Greenhouse gas emissions analysis for electricity generation

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Abstract: Modern society needs ever-increasing amounts of electricity as a resource. Electricity is obtained from renewable and non-renewable sources. The dilemma of greenhouse gas emissions has been raising concern among government organizations. These emissions cause intense changes in the climate, increasing the global average temperature and intensifying extreme events such as heavy rains and hurricanes. Targets to reduce greenhouse gas emissions have been established, seeking to reduce the impact of greenhouse gas emissions without slowing down the countries' economies. The energy sector is responsible for about 25% of greenhouse gas emissions, and the generation of electric energy is a part of this sector in which there is much interest in carrying out changes to increase the percentage of use of renewable sources that are low pollutant. In this work, the European plan to reduce greenhouse gas emissions will be analyzed and observed from the electricity generation point of view if the proposed objectives can be fulfilled. For analysis purposes, an analysis will be made with Brazil as it was present in this agreement. Generation data from several countries, including Brazil, were used to calculate greenhouse gas emissions. From the current results, a comparison is made between 1990 and 2020 greenhouse gas emissions and an evaluation is made assessing whether goals will be achieved.

Keywords: Power System, Generation, Carbon-neutral, Greenhouse gas emissions.

1. INTRODUCTION

The greenhouse gas emissions is a global concern of modern society (Tavassoli and Kamran-Pirzaman, 2023). One of the consequences is climate change, as the average temperature rise and increase in the sea level, end up increasing both quantity and intensity of extreme climatic events (Naranjo et al., 2011; Ibrahim et al., 2021).

Energy and transportation sectors (Junxia et al., 2018; Zheng et al., 2019) are the primary constributors to greenhouse gas emissions. Both sectors continues to rise (Tumiran et al., 2021; Nkosi and Govender, 2022), ending up increasing emissions, even if less harmful measures and technologies are being adopted. Electricity generation is directly connected with the energy sector, and to a certain extent also with the transport sector. It relies on thermal power facilities on a global scale (Yue et al., 2019), which is one of the sources with the highest emission rate of greenhouse gas.

Whether on a large scale, with the creation and expansion of new industries, or on a smaller scale, with the more significant number of electronic devices in the home, society increasingly depends on electricity and needs a greater amount (Arisoy and Ozturk, 2014; Ali et al., 2019). As much as some changes may come to directly reduce the greenhouse gas emissions, such as the transition from vehicles powered by fossil fuels to electric cars (Yan and Sun, 2021; Gai et al., 2019), the problem is not mitigated if the energy supplied is generated through generation sources with high greenhouse gas emissions.

To get around this problem, several countries have been setting goals and signing agreements to reduce greenhouse gas emissions (Lima et al., 2008; Kim and Jeong, 2018). Academic research also tries to make previsions and find electricity generation mixes to alleviate this problem (Chambile et al., 2020). For example, Europe has the 2030 Climate Target Plan (IPCC, 2022). Using as reference the 1990 values, its main objectives are to cut greenhouse gas emissions by at least 55% by 2030, limit the rise in global temperature to 1.5°C and achieve climate neutrality by 2050. The 2015 Paris Agreement collected the signature of 196 countries with similar objectives.

For example, Industry, electricity and transport sectors are responsible for 75% of greenhouse gas emissions in United States (Agency, 2023) in 2021. In Europe, the transport and storage sectors have a smaller influence, leaving the impact of the electricity and manufacturing sectors to be the most relevant (IPCC, 2022; eurostat, 2023).

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In the 2020 world energy matrix, 85% is generated by non-renewable sources (oil and derivatives, natural gas, mineral coal) and only 15% from renewable sources (hydro, solar, wind). It should be noted that renewable sources also emit greenhouse gases, even if in smaller quantities. The situation in Brazil is better, with 51.6% generated by non-renewable sources and 48.4% by renewable sources (de Pesquisa Energética EPE, 2022).

Considering only electricity generation, thermal power plants powered by coal, oil and natural gas dominate globally. Renewable sources add up to just over 20% of the electrical matrix. However, Brazil generates more than 80% of the electricity consumed in the country through renewable sources, against just over 28% in the world (de Pesquisa Energética EPE, 2022; Jones, 2022).

This research used the generation data of different European countries to estimate greenhouse gas emissions. In contrast, the Brazilian electricity matrix will be analyzed for comparison purposes. These analyses will assess whether the trend is really towards reducing greenhouse gas emissions and whether the stipulated targets will be achieved. The case of Brazil will be analyzed similarly, considering that the objective is the same.

Section 2 presents the data used in this work, describing how these data were obtained and how they will be handled. The form of calculation and values adopted for calculating the greenhouse gas emissions will be presented, as well as justifications and references. Section 3 presents the analysis results done using the generation data, including an analysis of the evolution of the electrical matrix and, consequently, the greenhouse gas emissions for the data referring to the countries analyzed. Section 4 summarizes the results achieved and what they mean. In addition, a brief analysis of possible contributions and future work based on the results presented will be made in this section.

2. MATERIAL AND METHODS

This research used generation data from power plants in eight countries: Brazil, France, Germany, the United States, the United Kingdom, Japan, Norway and Australia. These countries were chosen considering countries with different socioeconomic characteristics but with a stable or developing economic base. Another relevant point is the availability of generation data, especially considering the purpose of this work.

Several sources of electricity generation data were used, some of which were effectively used for analysis and others to verify the results achieved. For Brazil, "Operador Nacional do Sistema" (ONS), "Ministério de Minas e Energia" (MME) and "Empresa de Pesquisa Energética" (EPE) were the primary source of data. For Europe, Americas, Asia and Oceania countries, "European Network of Transmission System Operators for Electricity" (ENTSO-E) and "International Energy Agency" (IEA) information were used.

Due to the use of different data sources, different scales of time and units of power and energy were found. Therefore, it was necessary to standardize the data. For generation by sources, the information will be presented in gigawatt/hour(GWh) and the total generation in terawatt/hour (TWh). For CO_2 emissions, the scale adopted is tons (tCO2eq/KWh).

In this research, thirteen electricity generation sources were used: Coal (peat, oil shale and other similar uses, such as brown coal/lignite), Oil, Natural Gas, Biofuels, Hydro (pumped storage, run-of-river and poundage and Water Reservoir), Solar Photovoltaic, Wind (Onshore and Offshore), Solar Thermal, Geothermal, Waste, Nuclear, Tide and Others (all other possible sources, such as chemical heat).

The period of analysis was from 1990 to 2020. Tab. 1 presents data availability for each generation source by country. Darkened cells indicate the availability of data pertaining to this generation source. Some generation sources did not have data for any of the years analyzed in this work. For calculation purposes, it was assumed that there was no generation for these sources in the specific year where there is missing data for the respective country. For example, no information about wind generation was found for Brazil between 1990 and 1995.

Table 1. Electricity Generation Sources available data per country. The cells in the table represent electricity generation from that source for that country. Darkened cells represent that data referring to this generation source is available. The interpretation of the abbreviations is as follows: BRA for Brazil, FRA for France, DEU for Germany, USA for United States of America, GBR for United Kingdom, JPN for Japan, NOR for Norway and AUS for Australia.

	BRA	FRA	DEU	USA	GBR	JPN	NOR	AUS
Coal	■	■	■	■	■	■	■	■
Oil	■	■	■	■	■	■	■	■
Natural Gas	■	■	■	■	■	■	■	■
Biofuels	■	■	■	■	■	■	■	■
Hydro	■	■	■	■	■	■	■	■
SolarPV	■	■	■	■	■	■	■	■
Wind	■	■	■	■	■	■	■	■
SolarThermal				■				■
Geothermal		■	■	■		■		■
Waste	■	■	■	■	■	■	■	
Nuclear	■	■	■	■	■	■		
Tide		■			■			
Other	■	■	■	■		■	■	

One way to calculate CO_2 emissions from electricity generation sources is by converting grams of CO_2 per kilowatt/hour generated. Eq. 1 shows how this research calculates this variable. Also, the values used for the greenhouse gas emissions for each source of electricity generation are presented. These values were chosen considering some references, such as Fiorini and Aiello (2018), Life Cycle Assessment of Electricity Generation Options from "United Nations Economic Commission for Europe" and reports from "Intergovernmental Panel on Climate Change" (IPCC). Units presented in this equation are grams for CO_2 and KWh for electricity generation.

$$\begin{aligned} CO2_{Country} = {} & Coal * 800 + Oil * 520 + NaturalGas * 350 \\ & + Biofuels * 230 + Hydro * 24 + SolarPV \\ & * 45 + Wind * 12 + SolarThermal \\ & * 45 + Geothermal * 45 + Waste * 690 \\ & + Nuclear * 11 + Tide * 15 + Other * 247 \end{aligned} \quad (1)$$

Some generation sources do not emit greenhouse gas directly in the production of electricity, but the need for maintenance and operation ends up adding to greenhouse gas emissions. These aggregated values are present in the values considered for the calculation.

In Section 3, some generation sources will be highlited, exemplifying non-renewable and renewable sources. Non-renewable sources such as coal and oil come from sources that will eventually run out, as it takes thousands or millions of years to renew these resources. Renewable sources, as the name says, are sources that will not run out. They use natural resources and renew themselves. The impact of greenhouse emissions from these sources is almost always low or zero, and the values considered involve other factors that involve this type of electricity generation.

Although renewable energy sources have positive effects on greenhouse gas emissions, several other factors actually work against them. For example, the use of land is much higher than other sources, which impacts the fauna and flora of the places where this type of power plant is installed. Sound and visual impacts are other factors to consider for this type of source.

Renewable sources generally have low or zero greenhouse gas emissions. However, when considering factors such as material production and transportation, construction, operation and maintenance of the power plants, decommissioning and dismantlement, it is not possible to say that it is a totally carbon-neutral source.

3. RESULTS AND DISCUSSION

This section presents the achieved results of this research, and a discussion about them is made. The selected countries' electricity generation matrix from 1990 to 2020 is calculated. With this information, the total emissions of CO_2 are calculated. For the calculation, only electricity generation is considered.

At first, the organization of the data was carried out. Zero values replaced the missing data from some generation sources. The electricity generation sources by each country were identified. Gathering data from different sources and checking their coherence was the last step, verifying the scale of generation values and percentage of each source in the composition of the electrical matrix of each country. It is important to emphasize that the data used are only from the internal generation of each country, not considering possible imports to supply the demand.

Considering all the factors and the proposed analysis, it was decided to work with data on an annual scale. Data at smaller scales were converted to this format. 2020 was the last year where there was data available for all countries chosen for this work to do the pretended analysis.

For each generation source, data for each country was calculated by year. Fig. 1, 2, 3, and 4 show how this data looked after filtering and conversions.

Electricity Generation matrices can be analyzed considering renewable sources and non-renewable sources. As shown in the values presented in Eq. 1, these type of source

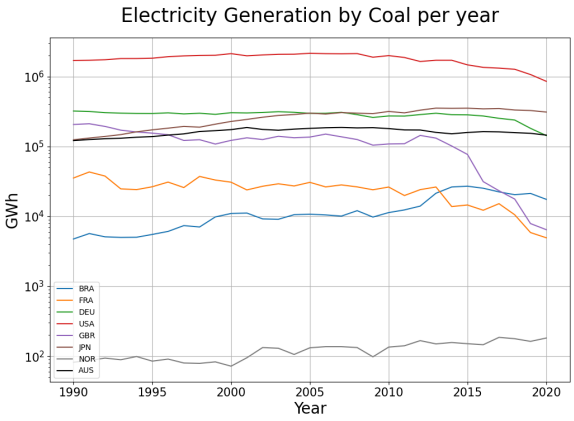


Figure 1. Electricity generation using coal by year per country. Axis Y is in log scale and represents the electricity generation in gigawatts/hour. The abbreviations are interpreted as follows: BRA for Brazil, FRA for France, DEU for Germany, USA for the United States of America, GBR for the United Kingdom, JPN for Japan, NOR for Norway and AUS for Australia.

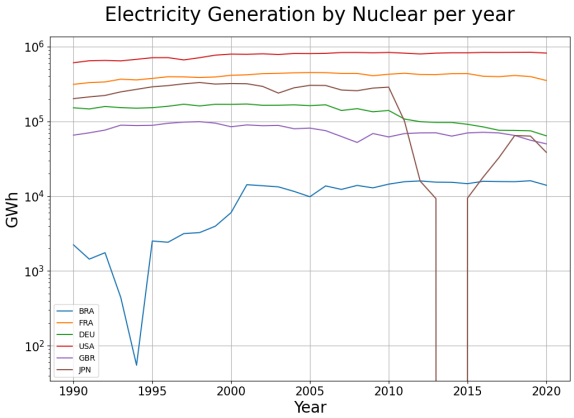


Figure 2. Nuclear generation by year per country. Axis Y is in log scale and represents the electricity generation in gigawatts/hour. The abbreviations are interpreted as follows: BRA for Brazil, FRA for France, DEU for Germany, USA for the United States of America, GBR for the United Kingdom, JPN for Japan, NOR for Norway and AUS for Australia.

is mainly responsible for the greenhouse gas emissions in the production of electricity.

Taking coal, for example, in Fig. 1, it is possible to observe that in terms of generation values, it is one of the most used sources globally. However, the United States, the main country that uses this source, has been considerably reducing production through this means (49.65% in 30 years), considering the quantities used of this resource in the generation of electricity. The United Kingdom (96.87%) and France (86.04%) are another countries reducing coal use considerably in the last three decades. On the other hand, Japan kept the rate of use of nuclear power plants constant from 1990 until around 2010. However, in the last decade it has been slowing down production by this means.

Nuclear energy is a particular case because it is not renewable energy, but part of the resources used can be recycled. However, as much as it is a practical form of generation, with little environmental and spatial impact in

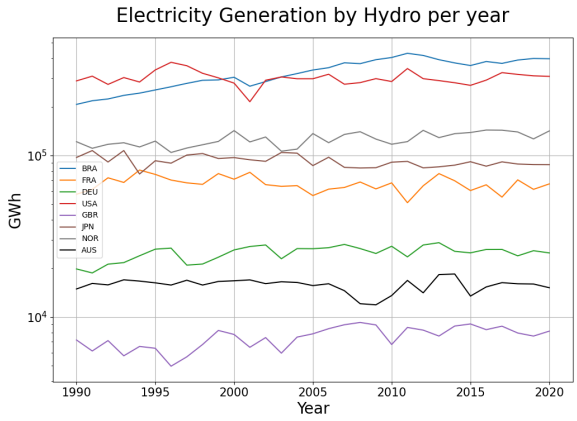


Figure 3. Hydroelectric generation by year per country. Axis Y is in log scale and represents the electricity generation in gigawatts/hour. The abbreviations are interpreted as follows: BRA for Brazil, FRA for France, DEU for Germany, USA for the United States of America, GBR for the United Kingdom, JPN for Japan, NOR for Norway and AUS for Australia.

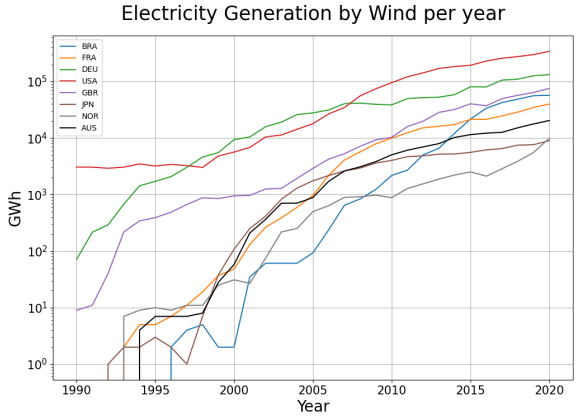


Figure 4. Wind generation by year per country. Axis Y is in log scale and represents the electricity generation in gigawatts/hour. The abbreviations are interpreted as follows: BRA for Brazil, FRA for France, DEU for Germany, USA for the United States of America, GBR for the United Kingdom, JPN for Japan, NOR for Norway and AUS for Australia.

terms of construction, discarding its non-recyclable waste and the danger presented in case of failures is a primary concern. Not all countries considered in this study use this source, but those generated from nuclear power plants showed slight variation in the values produced by this source. The exception is Japan, which drastically reduced its use due to accidents in some plants due to atmospheric events.

Hydroelectric plants and wind turbine farms are some of the most used renewable sources. Fig. 3 and 4 show the electricity generation by these sources. For hydro, some variations are presented in generation and for most of the analyzed countries, it can be deduced that the installed potential has not changed so much. The only exception is Brazil, which shows constant growth in the use of this source of electricity generation. However, due to the nature of this method, water availability in the plants' reservoirs needs to respect a minimum value. Therefore, in drier years, generation is lower. In addition, as the planning, in particular, for this source, is carried out in advance, the generation may be lower if the prediction of the amount of rain is wrong.

Energy wind onshore and offshore farms is another fundamental element to achieving a carbon-neutral network. In Fig. 4, it is possible to verify the significant investment in this source, being able to highlight the growth in the use by the United States and Germany from 1990 to 2020, that was 11048.66% and 185959.15% respectively.

In Fig. 5(a), the total electricity generation by year is presented. Although almost all countries show a positive variation in the total electricity generated during the analyzed period, the increase in the United States and Brazil stands out. In comparison, in 5(b), the CO_2 emissions for electrical. Japan stands out negatively, having considerably increased greenhouse gas emissions in the last decade. Considering the choice for the drastic reduction in the use of nuclear power plants, it is possible to state that sources with high greenhouse gas emissions are supplying the demand. On the other hand, as a positive example, the United States has been drastically reducing the CO_2 emission values, even increasing its electricity production.

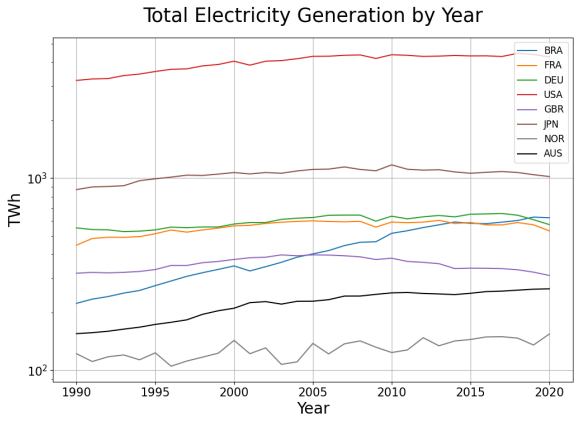
Assuming the values of 1990 as the initial reference, the year-by-year percentage variation in CO_2 emissions are presented in Fig. 6. Although on different scales, all countries showed significant variation in this period, with increasing and decreasing emissions. As the necessity of electricity as a resource is still increasing due to the continuous increase in demand, the decarbonization of the system can be a slow process.

As discussed previously, European countries have been establishing targets for decarbonizing the system, seeking climate neutrality by 2050. One of the current goals is to reduce greenhouse gas emissions by 55% by 2030 in reference to 1990 emission values. In Fig. 7, the percentage variation between CO_2 emissions in 1990 and 2020 is shown. All European countries showed a reduction in the results achieved, with the United Kingdom being very close to reaching this goal. It should be noted that the targets involve greenhouse gas emissions by all means, including other areas such as transport and industry. On average, the electricity generation area represents only 25% of the greenhouse gas emissions.

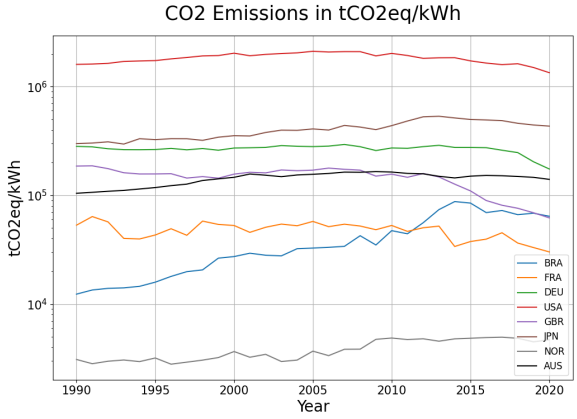
Another interesting result is to observe the reduction in emissions from the United States, given that it is one of the world's largest producers and consumers of electricity due to its population and economic development.

On the other hand, Brazil presented more than 400% increase in CO_2 emissions. Despite being an understandable result due to being a developing country and with a continuous increase in the necessary demand, there is no evidence indicating a slowdown in greenhouse gas emissions according to the results shown in Fig. 6.

However, even in electricity generation, the large percentage of renewable and low greenhouse gas emissions sources in the electrical matrix is a very positive factor. Allied with this, other sectors such as transport also have a good



(a)



(b)

Figure 5. Total Electricity Generation in terawatt/hour by year for the eight countries analyzed (a). Total CO_2 emissions in tons per kilowatt/hour per year (b). The abbreviations are interpreted as follows: BRA for Brazil, FRA for France, DEU for Germany, USA for the United States of America, GBR for the United Kingdom, JPN for Japan, NOR for Norway and AUS for Australia.

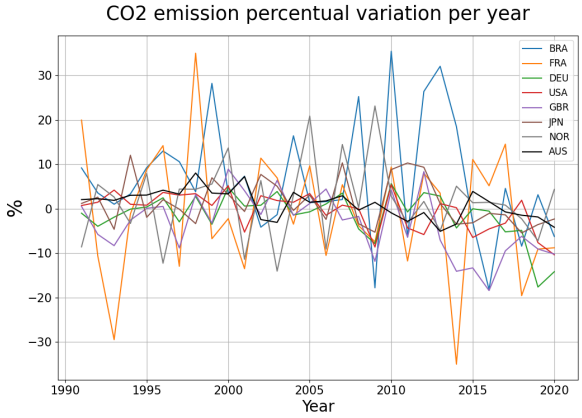


Figure 6. Variation per year of CO_2 emissions per country in percentage. The abbreviations are interpreted as follows: BRA for Brazil, FRA for France, DEU for Germany, USA for the United States of America, GBR for the United Kingdom, JPN for Japan, NOR for Norway and AUS for Australia.

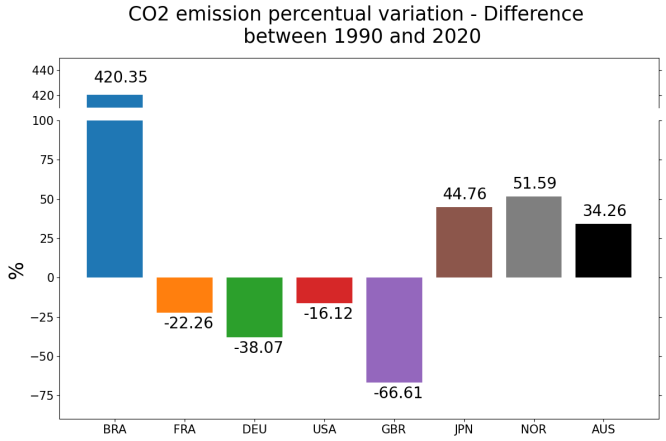


Figure 7. Variation between 1990 and 2020 for each country in percentage. The abbreviations are interpreted as follows: BRA for Brazil, FRA for France, DEU for Germany, USA for the United States of America, GBR for the United Kingdom, JPN for Japan, NOR for Norway and AUS for Australia.

percentage of using less polluting resources compared to the global average.

Considering all the results presented, a global effort is noted to reduce greenhouse gas emissions in the electricity generation sector. While non-renewable sources maintained a constant or negative production for the analyzed period, renewable sources had considerable increases.

Nonetheless, while the European countries participating in the 2030 Climate Target Plan must achieve the proposed goals, developing countries seem far from reaching a stabilization in need to increase electricity production.

4. CONCLUSION

The main objectives of this research were to compile electricity generation data from different countries and assess the CO_2 emissions by this activity. Considering the decarbonization plans by some European countries, an analysis of the results was made, showing the variation in greenhouse gas emissions between 1990 and 2020.

Some of the most used sources in the composition of the electrical matrices were analyzed individually, presenting results and discussions for the 8 countries present in the study for both renewable and non-renewable sources. While there is a tendency to maintain constant or decrease the dependence of electricity production on non-renewable sources with high greenhouse gas emissions such as coal-fired thermoelectric plants, there is an apparent increase in the use of renewable sources such as hydro and wind.

However, despite a reduction in greenhouse gas emissions by most European countries and the United States, some countries have not reduced emissions compared to 1990. In particular, Brazil has significantly increased emissions related to electricity production, even having an electrical matrix consisting mainly of renewable sources with low greenhouse gas emissions for a while.

Future works should include a complete analysis of other sectors that impact greenhouse gas emissions, such as transport. Considering Brazil, for example, it may be interesting to verify if the increase in greenhouse gas emissions

has been reduced. Including new countries, creating a more detailed analysis with countries with a large percentage of use of renewable sources in their electricity matrix or with more similar economic sectors (which directly impact the necessary demand to be produced and imported) may add a lot to this study. From Statistics, it would be interesting to use the results achieved to create forecast models, making a more realistic analysis of the plans for decarbonizing the system and advancing the use of each of the sources of electricity production.

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