necessitates taking into account emissions 'encapsulated' in construction, which accounts for approximately 9% of residential emissions in the U.S. (Berrill et al., 2022). Today, the United States serves as a vital global testing point for critical questions about how provincial and district responsibilities can make a significant contribution to greater benefits for national climate schemes. Latest nationwide setbacks in US climate policy have drawn media attention, including the start of resignation from the Paris Agreement and so many deregulatory activities powered by the Executive division. Nonetheless, the federal political system of the United States delegated numerous powers to sectoral and non-governmental stakeholders, providing an opportunity for multi-level policymaking (Hultman et al., 2020).

5. Materials and Methods

5.1. Materials

Most of the data used for this study were derived from online data sources. Data on carbon emissions in the United States were obtained from Anderson et al. (2021) and World Bank (2017). Tiseo (2024a), Tiseo (2024b), and The Climate Policy Info Hub provided data on carbon emissions in the European Union whereas the U.S. Energy Information Administration (2022, 2023) provided data on energy-related carbon emissions in the U.S. in 2000, 2010 and 2020. Data on the decarbonization strategies in the U.S. were acquired from Ristic et al. (2019) and D'Aprile et al. (2020). Finally, Lawson (2018) and the Office of Energy Efficiency & Renewable Energy (2022, 2023) provided data on the decarbonization strategies in the European Union.

5.2. Data Analysis

The study used a GIS-based methodology to visualise per capita energy-related carbon dioxide emissions in the United States of America and the European Union for the years 2000, 2010, and 2021. The ArcGIS software was used to combine carbon emissions data from the United States and the European Union into an attribute table, which was then linked to a shapefile. Six distinct maps were created using the symbology tool and the graduated colour option to illustrate the spatial distribution of carbon emissions. Furthermore, three bar charts were used to depict total carbon dioxide emissions and emissions by sector in the United States, as well as the percentage of total greenhouse gas abatement and the relative reduction of CO_2 in the EU compared to 1990. Furthermore, a pie chart was used to represent the RAF's (Resource Availability Factor) sensitivity to resource availability in the EU.

The average carbon emissions per state and country for the United States and European countries data, were respectively modeled according to the following formulation.

The models for the average carbon emissions per state and country for the United States and European countries years were modeled based on the following respective formulations.

Average carbon emissions, C $\propto f(t)$

Where C is the average carbon emissions per state and country for the United States and European countries.

For linear model, the expression for C can be transformed to the following equation.

$$C = +At + B \tag{1}$$

where C is the average carbon emissions per state and country for the United States and European countries, and A is the constant of proportionality.

where A is a coefficient of proportionality and B, the vertical axis intercept, respectively.

For quadratic model,

$$C = At^2 + Bt + C \tag{2}$$

where A and B are coefficients of proportionality, and C the vertical axis intercept, respectively.

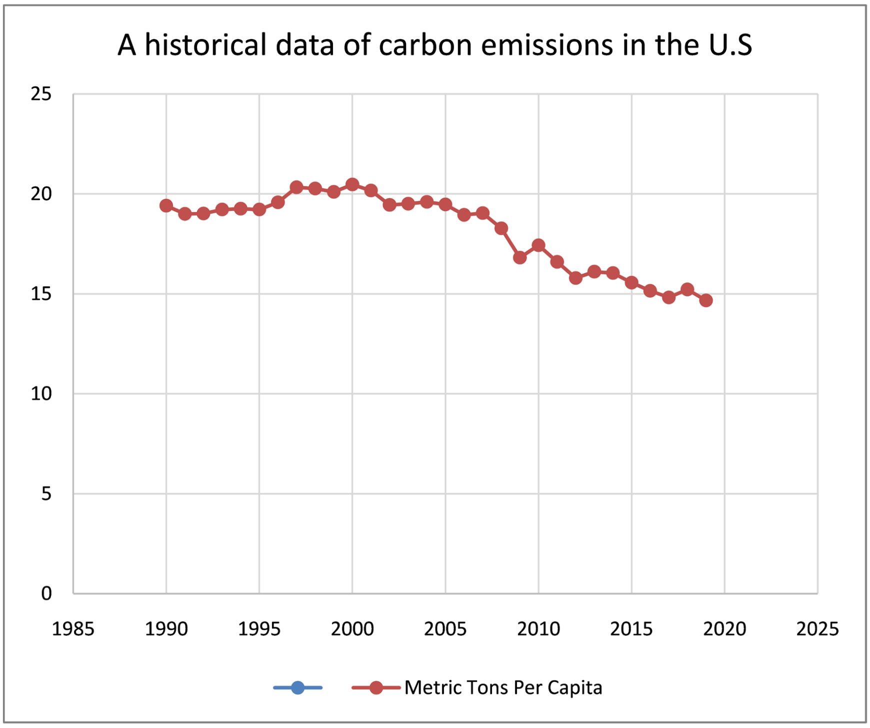
Curve fitting with statistical software was next applied to data pair sets for the United States and European countries to determine the models for prediction of average carbon emission. The models are presented in section 6.3.

6. Results

6.1. Carbon Emissions in the United States of America over the Years

6.1.1. US Carbon Emissions from 1990 to 2022

With reference to Figure 1, the pattern of the data on carbon emissions in the U.S. has been undulating. Carbon emissions in the U.S. slightly decreased and increased until 2018 when the country recorded a sharp drop in emissions. There was a slight increase from 2009 to 2010 and a sharp drop from 2010 to 2012 and the carbon emission rate in the U.S. has been decreasing since then. The increase in energy-related CO_2 emissions was caused by both short-term and long-term indicators.



Source: World Bank (2017).

Figure 1. Historical data of carbon emissions in the U.S.

Increased use of petroleum products, notably in the transportation sector, contributed to more than half of the increase in CO_2 emissions in the United States. Carbon emissions from motor gasoline in the United States went up by 9%, while jet fuel rose by 27%, as tourism began to recover (Sartor et al., 2017). In 2021, the United States energy consumption produced 4.9 billion metric tonnes of carbon dioxide ($GtCO_2$), a 7% increase over 2020 levels. Emissions fell in 2020 as a result of COVID-19, which significantly damaged polluting industries, but increased in 2021 as restrictions and lockdowns were lifted (U.S. EIA, 2021). The COVID-19 pandemic had a significant impact on the US and global economies, as well as carbon dioxide emissions, by 2020. In 2021, the energy market and carbon emissions from energy began to revert to pre-pandemic levels. Overall energy-related carbon emissions in the United States rose by 7%, or 325 million metric tonnes (MMmt), in 2021, especially in contrast to 2020; nevertheless, total emissions in 2021 were still 5%, or 242 MMmt, lower than in 2019 (Sartor et al., 2017).

6.2. Carbon Emission in the EU

Remarkably, certain countries have recorded lower carbon emissions in recent times which may be attributed to a decrease in their reliance on coal and other household resources for energy. For instance, an analysis of EU emissions shows that the union's carbon emissions have decreased by 5% (Myllyvirta, 2022). Data on the amount of carbon emitted by 26 countries in the EU has been represented in Table 1.

6.2.1. Carbon Dioxide Emissions (in Metric Tons)

Table 1. Carbon dioxide emissions in the EU in 2000, 2010, and 2021 (in metric tons).

Country	2000	2010	2021
Germany	628.9	783.2	854.4
Italy	311.2	397.1	434.4
Poland	309.1	323.8	299.8
France	273.6	360.4	381.5
Spain	245.7	300.1	309.3
Netherlands	178.7	226.5	216.2
Belgium	114.7	133.5	136.3
Czechia	92.4	116.5	124.1
Romania	70.3	78.2	88.9
Austria	58.4	67.8	63
Greece	56.5	94.6	102.6
Hungary	45.7	48.7	55.3
Bulgaria	41.7	45.6	43.4
Sweden	40.1	56.9	57.7
Portugal	39.4	51.5	61.3
Finland	37.2	63.1	58.9
Ireland	34.2	42.5	43.6
Slovakia	31.7	36.1	36.3
Denmark	28.1	51	55
Estonia	18	22.9	17.2
Croatia	15	18.8	17.5

Continued

Lithuania	12.1	13.2	10.9
Slovenia	11.6	15.2	14
Luxembourg	9.3	12	9
Latvia	7.4	9.2	6.9
Cyprus	7.2	8.8	8

Source: Tiseo (2024a).

6.2.2. Model for the Average Carbon Emission for EU Countries

Average linear model for average carbon emission for EU countries with respect to years, based on data from **Table 1** is presented in **Figure 2**.

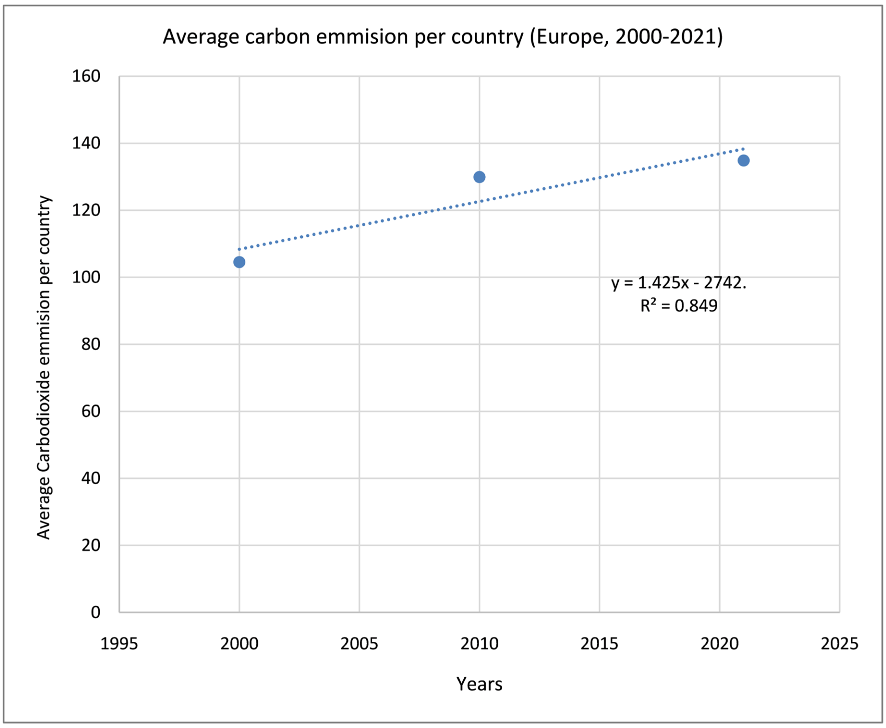


Figure 2. Average carbon emission for EU countries with respect to years (in metric tons).

Based on 2010-2021 data, the average emissions per country in European countries has been gradually increasing, specifically from 104.5 to 134.8 metric tons per country. **Figure 2** illustrates the general trend in average carbon emissions per country in Europe. However, the proportion of total global pollution attributable to Europe is reducing because of industrialization taking place in developing countries. **Figure 3**, **Figure 4** and **Figure 5** illustrate the carbon emission rates by each country in the EU in 2000, 2010 and 2021, respectively.

In 2000, countries like Croatia, Lithuania and Denmark recorded relatively low carbon emissions ranging from 7.4 to 28 Mt, while Romania, Greece, Portugal, and Sweden had slightly higher emissions between 28 and 92.4 Mt. In contrast, France, Spain, Italy, and Poland reported significantly higher emissions exceeding 178 Mt. Germany, however, is seen to have recorded the highest emissions ranging between 311Mt to 628 Mt approximately.

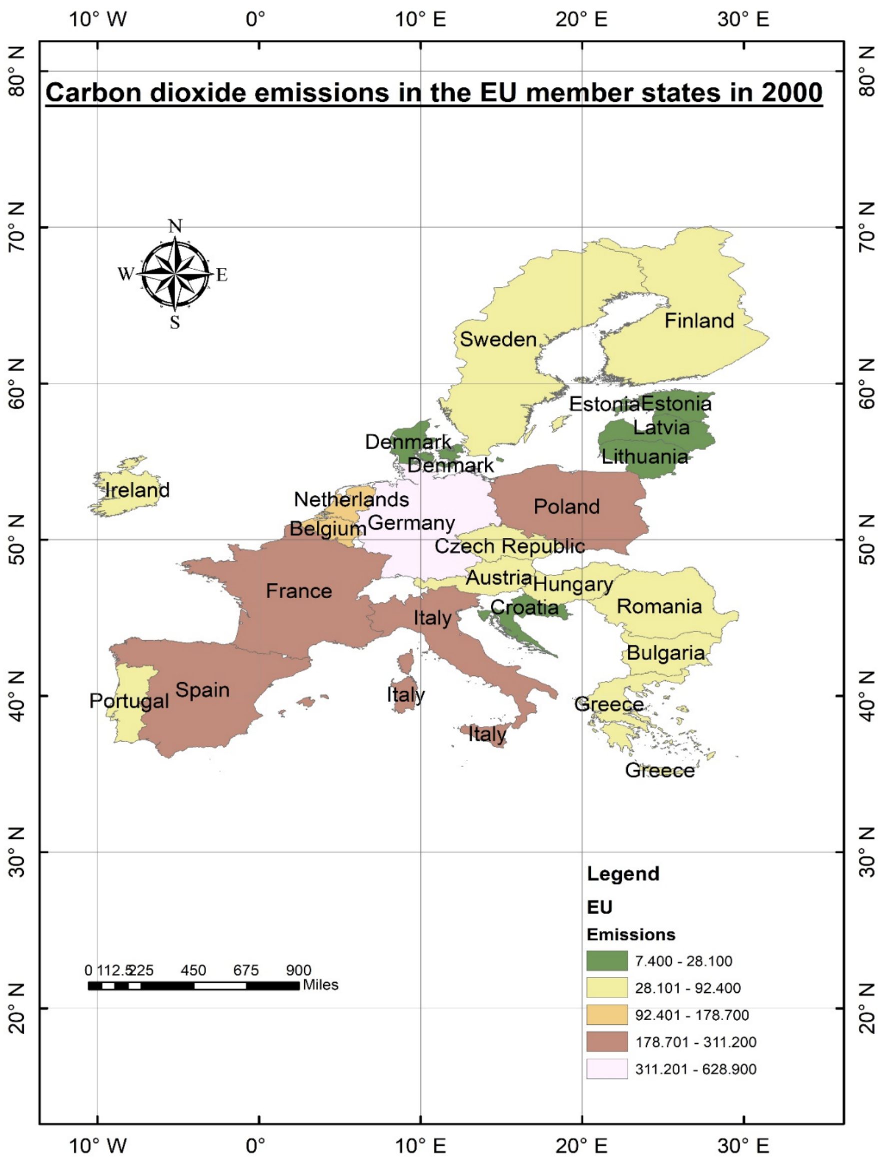


Figure 3. Carbon dioxide emissions in the EU in 2000 (in metric tons -Mt).

In 2010, Croatia and Lithuania maintained low carbon emissions between 9.2 and 22.9 Mt, reflecting a decrease of approximately 6 Mt compared to the emissions in 2000. Romania, Greece, Portugal, Sweden, and Finland recorded slightly higher emissions between 22 and 94.6 Mt. On the other hand, France, Spain, Italy, and Poland reported emissions exceeding 226.5 Mt, with Germany recording the highest at 783 Mt, which is approximately over 100 Mt of carbon emitted since 2000.

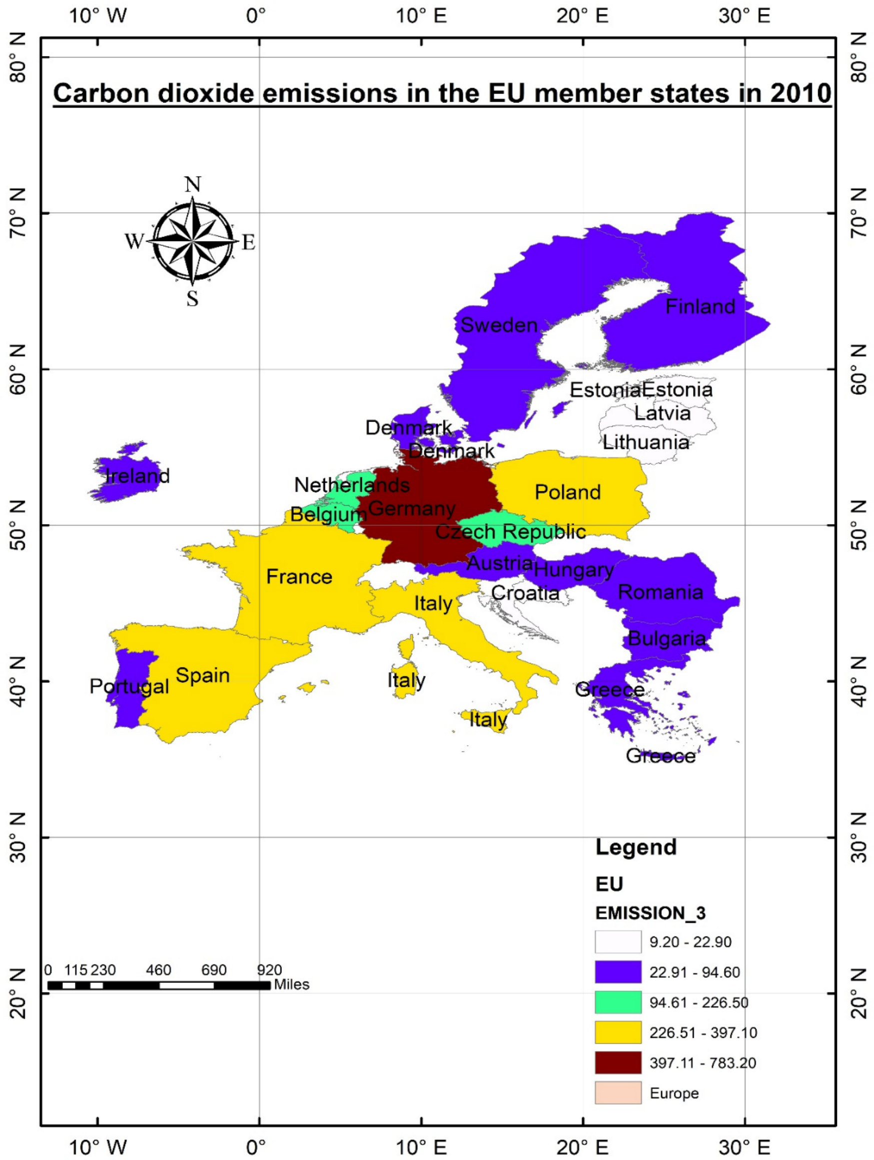


Figure 4. Carbon dioxide emissions in the EU in 2010 (in metric tons -Mt).

In 2021, Croatia and Lithuania for instance continued to record low carbon emissions, ranging from 6.9 to 17.5 Mt, reflecting a further decrease of approximately 6 Mt. Meanwhile, Greece, Portugal, Sweden, and Finland saw emissions rise slightly to between 17.5 and 102.6 Mt, an increase of about 8 Mt compared to 2010. France, Spain, Italy, and Poland slightly maintained emissions exceeding 216.5 Mt, with the highest at 434 Mt, marking a notable increase. Germany recorded the highest emissions at 854 Mt, an increase from 783 Mt in 2010, continuing its upward trend over the years.

Over time, Latvia, Estonia, Lithuania, and Croatia have consistently had the lowest levels of carbon emissions among countries, while Germany has consistently been the top emitter of carbon dioxide. An increase in carbon emissions between 2000 and 2010 was observed in all the countries. However, whiles some

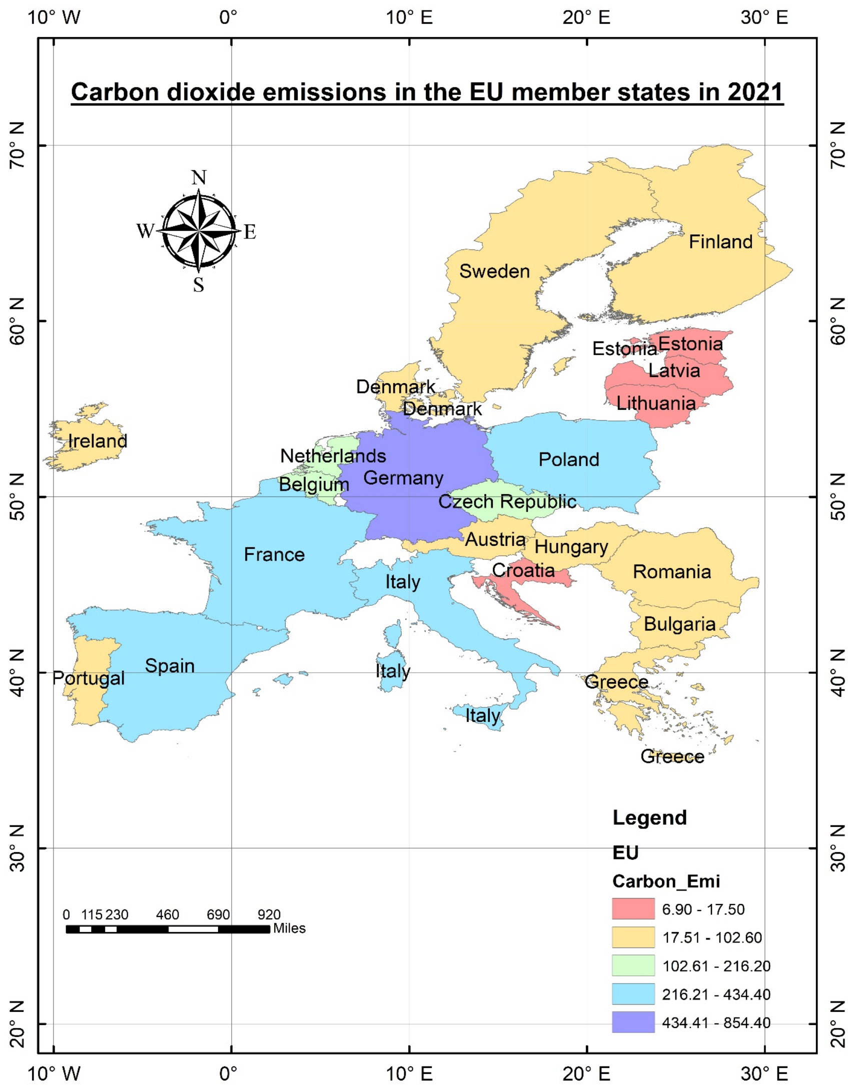


Figure 5. Carbon dioxide emissions in the EU in 2021 (in metric tons -Mt).

countries recorded a higher amount of carbon emissions between 2010 and 2020, others recorded low values. There was a drop in carbon emissions from 2010 to 2020 in countries such as Poland, Netherlands, Austria, Bulgaria, Finland, Estonia, Croatia, Lithuania, Slovenia, Luxembourg, Latvia, and Cyprus. On the other hand, countries that recorded an increase in carbon between 2010 and 2020 include Germany, Italy, France, Spain, Belgium, Czechia, Romania, Greece, Hungary, Sweden, Portugal, Ireland, Slovakia, and Denmark. The highest carbon emissions across the years were recorded by Germany and Cyprus. In 2021, the European Union generated nearly 2.73 billion metric tonnes of carbon dioxide. In comparison to 2020 levels, this represented a more than 6% increase. In 1979, the greatest amount of carbon emissions generated in the EU was 3.99 billion metric tonnes (Tiseo, 2024c). The significant decrease in emissions in 2020 was caused by the COVID-19 pandemic and the resultant lockdowns and restrictions. As travel was severely impacted, EU transportation emissions decreased, while emissions from industrial processes and power supply were also affected. Carbon emissions in the European Union dropped by 22% in April 2020, during lockdowns, against the same month in 2019. Germany is the EU's largest source of CO_2 emissions. Even though there has been a nearly 24 percent decrease in emissions since 2005, Germany still discharges significantly more than other major emitters in the EU, such as France, Italy, and Poland. This is primarily due to Germany's reliance on coal in its energy mix. Coal is the filthiest of all fossil fuels, emitting roughly half as much CO_2 as natural gas (Tiseo, 2024c). The Coronavirus pandemic took over the world beginning in early 2020, killing millions and halting day-to-day economic activity. These restrictions had a major and immediate impact on carbon emissions, which dropped in 2020. However, the decline was only momentary, and emissions increased as economies opened up. Following Russia's invasion of Ukraine in March 2022 and the militarization of energy supplies to Europe, the recovery from the pandemic has been accompanied by a worldwide energy crisis (Myllyvirta, 2022).

6.2.3. EU Carbon Emissions by Sector

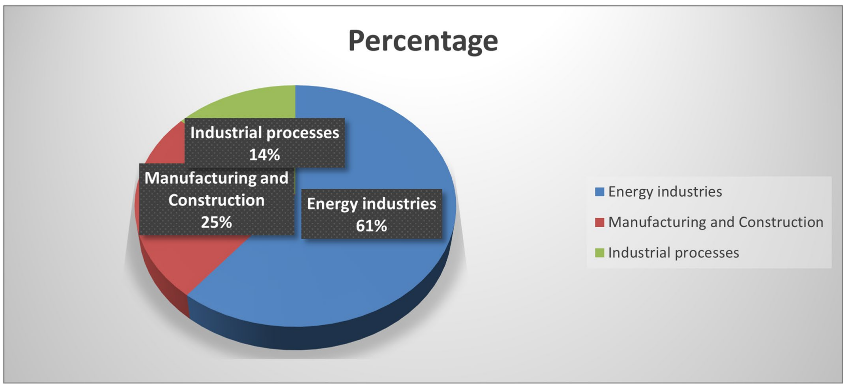


Figure 6. EU Carbon Emissions by Sector. Source: Karakosta (2016).

GHG emissions from the industrial sector are controlled by energy and process-related carbon dioxide, but they also encompass CH_4, N_2O, and fluorinated gases (HFC, PFC, SF6), with the fluorinated gases saturated in the chemical industry. Carbon dioxide recorded over 94% of carbon dioxide equal GHG emissions in the EU-28 manufacturing industry in 2012 (Myllyvirta, 2022). According to the Karakosta (2016), the industrial sector represents the largest share of carbon emissions in the EU, followed by the transport sector, other sectors, the agricultural sector, and the waste sector. Within the industrial sector, energy industries emitted the most carbon (31%), with manufacturing and construction following (13%), then industry processes (14%). According to new data, the European Union's carbon dioxide (CO_2) emissions from energy use have decreased by 5% in the last three months in comparison to the same period in 2021. In the EU6, industrial emissions are responsible for more than half of total GHG emissions. **Figure 6** depicts the proportion of industrial GHG emissions in the EU, along with a further dissection by the source of emissions (Myllyvirta, 2022).

6.3. Carbon Emission in USA

Data for average carbon emissions for states in the US is presented in Tables 2-6.

Table 2. US average carbon emissions per state (1970-1979).

Year	1970	1971	1972	1973	1974	1975	1976	1977	1978	1979
Average	83.42898	84.31452	88.62772	92.48919	89.1321	86.70525	91.99175	94.7101	95.51728	96.68472

Table 3. US average carbon emissions per state (1980-1989).

Year	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989
Average	93.2633	90.84021	86.10192	85.83961	90.25205	90.34233	90.39192	93.33464	97.82443	99.30135

Table 4. US average carbon emissions per state (1990-1999).

Year	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999
Average	98.51433	97.55656	99.42429	101.4042	102.8048	104.0614	107.9446	109.357	110.0589	111.3234

Table 5. US average carbon emissions per state (2000-2009).

Year	2000	2001	2002	2003	2004	2005	2006	**2007**	**2008**	**2009**
Average	115.0481	112.8942	113.6375	115.0308	116.965	117.4627	115.8395	117.608631	113.792472	105.795388

Table 6. US average carbon emissions per state (2010-2020).

Year	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**
Average	109.51036	106.857676	102.537887	105.11576	106.217304	103.277533	101.559229	100.850954	103.819638	101.153445	90.0476192

An examination of the data presented in Table 2, Table 3, Table 4, Table 5 and Table 6 reveals two trends that are identified as a rise (1970-2005) and a decrease (2005-2020). Hence, the models of average carbon emissions per state in the US for each trend was modeled using Microsoft Excel and presented in Figure 7 and Figure 8 respectively. In the rising trend, the emissions rose from about 80 to just below 120 Units.

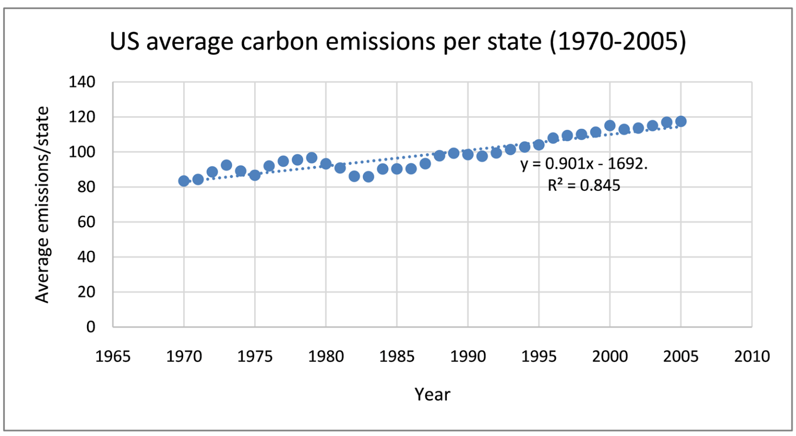


Figure 7. The average carbon emission per state versus years for rising trend for the United States.

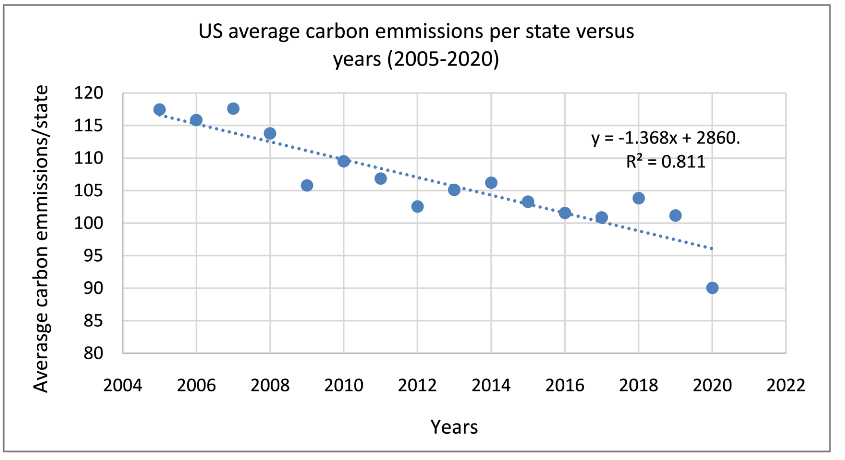


Figure 8. The average carbon emission per state versus years for decreasing trend for the United States.

According to the decreasing trend model, the average emission per state in the United States of America decreased steadily from 116 units to 100 units in 2018, according to the equation presented in **Figure 8**. The drops in 2019 and 2020 resulted mainly from reduction in the emission from the transportation sector following restriction from movements following lockdowns. Also, in April 2020, the social restrictions in the United States because of COVID-19 led to a drop in electricity demand from the industrial and commercial. In 2019, truck freight slowed down because of an initial spike at the beginning of the pandemic. According to the Energy Information Administration, the emission was expected to increase in 2021 and 2022, and then stabilize in 2023 (U.S. Energy Information Administration (EIA), 2022, 2023). As shown in **Figure 9**, if US keeps up with its decarbonization effort, its expected average carbon emissions per state by 2030 can be estimated by linear interpolation of the decreasing model using Microsoft Excel. The expected average state emission by 2030 is approximately 83 Units.

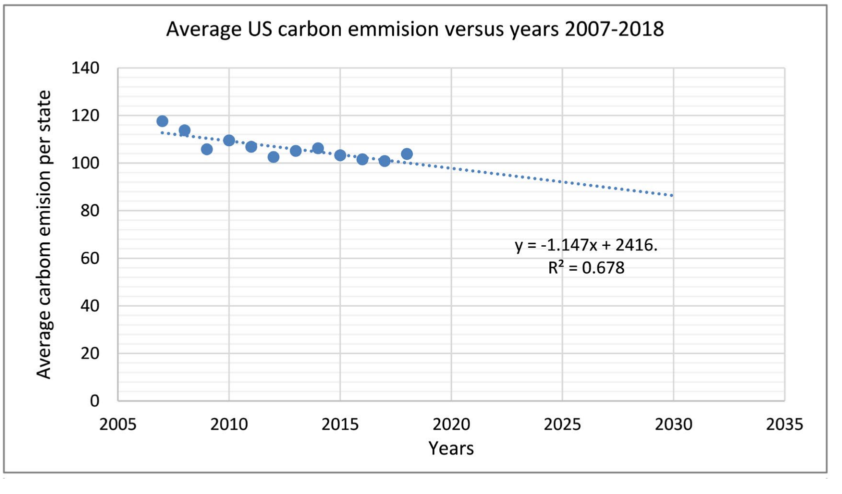


Figure 9. The model for the average carbon emission per state versus years for rising trend for the United States. (2005-2030).

Regression analysis using Microsoft Excel statistical tool kit was applied to the data to determine whether the decrease from 2005 to 2018 was statistically significant. The regression summary y is presented in **Table 7**.

Table 7. Regression summary for the decreasing trend data for the average carbon emission per state for the United States of America.

Regression Statistics									
Multiple R	0.823672								
R Square	0.678436								
Adjusted R Square	0.646279								
Standard Error	2.988615								
Observations	12								
ANOVA									
	df	*SS*	*MS*	*F*	*Significance F*				
Regression	1	188.4431477	188.4431	21.09796	0.000990303				
Residual	10	89.31818297	8.931818						
Total	11	277.7613307							
	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower* 95%	*Upper* 95%	*Lower* 95.0%	*Upper* 95.0%	
Intercept	2416.657	502.9657924	4.804814	0.0007184	1295.979313	3537.33456	1295.97931	3537.33456	
Year	−1.14795	0.249920523	−4.59325	0.0009903	−1.70480547	−0.5910902	−1.70480547	−0.591090216	

From the regression summary, the p value is less than 0.05. hence, the model is statistically significant. Hence, foe every additional year, the average carbon emission per state in US decreases by about 1.15 (in metric tons).

US Emissions by Sector

To make well-informed choices about how to lessen greenhouse gas emissions, it is essential to comprehend how various economic sectors play a part in greenhouse gas production and how these patterns have developed over time (U.S. Department of Commerce, 2010). The transportation sector is the primary source of CO_2 emissions in the United States (Schneer, 2019). Emissions of greenhouse gases have risen significantly since the pre-industrial era and are currently increasing at such a rate that their levels in the atmosphere are causing rising temperatures. For so many years, the electricity sector was the country's largest source of carbon emissions, however, a switch away from coal-based power generation has reduced emissions from this sector. In the meantime, transportation emissions have remained on the rise, with the exception of a historic drop in 2020. By far the largest contributor to worldwide transportation emissions is the United States. Texas and California have the highest transportation-related emissions in the United States (EIA, 2023).

According to Anderson et al. (2021), the transportation sector contributes the highest emissions in the US with 29% followed by the electrical power sector with a percentage of 25 then the industry, representing 23%. The least carbon emissions were recorded by the residential and commercial sectors and the agricultural sector, representing 13% and 10%, respectively. The industrial sector in the United States makes up 30% of national greenhouse gas (GHG) output, whereas the industrial sector internationally represents 40% of total GHG emissions. Using renewable energy only outlines a small portion of industrial emissions. Nevertheless, there are technologies and methods available now to help lower industrial emissions, as well as inventions that could completely decarbonize the sector. Manufacturing industries have been one of the fastest-growing international causes of greenhouse gas emissions since 1990, massively increasing in the last 30 years. This increase was primarily driven by increasing carbon pollution, but it was also caused by increased utilization of refrigeration and air conditioning, both of which generate hydrofluorocarbons (HFCs), which are powerful greenhouse gases. Direct industrial sector emissions result from on-site fuel combustion or carbon emissions from chemical reactions ingrained in industrial production. Direct industrial emissions now represent 23% of total greenhouse gas emissions in the United States, making it the third-highest emitting sector after transportation and electricity. The US Energy Information Administration (EIA) predicts that industrial energy demand in the United States will increase by 36% by the middle of the century. The United States is one of more than sixty countries that have set a goal of becoming a net-zero economy by 2050. Lowering global carbon emissions by 45% by the year 2030 will provide the entire world with the best chance of successfully achieving those targets (Anderson et al., 2021).

Table 8. Per capita energy-related carbon dioxide emissions by state in the US.

State	2000	2010	2020
Alabama	31.96	27.7	19.6
Alaska	69.39	52	49.1
Arizona	16.79	15.5	11.2
Arkansas	23.64	22.6	18.2
California	11.25	9.6	7.7
Colorado	19.76	19	13.8
Connecticut	12.53	10.2	9.4
Delaware	21.22	14.5	12.6
District of Columbia	7.54	5.3	3.5
Florida	14.9	13	9.6
Georgia	20.62	18	10.9
Hawaii	15.43	15	10.3
Idaho	12.08	10.3	10.5
Illinois	18.89	18.2	13.3

Continued

Indiana	39.35	33.6	22.7
Iowa	27.11	29.6	20.6
Kansas	28.14	25.4	19.7
Kentucky	36.32	35.2	22.6
Louisiana	49.33	44.8	39.4
Maine	17.42	13.4	9.9
Maryland	14.78	12.3	7.8
Massachusetts	12.94	11.1	7.4
Michigan	19.55	17	13.6
Minnesota	19.89	17.3	13.7
Mississippi	21.55	21.4	21.4
Missouri	22.6	22.8	17.7
Montana	35.15	35.3	24.1
Nebraska	24.31	27.3	23.7
Nevada	22.6	15.3	11.6
New Hampshire	14.09	12.7	9
New Jersey	14.78	12	9
New Mexico	31.99	26.1	21.3
New York	11.17	9.5	7.1
North Carolina	18.45	15.4	10.2
North Dakota	79.94	78.3	69.6
Ohio	23.47	21.4	15.7
Oklahoma	29	28.1	21.1
Oregon	12.11	10.6	8.8
Pennsylvania	22.67	20.1	14.9
Rhode Island	11.21	10.4	9
South Carolina	20.38	18.5	12.4
South Dakota	18.82	18.5	16.8
Tennessee	22.57	17.2	12
Texas	32.13	24.4	21.4
Utah	29.13	23.1	17.5
Vermont	11.12	9.4	8.4
Virginia	17.35	13.9	11.4
Washington	14.27	10.9	8.9
West Virginia	64.03	54.2	43
Wisconsin	20.06	17.4	14.8
Wyoming	128.49	116.1	96.4
AVERAGE OF ALL STATES	**20.79**	**18.1**	**13.9**

Source: U.S Energy Information Administration (EIA).

According to the trend in per capita energy-related carbon dioxide (CO_2) emissions in **Table 8**, a significant decline is observed in the average emissions by all states from 20.79 in the year 2000 to 18.1 in 2010, and a further substantial reduction to 13.9 in 2020. Notably, these major reductions depict progress towards mitigating the environmental impact of CO_2 emissions and fostering a more sustainable environment.

For instance, in the year 2000, the highest recorded CO_2 emissions varied significantly, ranging from approximately 50 to 128 metric tons as seen in Figure 10. By 2010, the highest emission rate narrowed to a range between 79 and 116 metric tons, and further reduced to 50 to 96 metric tons in 2020 as seen in Figure 12 and Figure 13 respectively. For the record, some of the states that recorded high CO_2 emissions in the year 2000 include Alaska, North Dakota, Wyoming and West Virginia as seen in Figure 10. States like Texas, Montana, New Mexico, Louisiana, Alabama and Indiana however recorded the second highest CO_2 emissions ranging between 30 to 49 metric tons. On the other hand, some states like Washington, Oregon, California, New York and Florida recorded low CO_2 emissions which ranged between 8 and 15 metric tons of CO_2 as seen in Figure 10.

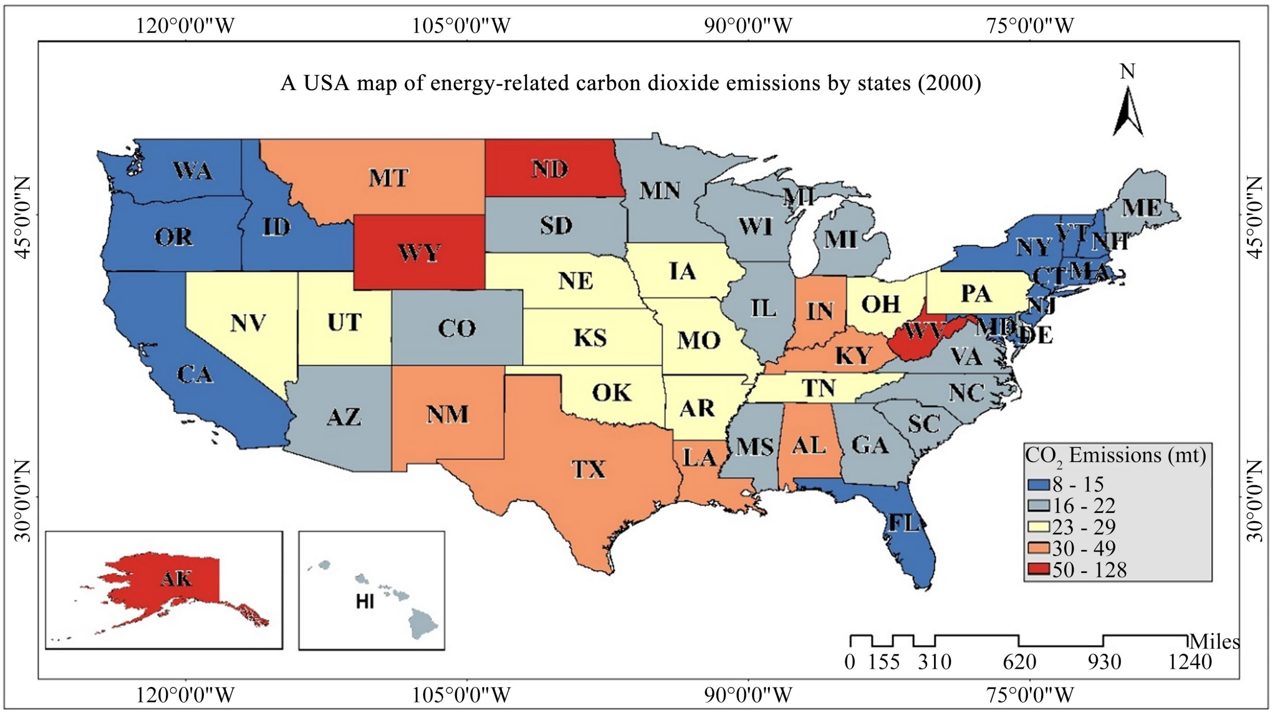


Figure 10. Map of CO_2 emissions by all USA states in 2000.

With respect to the reduction in CO2 emissions recorded in the year 2010, Figure 11 shows how states such as Alaska, North Dakota and West Virginia which recorded high CO_2 emissions in year 2000, recorded lower CO_2 emission rates in year 2010 ranging between 79 and 116. Even though the highest emission rate recorded in 2010 is a reduction from year 2000, Wyoming remains the only state that still recorded high CO_2 emissions in year 2010 as seen in Figure 11. Other significant reductions are also observed from states such as Nevada which recorded CO_2 emissions of about 23 metric tons in year 2000 but recorded lesser emissions of 15 metric tons in year 2010 and 12 metric tons by 2020 as seen in Table 8. Similarly, a state like Texas recorded a significant CO2 emission reduction from 32 metric tons in 2000 to 24 and 21 metric tons in the years 2000 and 2010 respectively. Even though the state of Louisiana stands out as the only state where CO_2 emissions still falls within a range expanding from 30 to 49 metric tons in the year 2000 to a broader range of 36 to 78 metric tons in 2010 in Figure 11, the state still recorded a reduction of CO2 emissions moving from 49.33 in 2000 to 44.8 and 39.4 in 2010 and 2020 respectively.

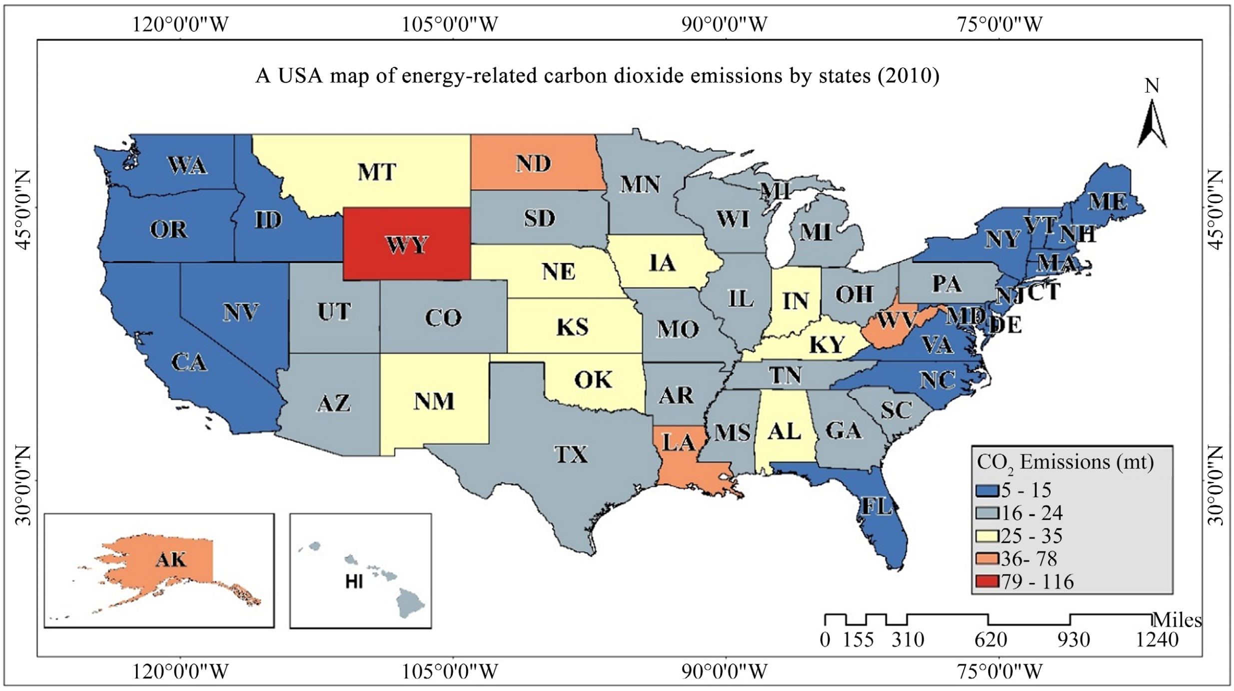


Figure 11. Map of CO_2 emissions by all USA states in 2010.

By the year 2020, as compared to 2010, a drastic reduction in CO_2 emissions was recorded from all the states by which the highest rate dropped to a range between 50 and 96 as seen in Figure 12. While this is still a reduced emission rate as compared to year 2010, a state like Wyoming still recorded the highest emissions of CO_2 as compared to the other states. That is, Wyoming recorded CO_2 emission rates of about 128 metric tons in year 2000 with a decrease to about 116 metric tons in 2010 and about 96 metric tons in 2020, still being the highest among the other states.

However, most of the western states such as Washington, Oregon, Idaho, California and a southeastern state like Florida have consistently recorded reduced CO_2 emission rates that range from 8 to 15 in 2000, 5 to 15 in 2010 and a significant reduction range between 4 and 11 in 2020.

The declining trend of CO_2 emissions recorded in the years 2000, 2010, and 2020 by most of the USA states is therefore an indication and reflection of the states' commitment in reducing greenhouse gas related climate change effects to create a healthy environment and a sustainable future.

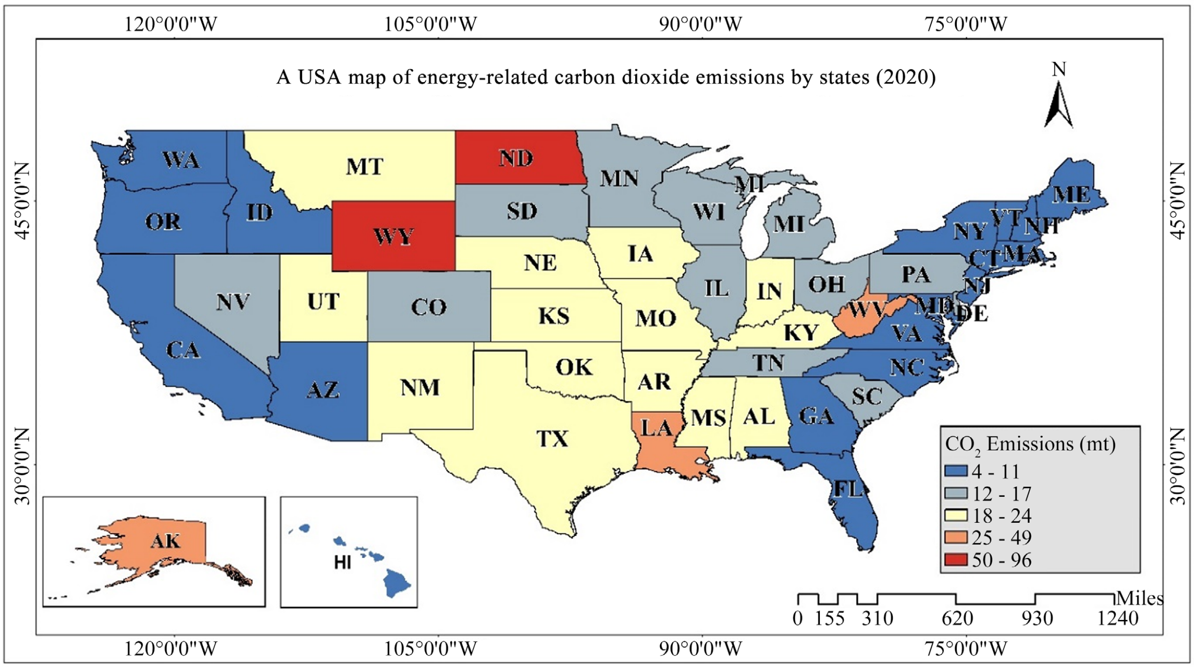


Figure 12. Map of CO_2 emissions by all USA states in 2020.

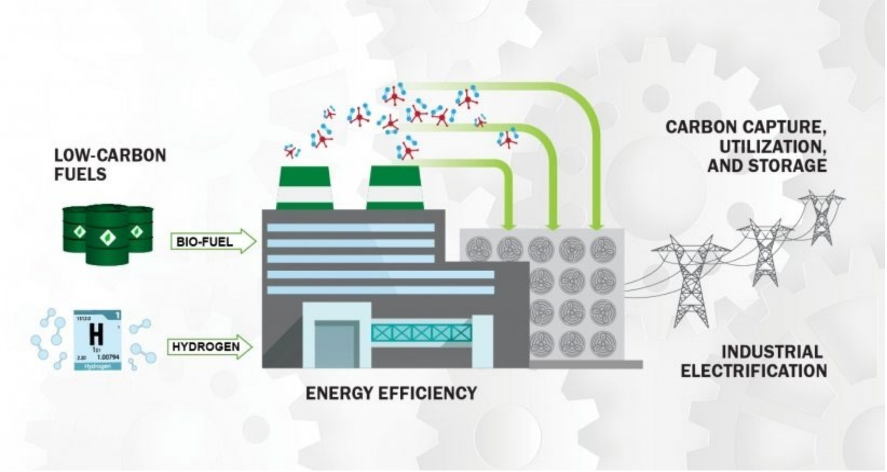
6.4. Decarbonization Strategies in the US

Over the last decade, the United States has seen an unexpected massive increase in extreme weather events driven by climate change that has caused over $800 billion in losses and killed over 5200 people—a pattern that appears set to continue. Simultaneously, the significance of a substantial initiative to decarbonize the United States' electricity grid has become completely obvious, as have the growing climate threats and consequences that such an initiative will encounter (Pawar, 2021).

6.4.1. Total Electricity Generation in the U.S. by Energy Source and Total Sector Emissions

According to Lawson (2018), the use of coal to generate electricity in the U.S. slightly increased in 2000, slightly dropped in 2015, and further dropped in 2015. The use of this energy source has been projected to be stable till 2050. Petroleum was only used to generate electricity from 1990 to 2005. There has been an increase in the use of natural gas to generate electricity from 2010 to 2050. With regards to the use of nuclear for electricity generation, the amount is stable throughout the year whereas the use of renewables is stable at the beginning but slightly increases throughout the years. Finally, there has been minimal use of other energy sources in the US for the generation of energy. On the other hand, since the country has made a conscious effort to adopt some decarbonization strategies to fight climate change, carbon emissions dropped sharply in 2015 and it is projected to further decrease in the coming years.

6.4.2. The Industrial Decarbonization Roadmap in the U.S



Source: Office of Energy Efficiency & Renewable Energy (2022, 2023).

Figure 13. Strategies for decarbonizing US industries.

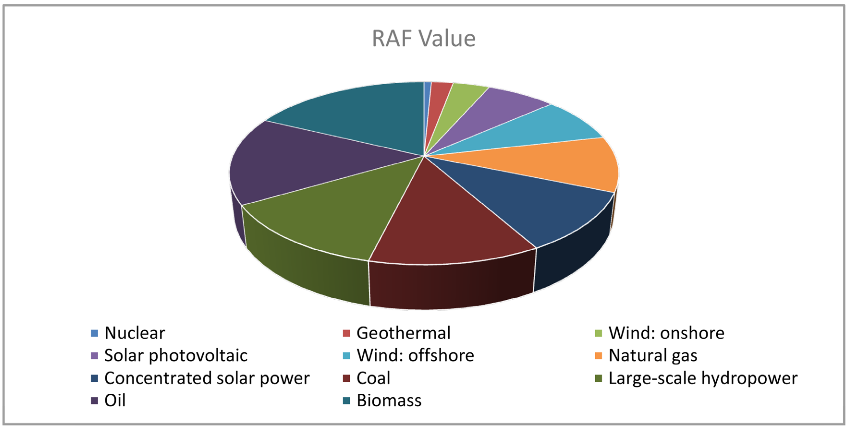
The Masterplan identifies four crucial technological core elements for substantially emissions reduction in the subsectors. Alternative methods have the ability to reduce 100 percent of CO_2 emissions each year. Energy efficiency; industrial electrification; low-carbon fuels, feedstocks, and energy sources (LCFFES); and carbon capture, utilization, and storage are the major decarbonization foundations (CCUS). These foundations are relevant across all industrial subsectors and have the potential to achieve current and future cuts. Entergy efficiency is a fundamental decarbonization strategy that is also the most economical alternative for reducing GHG emissions in the short term. Decarbonization efforts encompass a) tactical energy conservation strategies to optimize the system-level performance of manufacturing processes; b) systems management and enhancement of thermal heat from production process heating, boiler, and combined heat and power (CHP) sources; and c) smart factory and sophisticated data analytics to maximize energy productivity in production processes (Office of Energy Efficiency & Renewable Energy, 2022, 2023).

In terms of industrial electrification, harnessing progress in low-carbon electricity from both power systems and onshore renewable power sources will be essential to decarbonization endeavors. Decarbonization initiatives include a) electrification of heat sources via induction, thermal radiation heating, or innovative heat pumps, b) electrification of high-temperature range processes such as those encountered in iron, steel, and cement manufacturing, and c) substituting high-temperature processes with electrochemical ones. Low-Carbon Fuels, Feedstocks, and Energy Sources (LCFFES) involve replacing low- and no-carbon fuels and feedstocks for manufacturing processes to reduce combustion-related emissions. Carbon Capture, Utilization, and Storage (CCUS) is a multi-component approach that entails collecting derived carbon dioxide (CO_2) from a single point and either utilizing the captured CO_2 to create value-added products or stockpiling it long-term to avoid discharge (Office of Energy Efficiency & Renewable Energy, 2022, 2023).

6.5. Decarbonization Strategies in the EU

The European Union (EU) has set a goal of achieving climate neutrality by 2050, which means that its economy will emit no net greenhouse gases. This transition to a climate-neutral society is seen as both a pressing challenge and an opportunity to create a better future for all (European Commission, 2023). The European Commission proposed an ambitious plan in December 2019 to ensure that the European Union (EU) achieves climate neutrality by 2050. While this proposal outlined specific emission reduction targets for 2030 and 2050, it did not provide explicit details on the distribution of responsibilities among sectors and member states, nor did it provide estimates of the costs associated with achieving these reductions (D'Aprile et al., 2020). By 2030, the European Union (EU) intends to reduce emissions significantly through two main strategies: large-scale electrification and improved energy efficiency. These strategies are expected to contribute 47 percent and 17 percent of the total reduction, respectively. Additional measures focusing on the demand side and circularity would cut emissions by 15%. The use of hydrogen as an alternative energy source is expected to contribute another 13% to the reduction of emissions. The remaining reduction is expected to come from increased biomass utilisation, changes in land use, and other innovative solutions (D'Aprile et al., 2020). Member states of the EU are required to develop national long-term strategies in order to meet their obligations under the Paris Agreement and the EU's goals. These strategies outline how they intend to reduce greenhouse gas emissions to the required levels (European Commission, 2023).

6.5.1. RAF Sensitivity to Resource Availability

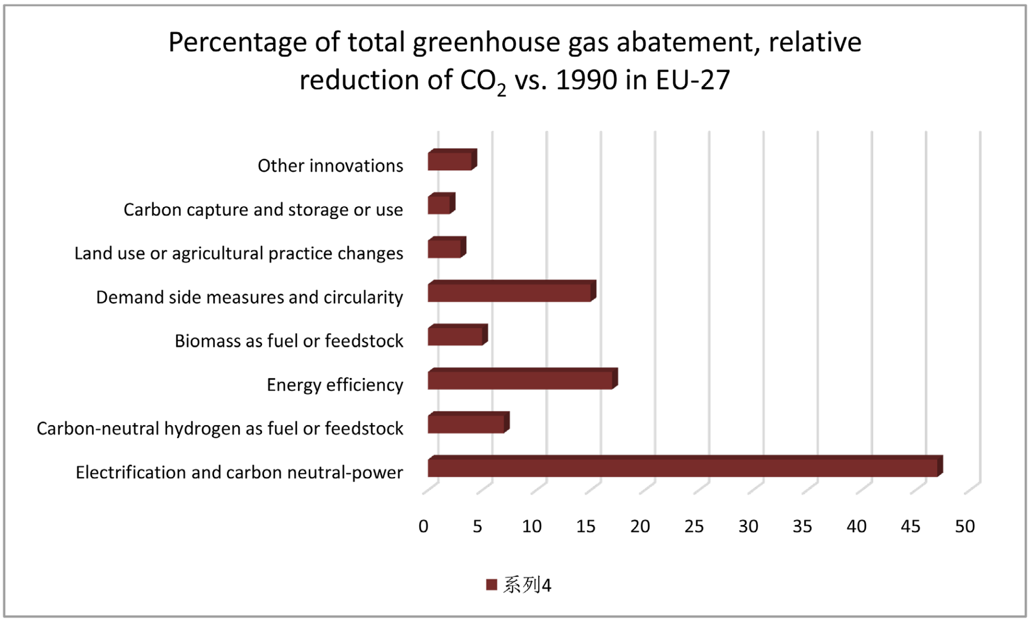


Source: Ristic et al. (2019).

Figure 14. Sensitivity analysis of the RAF of electricity generation technologies.

Figure 14 depicts the results of the RAF analysis using all criteria (levelized cost, carbon, water, and land footprint). There were no exclusively ideal or strictly poor technologies when all preconditions were equally valued. This is due to uncertainty in performance scores as well as discrepancies in the optimality principles of various MCDM methods. A non-zero RAF value indicates that the MCDM methods disagree in assessing the complete safest alternative for the unclear performance values. Similarly, the omission of RAF = 100 indicates that the MCDM methods disagree in assessing the worst alternative. According to Figure 14, nuclear and geothermal operate comparatively better than the other technologies. Biomass, oil, and large-scale hydropower are the poorest roughly comparable technologies. Figure 14 shows that low-carbon technologies are generally desirable to hydrocarbons. This illustrates that switching from fossil fuels to renewable sources is probable to result in co-benefits for water and land because these technologies function better throughout all these eligibility requirements. However, biomass has the prospect to provide 19.1% of the European Union's renewable power by 2020. (Beurskens & Hekkenberg, 2011). As of now, biomass accounts for 54.5% of the renewable energy goals (Atanasiu, 2010). The findings show that biomass was listed as the worst energy technology by 13 of 28 MSs (RAF = 100) (Ristic et al., 2019).

6.5.2. Greenhouse Gas Abatement



Source: D'Aprile et al. (2020).

Figure 15. Percentage of total greenhouse gas abatement.

With reference to Figure 15, the most used decarbonization strategy to fight climate change in the EU is electrification and carbon neutral power, followed by energy efficiency and demand side measures and circularity. On the other hand, the least used methods to reduce carbon emissions are land use or agricultural practice changes and carbon capture and storage or use. Energy efficiency and electrification could reduce emissions by approximately two-thirds by 2030. The majority of the total carbon output lowered by bioenergy carbon capture and storage is credited to biomass, with the remaining half attributed to carbon capture and storage. Massive electrification and energy efficiency improvements would represent 47 percent and 17 percent of the European Union's decarbonization strategy by 2030, respectively (D'Aprile et al., 2020). The incorporation of digitalization is regarded as a critical factor in accelerating energy decarbonization in buildings. Given that people spend roughly 80% of their lives inside buildings such as offices, schools, hospitals, and homes, the impact of digital technologies becomes significant. According to Frei (2021), buildings are also significant capital investments for businesses (Frei, 2021). The efficiency of a building's entire lifecycle, including its design, construction, and operation, can be greatly improved by incorporating digital technologies. Greater digitalization of the building value chain is critical for increasing competitiveness and fostering innovation (ibid).

7. Discussion

In the U.S., carbon dioxide (CO_2) emissions from the combustion of fossil fuels to produce electricity make up nearly a hundred percent of the industry's greenhouse gas emissions. Electricity generation emissions increased rapidly from 1990 to 2000 as total sector output increased, largely depending on coal and nuclear power. Beginning in 2000, the rising utilization of natural gas enabled total industrial output to expand while emissions largely remained stagnant. Amid rising economic activity since 2008, energy efficiency has kept total electricity consumption stable, while boosting natural gas and renewables replacement for coal has lowered emissions. Between 2005 and 2015, the industry's greenhouse gas emissions decreased by 20.5 percent. Since 2008, the sector has been reducing emissions at a 3 percent annual rate. The premature retirement of nuclear plants, which are being substituted with the natural gas generation, has strongly influenced the pattern toward decarbonization (Office of Energy Efficiency & Renewable Energy, 2022, 2023). Thinking forwards to 2050, electricity consumption is anticipated to rise progressively as the economy picks up and new electricity-using technologies, such as electric vehicles, become more common. Greenhouse gas emissions, on the other hand, are predicted to keep declining in the 2020s before rising to roughly current levels by 2030 and remaining basically stable through 2050. The leaders of the departments of Energy, Transportation, Housing and Urban Development, and the Environmental Protection Agency endorsed a legendary binding agreement in September 2022 to allow the four federal agencies to expedite the country's cost-effective and inclusive clean transportation future. The departments agreed to issue a detailed plan for decarbonizing transportation, which will help direct future strategic decisions in both public and private sectors (Office of Energy Efficiency & Renewable Energy, 2022, 2023).

By 2020, biomass is expected to account for approximately 20% of the EU's renewable electricity. Geothermal, on the other hand, has a low RAF throughout many EU MSs, and investing in this technology would be a step in the right direction, given its high suitability across the markers considered. While it is critical to combat climate change efficiently and successfully, it is also critical not to lose track of other environmental goals. It is conceivable that consequences will be shifted from one area (climate) to another if we do not fully comprehend how energy industry actions are connected to water governance, land use, and ecosystems. There is growing awareness that deep reductions in GHG emissions necessitate a close relationship between the long-term planning process and short-term policy interventions. As a result, Article 4.19 of the Paris Climate Agreement required countries to formulate long-term low-GHG-emissions strategic initiatives by 2020. The EU is in the process of consenting to recommendations and basic requirements to enforce this demand across all 28 EU countries (Sartor et al., 2017). Between now and 2030, developing technologies such as heat pumps in buildings, heat cascading in industry, and EVs in transportation would attain 75 percent of mitigation efforts. Although the majority of emissions would be reduced through the use of technologies, ongoing innovation will be needed to drive down transition expenses. Solar panels are an excellent demonstration of a remedy that has become much more affordable as a result of ongoing innovation (D'Aprile et al., 2020).

8. Conclusion

It is imperative to decarbonize the energy system in order to combat climate change. This includes not only specific and orchestrated plans for zero carbon phase-in but also strategies for fossil carbon phase-out. Evidently from the results, the shift from coal to natural gas in the United States, combined with improved energy efficiency measures, has led to a notable decrease in greenhouse gas emissions since 2005. As electricity consumption is expected to rise with economic growth and the adoption of new technologies like electric vehicles, it remains critical to maintain the efforts of emissions reductions through sustained investment in clean energy sources and innovative technologies. Even faster decarbonization will most likely take eons, resulting in a variable future in which the traditional, fossil-based energy system exists alongside the latest, zero-carbon energy system. Meanwhile, the European Union is also striving to enhance its renewable energy mix, with biomass and geothermal energy playing pivotal roles in achieving climate goals. Given the urgency to align long-term planning with short-term policies, this research highlighted the commitments of the Paris Climate Agreement, which emphasizes on the necessity of strategic initiatives across member states. More so, looking ahead to 2030, the successful integration of emerging technologies such as heat pumps, industrial heat cascading, and electric vehicles will be essential and play a significant role in meeting mitigation targets. As evidenced by the decreasing costs of solar panels, ongoing innovation will be vital to ensure that the transition to a low-carbon future will remain economically viable. By prioritizing comprehensive decarbonization strategies, both the United States and the European Union can effectively combat climate change while also advancing broader environmental objectives. That is, Climate adjustment must be prioritized alongside economic development, social justice, democratic values, and tranquility in global governance.

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Conflicts of Interest

The authors declare no conflict of interest. The authors declare that they have no competing interests.

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