

Research

## Balancing cleaner energy and geopolitical interests in the complex transition of the European electricity mix: from Fukushima to the Ukraine war

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### Abstract

In the modern world, electric energy plays a pivotal role in sustaining life and driving technological, scientific, and human development. Consequently, the selection and availability of the energy sources used for electricity generation have become crucial elements of strategic planning for countries and economic blocks. Moreover, the impact of these choices extends beyond the mere energy demand/supply, affecting economies, societies and the environment across geographical boundaries. This study delves into the various factors influencing the composition and the recent expansion of the European electricity mix. It explores the interplay of environmental, climatic, political, economic, and external factors that shape Europe's energy choices. To conduct this analysis, we utilized data from the International Energy Agency on electricity generation and GHG emissions. Data mining techniques were employed to uncover patterns and trends in the monthly data from 2010 to 2022, from which political and economic milestones such as the shutdown of nuclear power plants and the European Union's increased reliance on natural gas imports from Russia were examined. The study also discusses the impact of using natural gas for power generation on increasing GHG emissions. Ultimately, this research reveals that the European Union choices in transitioning towards a cleaner electricity mix have not yet proven efficient. In fact, these choices may have inadvertently created favorable conditions for Russia's invasion of Ukraine, triggering, not only a humanitarian crisis, but also an economic downturn in Europe due to soaring energy prices. This crisis could potentially extend beyond Europe and impact the whole planet in 2023 and on, including developing countries that rely on stable energy prices for their sustainable growth.

**Keywords** Clean energy · Climate change · Natural gas · Greenhouse effect

### 1 Introduction

In the year 2022, the consumption of electricity from all the countries in the Americas, Asia, Oceania, and Europe encompassing the Organization for Economic Cooperation and Development (OECD) reached a staggering 11,390 TWh versus 10,850 TWh consumed in 2012. This means an increase of 5% in 20 years. Despite the seemingly modest difference in relative figures,

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the observed increase amount to a substantial energy expansion of 540,000 GWh over this period. To put this into perspective, the mentioned value exceeds the combined energy consumption of Portugal, Spain, Belgium, and Greece, in the year 2022, which was close to 518,000 GWh, as observed using the data by the US Energy Information Administration (EIA).<sup>1</sup>

To meet this ever-increasing demand, electricity generation has become a significant contributor to the planetary degradation and greenhouse gas (GHG) emissions. The release of GHGs into the troposphere intensifies the global greenhouse effect, disrupting the Earth's natural climate balance [1, 2]. According to the International Energy Agency (IEA) estimates for 2020, power generation of all OECD countries (from all sources) accounted for 11.085 million tonnes of CO<sub>2</sub> eq, while non-OECD countries (with some major oil and gas producers, such as Russia and the Middle East countries, included here) contributed around 23.446 million tonnes of CO<sub>2</sub> eq.

However, a comprehensive analysis of the life cycle of electricity generation, including seemingly cleaner and renewable such as geothermal, hydro, wind and solar, reveals varying degrees of environmental degradation at different stages (installation, operation, or disposal) [1–3]. Importantly, studies that consider the life cycles of generation sources often underestimate the impact of vegetation suppression during installation, and the subsequent loss of carbon sequestration capacity [4, 5]. This underestimation means that the contribution of electrical generation, regardless of the source, to the intensification of the planetary greenhouse effect may be greater than currently believed. Moreover, the benefits of power generation from natural gas, compared to other fossil fuels such as coal, are subject to significant controversy, particularly when considering the whole cycle, including extraction and transport [6–8].

Given the indispensable nature of energy production for all activities in the contemporary world, and at the same time knowing that any source of generation will at some point causes damage to the environment, attention must always be focused on technologies and sources that have less environmental impact, to mitigate the on ongoing climate change and its adverse effects on the planet.

In the overall, the selection of an electricity mix for a country or economic block should be guided by several pillars, including technological efficiency, societal impact, economic viability, the security of the service, and environmental considerations, and should be thought in a context of climate change. Climate change, with its devastating and abrupt consequences, may disrupt the availability of natural resources used for energy generation [9] and affects the patterns of energy demand. Such disruptions have already been observed in the form of heat waves, droughts, unprecedented wildfires, and other extreme events hitting all regions around the globe [10–15].

Nonetheless, the process of generating electricity carries additional societal implications, beyond the direct environmental impact, intertwined with its entire life cycle. Catastrophic incidents occurring in nuclear power plants, like the Fukushima disaster in 2011, the bursting of dams in reservoirs regulating power generation, accidents associated with oil exploration, explosions in gas pipelines, and similar occurrences, can directly endanger the lives of thousands of people, resulting in irreparable environmental, social and economic consequences [16–19].

Furthermore, spotlights have recently been directed towards the energy mix of OECD Europe, as it potentially holds an indirect yet significant link to the Russian invasion of Ukraine [20–23].

Therefore, this paper aims to delve on the expansion of European electricity mix over the past two decades, with a specific focus on its interconnections with events such as the Fukushima Tsunami, the Ukraine war, the global climate change, the recent energy-related protests in Europe (including those against wind power deployments), and its potential economic and social implications for the entire planet.

## 2 Understanding the European energy market

Europe is not a homogeneous entity, but it relies on a robust regulatory mechanism. The EU has set four main goals to develop its internal energy market, preserve and improve the environment, and promote renewable energy sources. These goals include ensuring the functioning of the energy market, guaranteeing energy supply security, promoting energy efficiency, and saving, and fostering the interconnection of energy networks [24].

The main actors in this process are the European Union Agency for the Cooperation of Energy Regulators (ACER) and the National Energy Regulators, all bind into the Council of European Energy Regulators (CEER). To track relevant policy instruments, actions of the European Parliament through EU Directives, as well as the actions of ACER, CEER and the National Energy Agencies act to observe and identify patterns, actions plans and raising of best practices among member countries, indicating a coordinated approach to address European energy issues.

<sup>1</sup> <https://www.eia.gov/opendata/>.

Article 194 of the Treaty on the Functioning of the European Union, as amended by the Treaty of Lisbon, highlights the shared competences of the energy policy among member states; particularly in areas related to the energy transition, energy efficiency, internal energy networks interconnection and most importantly supply security, signaling a move towards a common energy policy [25].

While member states retain the right to “determine their energy resources, energy sources, and energy supply structure, the Council, rather than the Commission, holds the authority to authorize negotiations and conclude international agreements” [26].

Environmental and economic aspects, such as the taxes in the internal energy market, are also important considerations. The EU has issued directives to regulate the internal energy market, aiming to eliminate competition distortions among different tax systems and transition towards a low-carbon, energy-efficient economy to protect the environment and climate [27]. The 2020 Climate and Energy Package, also known as the 20–20–20 horizon, exemplifies the unified approach taken by the EU to address energy challenges. The package set targets for member states that should have been achieved by 2020, including a 20% reduction in GHG emissions based on 1990 levels, ensuring that at least 20% of EU energy comes from renewable sources, and improving energy efficiency by 20% [28].

Furthermore, the EU employs a strategy outlined by [29], effecting a policy change. The European Commission, as a supra national policy entrepreneur, seeks legitimacy by building on existing norms, exercises authority based on expertise, advocates for its own targets persistently, building alliances within member states, leveraging policy window opportunities during crises, and constructing a narrative on energy, as a supra national solution. An illustration of this strategy can be seen in the study done by [30], where different alternatives for Asina Natural Gas pipelines were analyzed, including the Nabuco project. Another manifestation of EU’s vision can be seen in the Energy Integration Policy, which treats one member’s problem as a concern for all. For instance, the EU regulates the internal energy market by setting taxes as in the Council Directive 2003/96/EC aiming to protect consumers and ensure affordable energy prices across Europe, albeit with limited consideration for environmental and social interests [31].

Consequently, individual member states may forfeit the possibility to increase taxes on fossil fuel to subsidize economically unsound renewable energy generation. Notably, gas supply disruptions in 2006 and 2009 prompted a shift in the perception from secure to insecure gas supply and heightened concerns about dependency on a small number of suppliers, particularly Russia. The results have been a power transfer from member states to the EU, exemplified by the case of the Caspian pipeline (in 2011) [29].

The Third Energy Package, implemented in 2009, reflects the EU’s vision of creating an open framework for common solutions adopted by all countries, in a “one fix for all” vision [32]. It involves the de-verticalization of each country’s energy-related industries (put apart supply and generation from the operation of transmission of energy), the decoupling of energy regulators from national policies and stakeholders, the establishment of the Agency for the Cooperation of Energy Regulators (ACER). Emphasis is placed on creating a European Energy Market as a solution to the internal difficulties, by the removal of cross-border barriers and fostering inter-country cooperation (thus an EU vision solution).

Understanding how energy solutions are developed, whether driven by regulation or opportunity costs, is crucial. In Brazil for instance, the growth of the photovoltaic market is driven by commercial uses rather than private housing. This new trend is not a result of the regulation or policy, but rather favorable market conditions.

On the other hand, Germany independently implemented its own liquefied natural gas station, demonstrating the country’s ability to pursue its own solutions [33].

### 3 Methodology

The methodology employed in this work consisted of three main components. Firstly, an extensive literature review was conducted to examine GHG emissions and factors influencing energy generation in Europe. This review also encompassed scholarly articles, newspaper publications, as well as legal frameworks, agreements and governments processes related to promoting renewable energy generation, and to expand the natural gas utilization and importation.

The second part of the methodology involved describing the data used in the study, which was sourced from the International Energy Agency—IEA. The IEA provides consistent, accurate and timely energy data and statistics serving as a vital resource for developing effective energy policies and long-term planning.

Finally, in order to evaluate the monthly time series of energy generation according to their source, data mining techniques were applied, such as clustering, principal component analysis, trends and Pearson correlations [34].

Overall, the methodology employed a combination of literature review, data sourcing, manipulation, and data mining techniques to gain insights into the European electricity mix expansion and its associated factors. The Python programming language served as a valuable tool for data analysis and visualization, leveraging various libraries specifically tailored for these purposes.

### 3.1 Database

The IEA Energy Data Centre offers comprehensive global energy data, including supply and demand statistics compiled into energy balances. The dataset covers a time series starting from 1971, encompassing up to 95% of global energy supply and over 150 countries. The focus is on ensuring data quality, comparability, and alignment with internationally agreed definitions and methodologies, achieved through close collaboration with national energy statistical offices and other stakeholders. This study primarily utilized monthly power generation data from 2010 to 2022, categorized by source and economic bloc, with a specific emphasis on the OECD Europe generation data. The analyzed sources included Coal, Natural Gas, Hydro, Wind, Solar, and Nuclear, excluding other sources due to their minimal contribution to the overall OECD Europe energy mix.

Furthermore, GHG emission analysis associated with coal and natural gas power generation relied on IEA data [35] available at <https://www.iea.org/data-and-statistics/data-product/greenhouse-gas-emissions-from-energy-highlight>. The analysis employed the concept of CO<sub>2</sub> equivalent (CO<sub>2</sub> eq) to account for the varying greenhouse effect potentials of different gases, with a molecule of Methane having approximately 25 times greater long-wave radiation trapping capacity than CO<sub>2</sub> [36].

### 3.2 Applying data mining techniques

The data manipulation and analysis were carried out using Microsoft Excel PivotTable and Python 3.11 algorithms. Python libraries included Pandas, Datetime, Numpy, Matplotlib, Openpyxl, Seaborn, Plotly.express and Statsmodels, which can be accessed from the Python website.<sup>2</sup>

These techniques encompassed principal component analysis, trend analysis, and Pearson correlations, aiming to uncover non-trivial patterns related to the time series of power generation by source in OECD Europe, in isolation or together. These results were complemented by graphical visualizations and secondary calculations.

Temporal decomposition seeks to establish a framework for the series that could enhance its predictability. For instance, this  $Z_t$  pattern can be derived using Eq. 1:

$$Z_t = T_t * S_t + E_t \quad (1)$$

where  $T_t$  represents the trend of the series,  $S_t$  represents its seasonality, and  $E_t$  denotes the residual or random error [37].

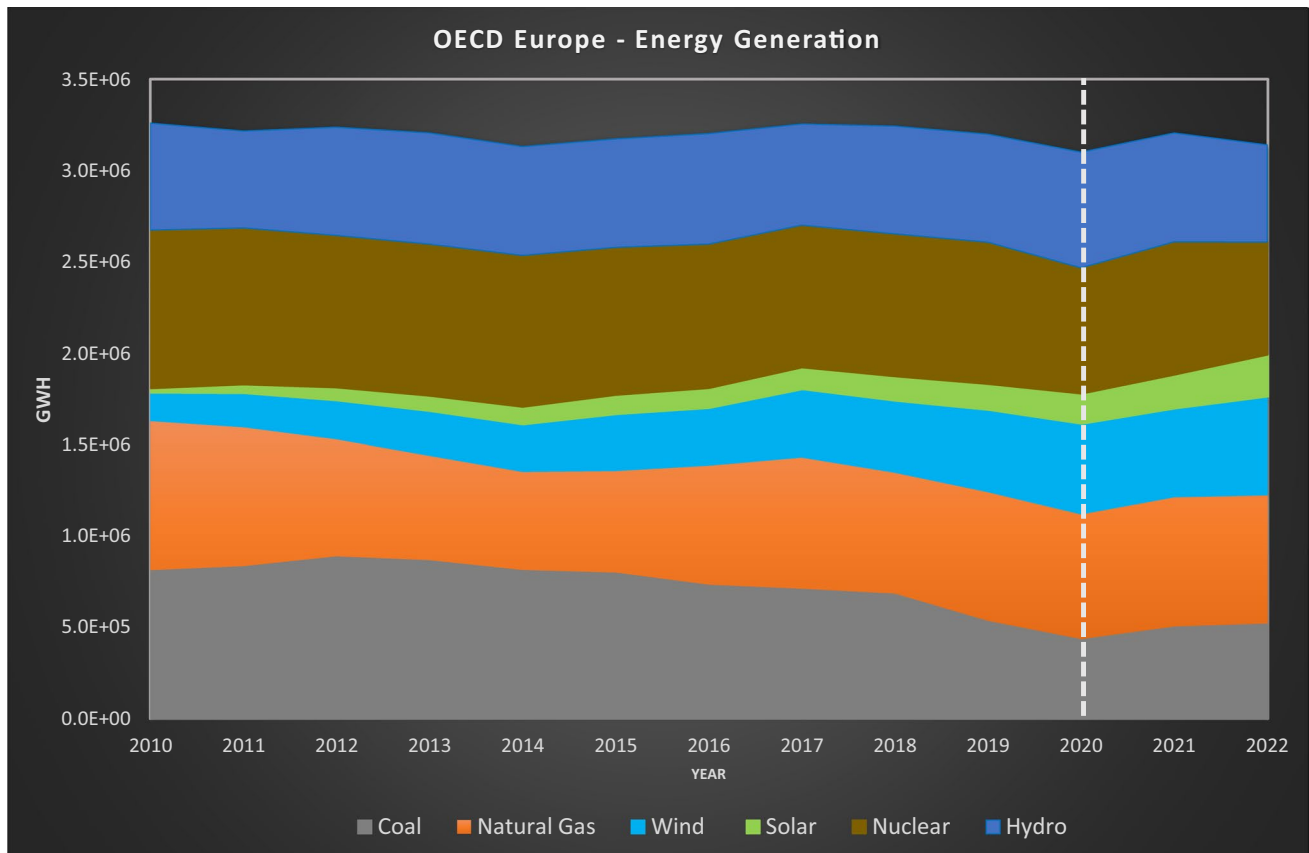
The Pearson correlation, as extensively employed for assessing the correlation of time series [38], constituted another pertinent aspect of the analyses. This correlation is elucidated by Eq. 2.

$$r = \frac{\sum_{j=1}^n (P_j - \bar{P})(O_j - \bar{O})}{\sqrt{\sum_{j=1}^n (P_j - \bar{P})^2} \sqrt{\sum_{j=1}^n (O_j - \bar{O})^2}} \quad (2)$$

The Pearson coefficient ( $r$ ) represents the correlation between two variables, denoted as  $P$  and  $O$ . The average values of these variables are represented by  $\bar{P}$  and  $\bar{O}$ , respectively.

Furthermore, an analysis of the generational series trend by energy source was undertaken, considering the cumulative differences between each source and the benchmark years of 2010 and 2016. This approach was based on the Rippl method, also referred to as the mass curve method [39], which entails consolidating the deviations in measurements for each year in relation to the reference year, resulting in an accumulation graph of variances.

<sup>2</sup> <https://docs.python.org/3/>.



**Fig. 1** Time evolution of total annual energy generation by source in OECD Europe for the period 2010 to 2022. The white dotted line indicates the year of the COVID-19 Pandemic (2020). Source of data: IEA

## 4 Results

The results section is structured into two main parts: a time series analysis examining the evolution of the electricity matrix in OECD Europe, focusing on its primary generation sources, and an analysis of the CO<sub>2</sub> eq emissions stemming from the power generation process.

### 4.1 European electricity mix data analysis

To assess the temporal evolution of the OECD Europe electricity mix in relation to its sources of generation, an analysis was conducted of the total annual generation by each source from 2010 to 2022 (Fig. 1). The analysis reveals several trends.

Wind generation shows a significant increase, followed by a relatively less significant increase in solar generation over the period. Hydroelectric generation remains relatively constant, with low variability considering these are annual totals where seasonal variations are filtered out.

Nuclear generation experienced a small decrease in 2012 compared to the previous year, which may reflect the shutdown of some nuclear plants after the tsunami that hit the Fukushima plant in Japan [40, 41]. The generation from this source remains stable, with slight declines in 2015, 2016 and 2020, possibly influenced by the COVID-19 pandemic<sup>3</sup>. [42]. The highest rate of decrease since 2010 is observed in 2022 primarily due to the shutdown of nuclear power plants in Germany that began during this year. This occurred ten years after the disaster of Fukushima and despite the limited availability of natural gas for power generation from Russia, and in liquefied form, which lead to increased energy prices and difficulties in meeting demand in Germany [43, 44]. It is important to note that the reduction in the generation of energy by nuclear sources does not significantly contribute to reducing the emission of GHGs, since during the operation

<sup>3</sup> <https://www.iea.org/reports/covid-19-impact-on-electricity>.

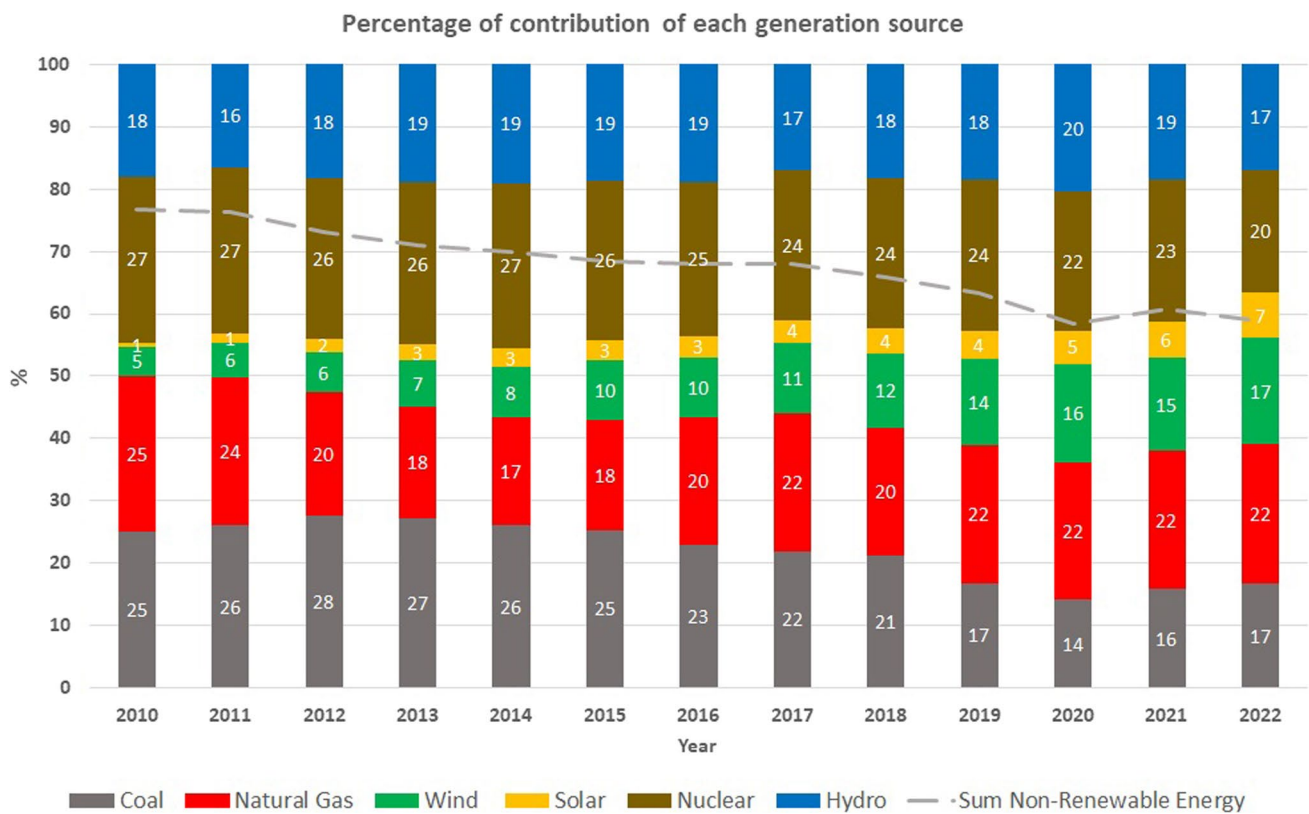


Fig. 2 Distribution of generation contribution by energy source in OECD Europe for the period 2010 to 2022. Source of data: IEA

phase of the nuclear power plant, its greenhouse gas emissions are practically zero. Therefore its generation could be part of the decarbonization plan of the European electricity mix [45].

Coal-fired generation starts to show signs of decline in 2015/2016, with a more pronounced fall between 2018 and 2020. It experiences a small increase in generation after the pandemic, in the years 2021 and 2022.

Natural gas generation exhibits a peculiar behavior, with a significant drop from 2010 to 2014, remaining stable in 2015, followed by a significant increase again in 2016 and 2017. Then it returns to almost the same generation levels as in 2011; remaining at this level until the end of 2022, despite the invasion of Ukraine by Russia (the main supplier of natural gas for Europe) in February of that year [46].

Figure 1 illustrates that, except for the year 2020, which was impacted by the COVID-19 Pandemic, in all remaining years the total generation from all these non-renewable sources, has exhibited a relatively stable trend.

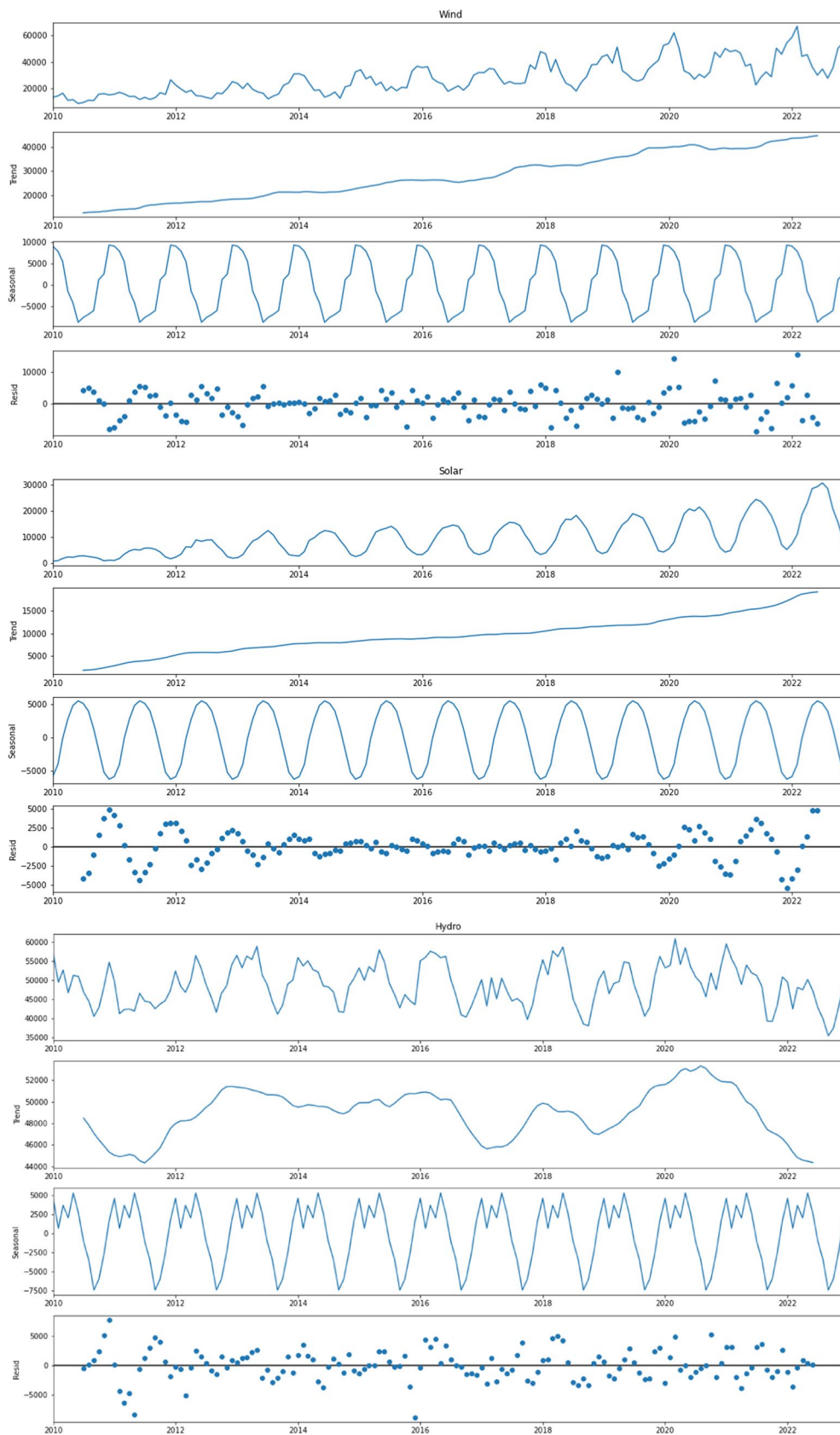
In summary, the analysis reveals the increasing prominence of wind and solar generation in the OECD Europe electricity mix, the stability of hydroelectric generation, and fluctuations in nuclear, coal, and natural gas generation.

To further illustrate the above insights, Fig. 2 depicts the temporal evolution of each energy source's relative contribution to the electric matrix of OECD Europe between 2010 and 2022, exclusively considering their generation. Prior to 2015, the contribution from the burning of natural gas experienced a decline, reaching its lowest percentage of 17% in 2017. However, from 2016 onwards it started to rise again, reaching a contribution of 22% in 2022, only 3% less than in 2010. Notably, an increase contribution of solar and wind energy can be observed, which in conjunction with the reduction in coal-based generation, contributed to the decrease in the percentage of generation from non-renewable sources from 77% in 2010 to 59% in 2022.

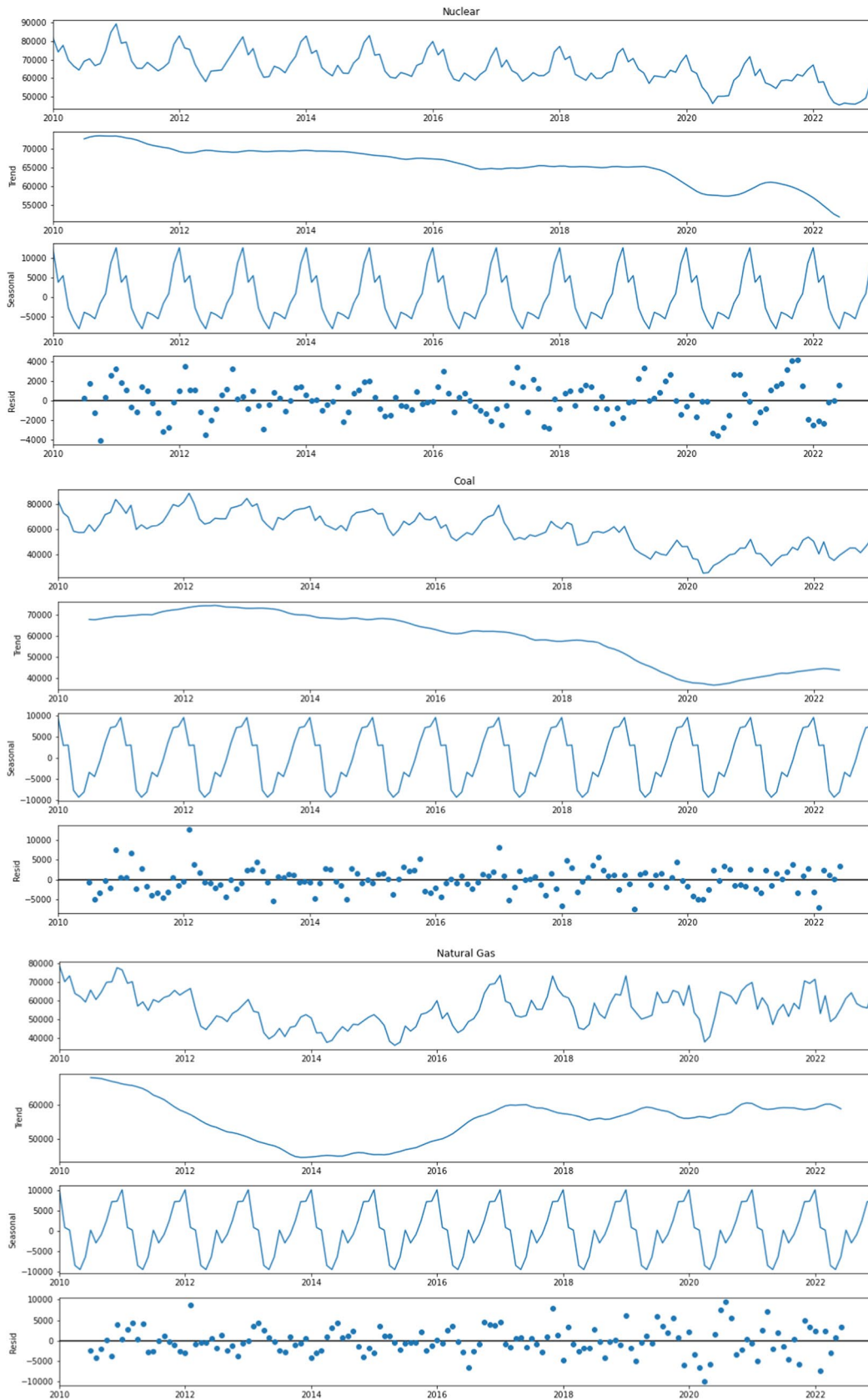
#### 4.1.1 Time decomposition of power generation series

To make a more detailed evaluation, a time decomposition of the monthly generation series of OECD Europe was made, by source, grouped in Fig. 3 for renewable generation sources (Wind, Solar and Hydro) and Fig. 4 for fossil generation sources (Nuclear, Coal and Natural Gas).





**Fig. 3** Time decomposition of OECD Europe's monthly generation by generation source from 2010 to 2022 of Wind (top), Solar (middle) and Hydro (bottom) generation



**Fig. 4** Time decomposition of OECD Europe's monthly generation, by generation source, from 2010 to 2022 of Nuclear generation (top), derived from coal burning (middle) and Natural Gas burning (bottom)



The results reveal distinct seasonal patterns for renewable and clean energy sources, particularly wind, solar, and hydro generation. Although both wind and solar show a steady growth march in the generation of solar and wind energy sources, practically constant, since 2010, wind generation has experienced a significantly higher growth rate compared to solar generation. Seasonally, solar generation exhibits, as expected, a pronounced cyclic behavior, like a normal distribution, with minimum in winter and maximum in summer, the opposite to the wind pattern. Notably, while the maximum solar generation has nearly tripled since 2012, the minimum seasonal solar generation has remained relatively unchanged over time. This suggests that solar expansion may be occurring in regions with limited solar radiation throughout the year, resulting in a reduced contribution from this source.

Hydroelectric generation, distributed across different regions of Europe, does not present any discernible trend in its availability for generation, except for a slight decrease in 2021 and 2022. This decrease may be attributed to the severe drought that affected Europe during this period, as discussed by [47].

Figure 4 presents the time decomposition of monthly generation for non-renewable sources, namely nuclear, coal, and natural gas. These sources present a certain degree of seasonality, with higher generation during the boreal winter. This seasonal pattern is associated with the complementary nature of non-renewable sources to the renewable generation sources, except wind power, which also peaks in winter). The increased energy demand during this time of the year in Europe contributes to the observed seasonal pattern.

An analysis of the annual generation trends reveals a downward trend in nuclear and coal-based sources over the last decade, with a more pronounced decline since 2019 for coal and since 2020 for nuclear. Additionally, there was a decrease in natural gas-based generation from 2013 to 2016, followed by an increase that brought the generation levels back to nearly the same values as in 2012 by 2022.

When analyzing the noises of the temporal decompositions, it can be seen that the solar and wind generation noises show a seasonal behavior both at the beginning and at the end of the time series. This behavior shows that this decomposition was not able to fully eliminate the trend of the series, requiring the application of another method for these statistical analyses, as will be shown further on.

#### 4.1.2 Analysis of power generation trends

To further analyze the evolution of the OECD Europe electricity mix, the reference years of 2010 (Fig. 5) and 2016 (Fig. 6) were examined. These analyses aimed at confirming the observed trends in the time series data and highlight the year 2016, which marked a crucial point for the resurgence of natural gas-based generation in OECD Europe.

Figure 5 shows a very promising trend towards cleaner energy generation, with an almost progressive decrease in all non-renewable and/or dirty sources such as coal, natural gas and nuclear. Conversely, there has been an increase in the generation of cleaner renewable energies, particularly solar and wind, while hydroelectric generation has been maintained. In fact, several studies have highlighted that hydroelectric power is over exploited in Europe, particularly when environmental constraints are considered, e.g. [48], hence an upward trend was not and should not be expected.

However, when assessing the trend in energy generation based on the year 2016 in OECD Europe (Fig. 6), a significant increase in natural gas-based generation is observed, comparable to the growth of solar generation that year. On the other hand, the decline in coal-fired generation becomes more pronounced from 2019 onward, remaining practically constant until 2022.

Monthly averages of the generation from each source, computed for the entire period spanning from 2010 to 2022 (Fig. 7), revealed higher values during the winter period, except for solar power. This can be attributed to a larger energy demand experienced by thermal plants, and the greater intensity of wind and rainfall, in this season, which benefits wind and hydroelectric plants. Conversely, solar generation exhibits a higher generation during summer and lower during winter, building on the complementary nature of, in particular, wind and solar electricity generation [49–52].

This aspect holds significant importance when considering a renewable energy matrix for OECD Europe. If solar generation expands in the future, it can play a complementary crucial role alongside other renewables sources, mitigating the need for substantial thermal generation to supply sudden fluctuations in energy demand. Such fluctuations present a great challenge in achieving a renewable electricity matrix [53, 54].

However, given that that Europe has regions with ample solar radiation all year-round, this finding raises questions about the optimal deployment of solar generation resources. Optimal sitting of variable renewable energies facilities is crucial to guarantee the efficiency and safety of the energy transition aimed at achieving and, importantly, maintain net greenhouse gas neutrality. However, it should be thought in a comprehensive rather than individual or local way.

**Temporal evolution of the accumulated generation differences - reference 2010**

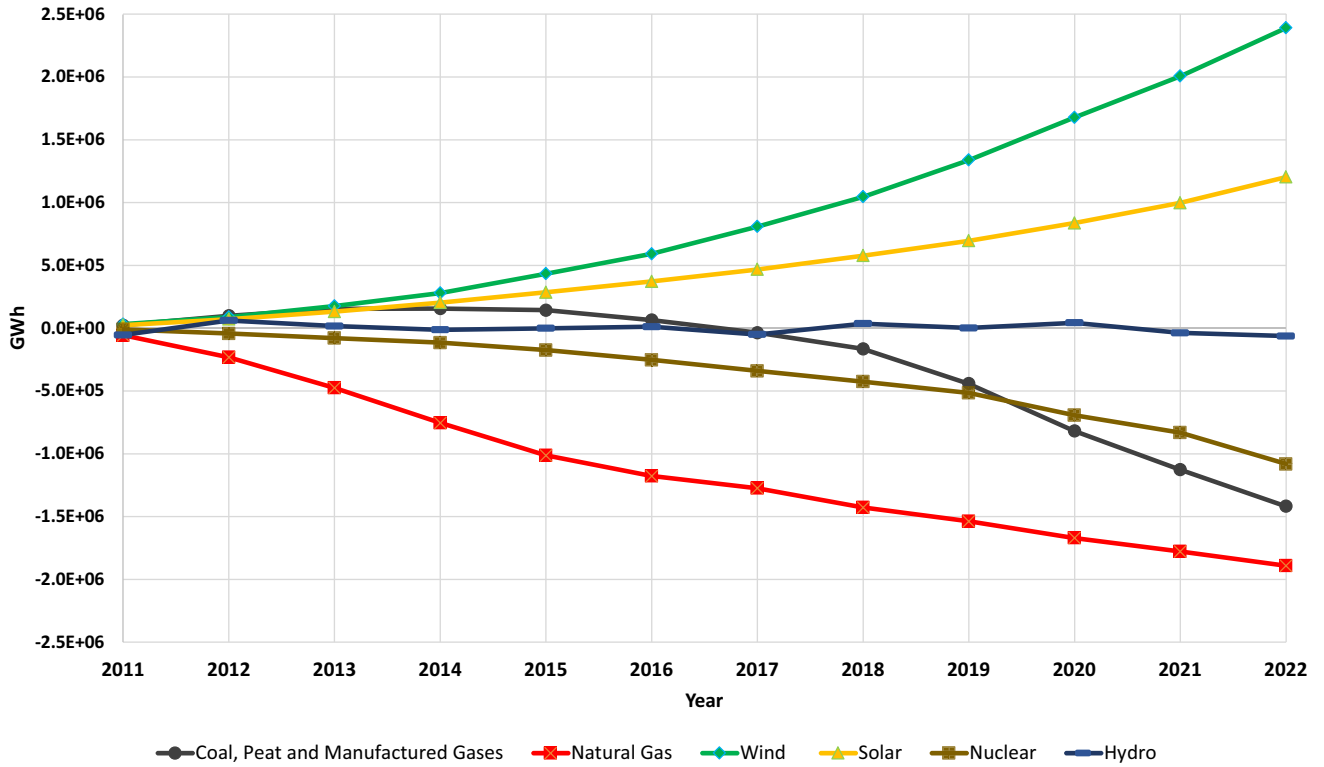


Fig. 5 Annual time series trend of power generation, by source, in OECD Europe based on the year 2010. Source of data IEA

**Temporal evolution of the accumulated generation differences - reference 2016**

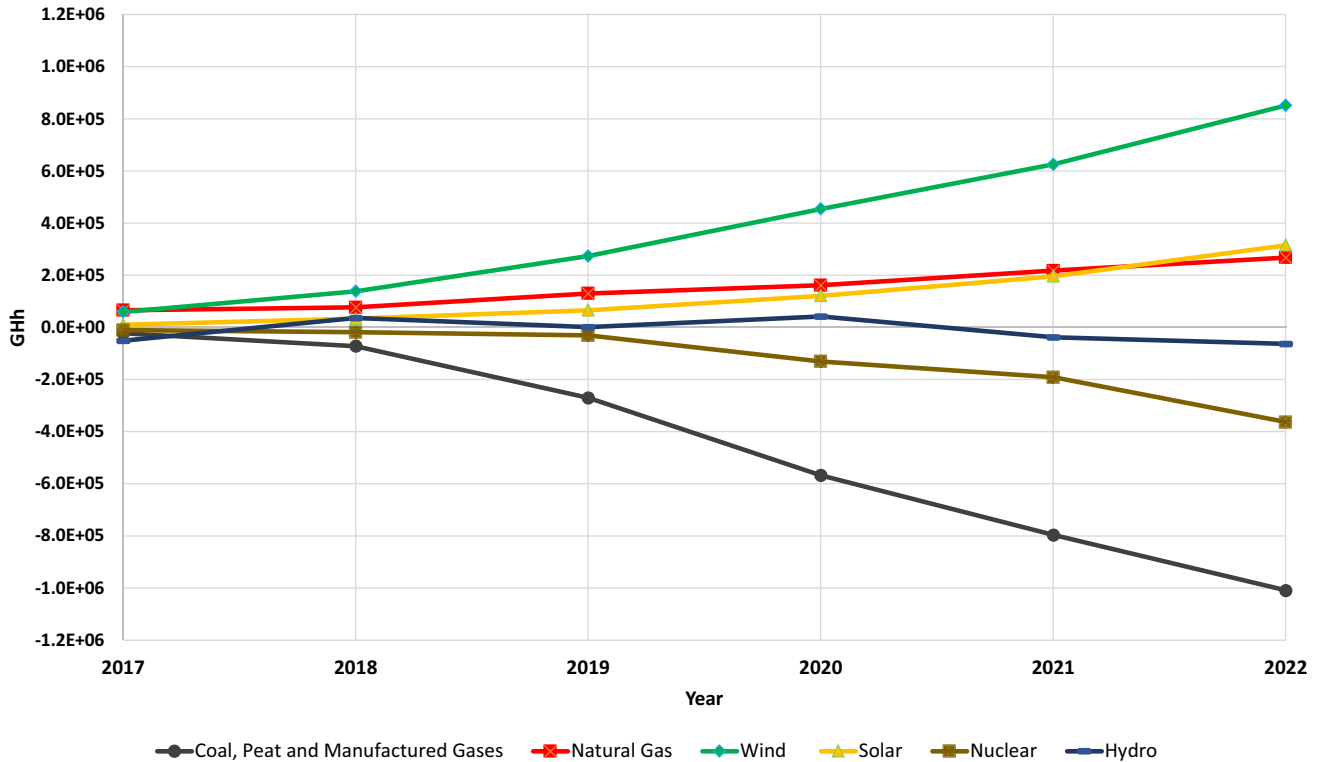


Fig. 6 Annual time series trend of power generation, by source, in OECD Europe based on 2016. Source of data IEA

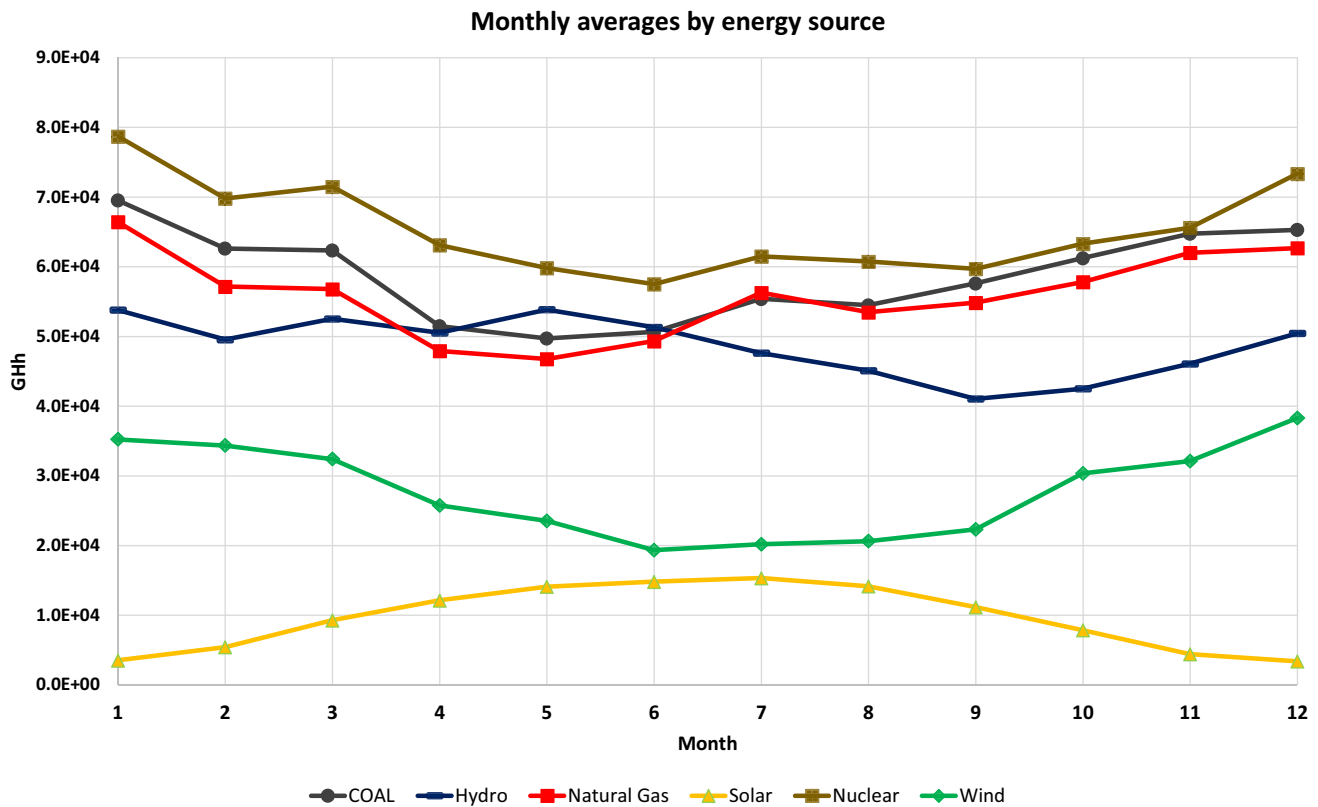


Fig. 7 Average monthly electricity generation for each energy source from 2010 to 2022 in OECD Europe. Source of data IEA

Therefore, it must do not only with high-capacity factors (of a single resource at a particular location), but also with the capability (of the whole system) to guarantee the supply under different weather situations. In this sense, several works, focused on balancing productivity and stability, came to the general conclusion that wind and solar powers are called to play, jointly, a decisive role [50, 55, 56]

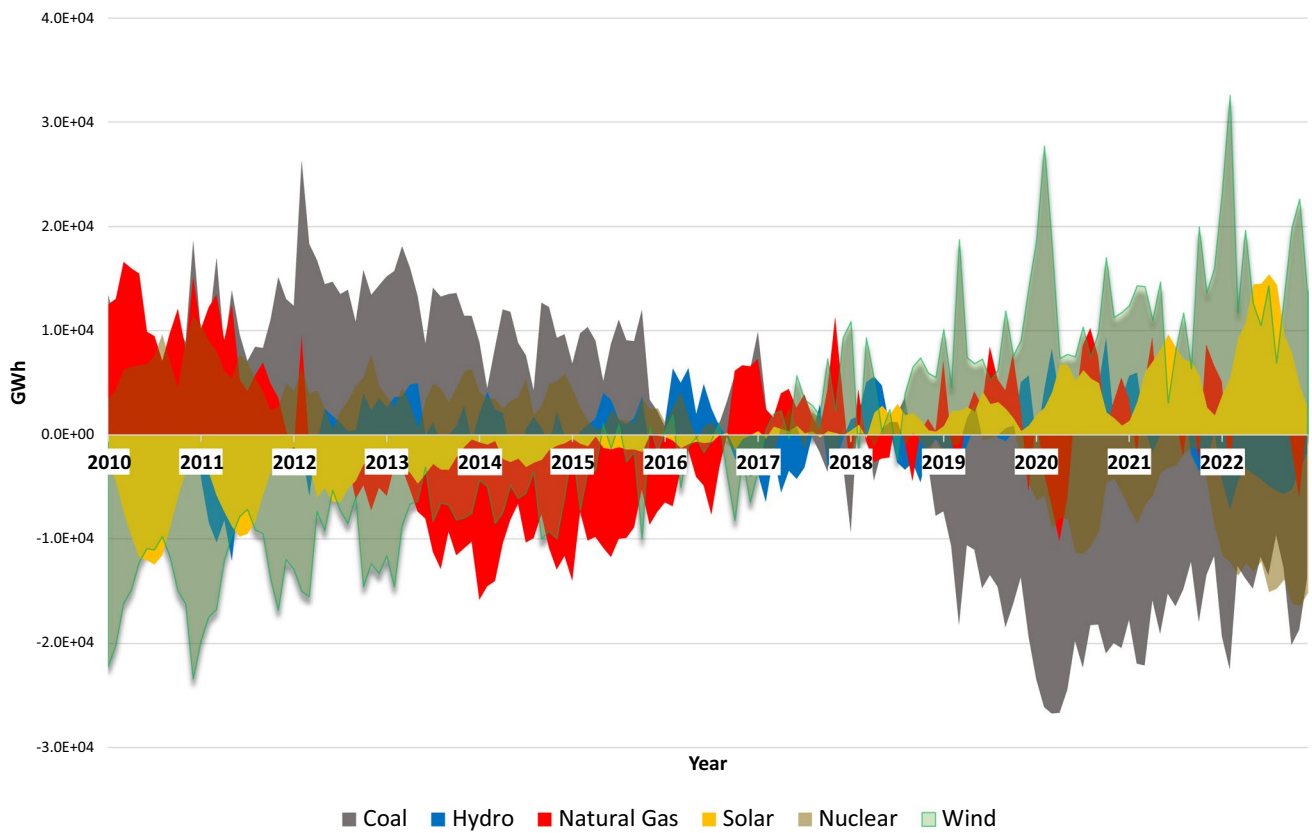
Subsequently, Fig. 8 displays the difference of each source's monthly generation with respect to its monthly average. It is important to note that these differences follow the trend of the series that have a trend, as is the case of coal, wind and solar. In the case of natural gas, it is observed that the trend of these differences was negative from 2010 to 2016. Then these differences become positive, corroborating what has already been shown regarding the increase in natural gas generation, starting in 2016.

Another important point is that the variation of generation in relation to the average of hydroelectric and nuclear plants is much smaller than that of the others, except in the years 2021 and 2022, when significant negative differences appear in nuclear generation, due to the shutdown of nuclear plants in Germany. The fact that the variability of the hydraulic generation be small is important, since it accredits this type of generation to be considered with a more stable generation, among the renewable ones, and that, due to its fast operational response. This means that in a future renewable matrix of OECD Europe, the hydro generation that could attend the large fluctuations in energy demand as is currently the case in Brazil, where thermal generation (conventional, biomass and nuclear) was limited to less than 11% during the month of April 2023, with all other generation based on renewable sources, such as solar, wind and hydro.<sup>4</sup>

To complement the study of the time series variability, the series trend was removed. For this process the monthly generation of each generation source was subtracted by its annual average generation. And then this difference was divided by its annual average, eliminating any kind of trend from the time series to be analyzed. The Pearson correlation (Fig. 9) was then computed for this noise series, along with their principal components (Fig. 10).

In terms of correlation (Fig. 9), positive correlation values stand out among the non-renewable sources, indicating a relatively coordinated dispatch of these sources. On the other hand, the noise from solar generation presents a stronger negative correlation with practically all other sources. This can be attributed to the that solar generation experiences

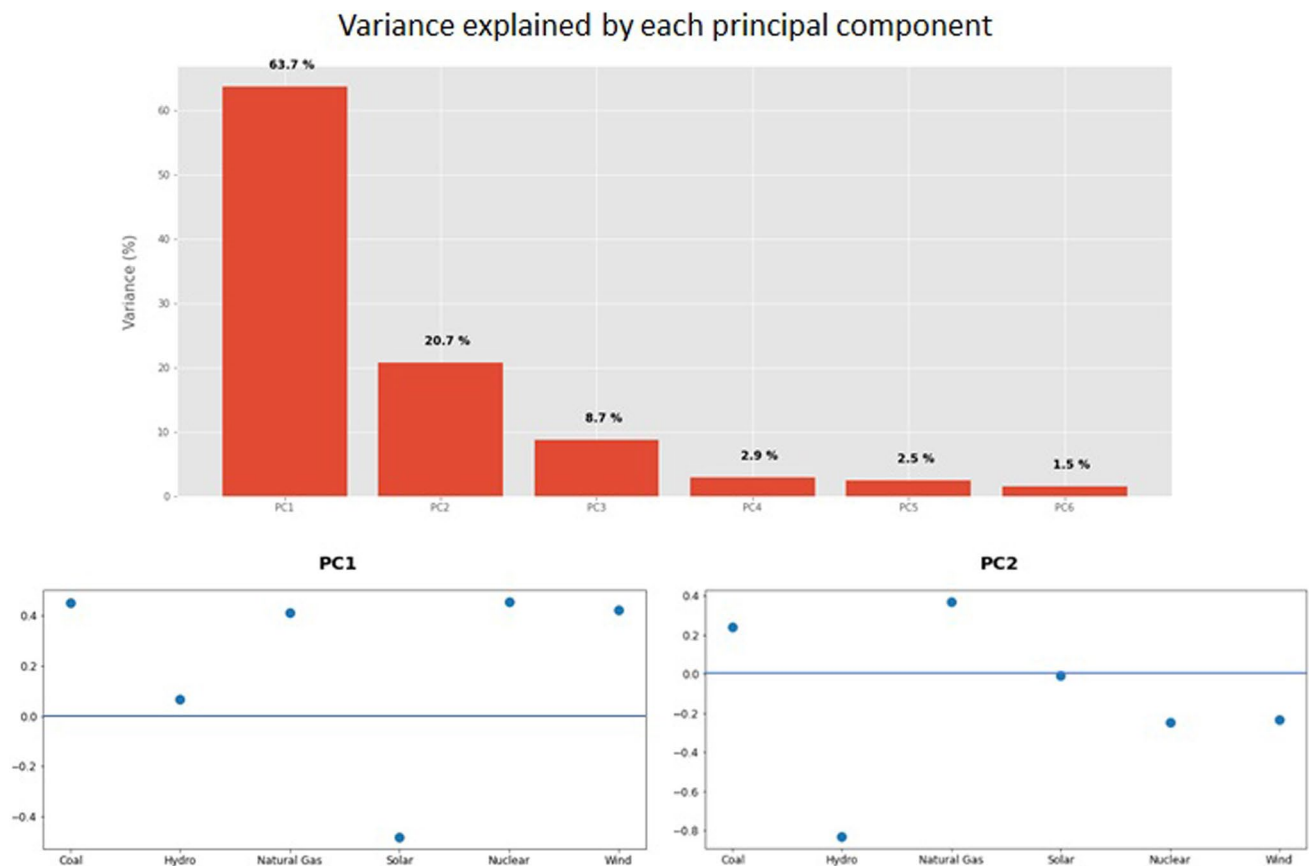
<sup>4</sup> <https://www.ccee.org.br/dados-e-analises/dados-geracao>.



**Fig. 8** Differences between monthly generation and its average (period 2010 to 2022) for each source of power generation in OECD Europe. Source of data IEA

**Fig. 9** Pearson correlation of the noise monthly time series of OECD Europe generation sources over the period 2010 to 2022. Source of data IEA





**Fig. 10** Principal Component Analysis based on the monthly series of OECD Europe's electricity generation sources for the period 2010 to 2022. Data source: IEA

its highest outputs, and corresponding fluctuations, during summer, while other sources, especially wind generation, exhibit this pattern in the winter. This leads to a greater negative correlation between solar and other sources.

Lastly, a principal component analysis (PCA) was performed to determine the most significant modes of variability explaining the total variability of the OECD Europe's power generation mix (Fig. 10). It is important to remember that this PCA was also done with the residuals of the monthly difference of each generation source.

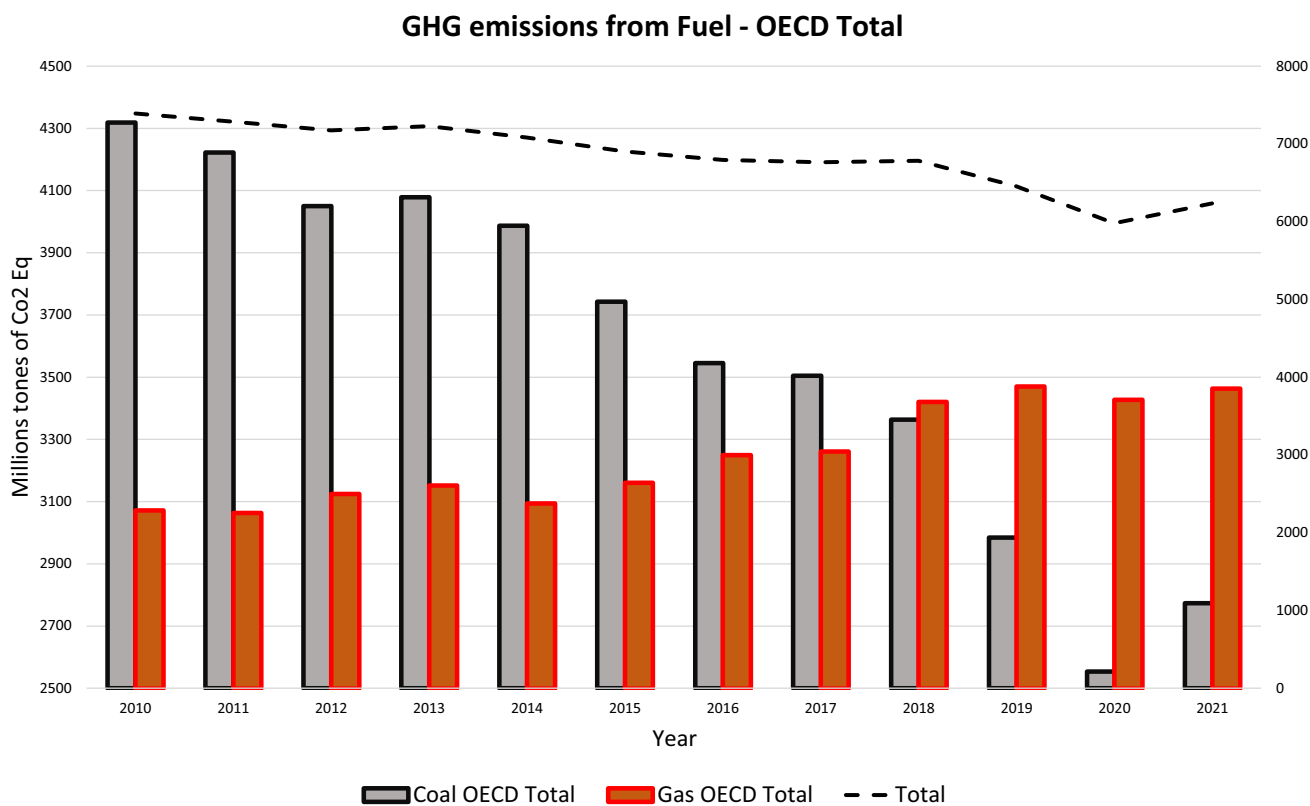
By analyzing Fig. 10 we observe that Principal Component 1 (PC1) explains almost 64% of the variability of power generation from its different sources. This PC1 is composed of the variability of natural gas, nuclear, wind and coal generation plus solar generation, which is orthogonally opposite. This analysis corroborates the previous one based on Pearson correlation, emphasizing the essential role that solar generation can play in complementing generation in OECD Europe.

PC2 has the largest contribution from hydro generation, which shows that this generation does not follow any pattern of variability similar to the others, as was also observed in the correlations. This fact is due to the fact that hydropower plants in Europe are installed in different countries and often have different seasonal precipitation regimes, which often complement each other. It's may also explain the small variability of hydropower generation in OECD Europe, when analyzing total generation rather than generation by each region.

## 4.2 Natural gas as part of a green matrix in Europe

The idea that thermoelectric plants powered by burning natural gas are a more environmentally efficient way to generate energy, by emitting fewer GHGs into the atmosphere, than burning coal and oil, is not new and it is supported by many authors [57, 58]. In fact, when considering only the process of power generation, this information holds relatively true in terms of CO<sub>2</sub> eq emissions. Additionally, the low cost of power generation using natural gas makes it an attractive option [58].





**Fig. 11** Total annual GHG emissions from coal and gas-fired power generation in the period 2010 to 2021 from all OECDs. Data source: IEA

However, the entire life cycle of natural gas has been studied extensively, encompassing extraction, separation, storage, and transport until it is burned for energy generation [59]. Throughout these processes, natural gas is susceptible to leaks due to cracks or ruptures in structures, resulting in large amounts of methane emissions to the atmosphere [59–61]. The displacement of natural gas during transport to the energy generation site can further increase these emissions [59]. This is particularly relevant for large pipelines supplying the OECD Europe from Russia [62].

It is important to note that methane, the primary component of natural gas, has a greenhouse effect that is about 25 times greater than CO<sub>2</sub> [36]. Under natural climatic conditions, methane would not be part of the atmospheric chemical composition of the atmosphere, as it originates from the extraction of fossil fuels [63]. Thus, even though the emissions from natural gas for energy generation appear lower in terms of CO<sub>2</sub> eq compared to the burning of other fuels such as coal and oil, its influence on the current unbalance of the planet's climatic conditions cannot be neglected [63, 64].

Analyzing the emissions associated with energy generation (including all types of generation and not only electricity) a decrease in CO<sub>2</sub> eq emissions can be observed for coal from 2010 to 2021, in both the sum of emissions from all OECD (Fig. 11), and in the case of OECD Europe (Fig. 12) (data for 2022 were not yet available at the preparation of this work). Notably, the decrease in emissions in 2020, attributed to COVID-19 pandemic, does not significantly impact the analyses in this study.

Simultaneously, an increase in CO<sub>2</sub> eq emissions associated with the use of natural gas is observed. The emissions from gas surpasses those from coal in 2018, and in the case of Europe (Fig. 12) these emissions increase significantly from 2016, aligning with the increase in power generation from natural gas during the same period.

Focusing on OECD Europe again, when comparing the amount of CO<sub>2</sub> eq emitted in 2021 with those in 2010, a reduction of approximately 34% is observed for emissions from coal burning, while the reduction for gas burning is only 6%. If the decrease in CO<sub>2</sub> eq emissions gas-derived had followed the same rate of decay observed from 2010 to 2015 (indicated in dashed blue line in Fig. 12), the reduction in gas emissions in 2021, compared to the base year 2010, would have been about 47%. This translates into a saving almost 502 million tons of CO<sub>2</sub> eq per year, instead of the 66 million tons of CO<sub>2</sub> eq per year indicated by the current policies governing the expansion of the European electricity mix. This would mean a decrease in emissions about 8 times greater, relatively, than what was observed in this period.

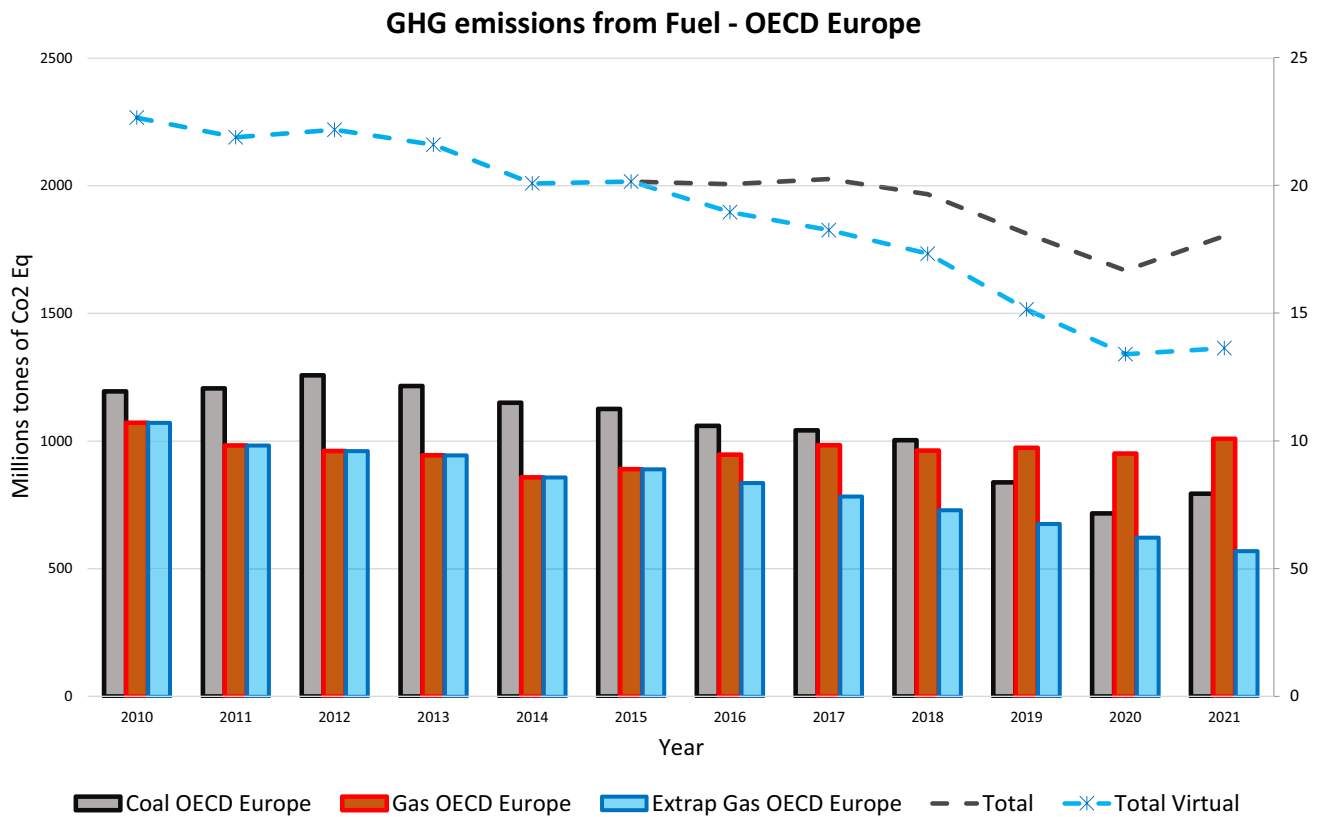


Fig. 12 Total annual GHG emissions from coal- and gas-fired power generation from 2010 to 2021 for OECD Europe. Data source: IEA

## 5 Discussion

The electricity mix of the OECD Europe has undergone a complex transition over the past 12 years, characterized by a struggle between cleaner and renewable mix and geopolitical and economic interests. While significant changes were only witnessed almost a decade after the Fukushima incident in Japan in 2011<sup>5,6</sup>, Germany played a prominent role in the EU driving the shift towards cleaner generation. However, the inclusion of natural gas in the energy mix has sparked debates due to its status as a fossil fuel<sup>7,8</sup>. [65].

The notion that thermoelectric generation using natural gas is a cleaner alternative gained widespread acceptance in OECD Europe [61, 66, 67]. Nevertheless, the burning and exploitation of any fossil fuel, exacerbates climate change, contributing to an unnatural alteration of the planet cycles and intensifying the greenhouse effect, the global temperature rise, and the frequency of extreme weather events [68].

This study highlights the crucial bloc decisions made in 2015 and 2016 that lead to OECD Europe's increased dependency on natural gas, primarily sourced from Russia. Germany's support for the Nordstream 2 pipeline project, connecting Russia directly to Germany across the Baltic Sea, played a significant role. However, this project was controversial, as it increased Europe's dependence on Russian gas, raising concerns about energy security [69]. Germany's decision to

<sup>5</sup> <https://www.bbc.com/news/world-europe-13592208>.

<sup>6</sup> <https://www.theguardian.com/environment/2011/may/25/europe-divided-nuclear-power-fukushima>.

<sup>7</sup> <https://www.cnbc.com/2023/04/18/germany-shuts-down-last-nuclear-power-plants-some-scientists-aghast.html>.

<sup>8</sup> <https://www.dw.com/en/germany-shuts-down-its-last-nuclear-power-stations/a-65249019>.

decrease nuclear generation in 2022 further complicated the energy mix situation, aiming for a cleaner generation but potentially compromising security<sup>9</sup> [70].

Germany's agreement with Russia raised concerns, particularly given the strained relations between the two countries since 2014. Germany suspected Putin of lying on several issues, including the invasion of Crimea, which led to doubts about the agreement's implications [71]. The dependence on Russian gas supply created a geopolitical dilemma, as it potentially emboldened Russia to invade Ukraine, knowing that European bloc sanctions would be difficult to impose due to the reliance on natural gas imports to meet its energy demand, especially in winter [72]. Efforts to diversify and reduce reliance on Russian gas imports have been challenging and have led to increase the price of energy for the final consumer in the EU [72].

While limited efforts have been made to generate energy from other than natural gas, such as coal based thermoelectric generation, renewable sources like hydro, solar and wind depended on installed capacity and weather conditions. The narrative that coal-fired thermal generation contributes more to climate change than using natural gas, led to protests regarding the reuse of decommissioned coal mines<sup>10,11</sup> [73].

Amid the energy crisis that has led Europe to deep reflections on its electricity mix, the European Commission's response has been the EU Taxonomy Regulation and the REPowerEU Strategy. The Commission introduced the REPowerEU strategy, setting targets for renewable energy capacity to be at 1236 GW in 2030 and to save up to 21 bcm of gas per year [73]. The Commission also introduced, for example, a new target for sustainable biomethane production by 2030 as a cost-efficient way to reduce natural gas imports from Russia, and an ambitious target of 20 million tons of renewable hydrogen, of which 10 produced domestically and 10 imported via priority corridors by 2030.

The technical, economic, and logistical aspects of hydrogen production, storage, transportation, distribution, and utilization pose significant challenges in achieving net-zero emissions. It is worth noting that most of the hydrogen produced worldwide, approximately 95%, comes from processes that heavily rely on fossil fuels. This type of hydrogen is commonly referred to as "grey hydrogen" and contributes to around 2% of global carbon emissions [74].

Hydrogen used in a Net Zero system will be either produced by processes which generate carbon dioxide, but which is permanently extracted and stored ("blue hydrogen"), or through the use of renewable power to allow the electrolysis of water ("green hydrogen"). The current deployment of carbon capture, utilization, and storage (CCUS) technology is insufficient to significantly reduce our emissions on a large scale. Moreover, the economic and commercial conditions necessary for widespread utilization of CCUS have not been established [75].

Consequently, relying on blue hydrogen as a substantial means of decarbonization in the near to medium future is not feasible, and there are also several drawbacks for the large-scale production of green hydrogen via electrolysis and solar photovoltaics [76–78].

While hydrogen is expected to play a role in our energy portfolio, it is important to avoid viewing it as a miraculous solution to all our challenges, as some may perceive it to be. There are critical questions that still need to be addressed regarding the future production, distribution, and utilization of large quantities of hydrogen in a manner that aligns with the goal of achieving Net Zero emissions while maintaining cost efficiency [79].

We must carefully consider how to overcome hurdles such as scaling up hydrogen production to meet demand, establishing efficient distribution networks, and ensuring its compatibility with Net Zero objectives. Furthermore, cost-effective methods and technologies need to be developed to make hydrogen a viable option in the transition to a sustainable energy future. By addressing these key concerns, we can better understand the role hydrogen can play in our overall decarbonization efforts. It is very likely that any future use of hydrogen will be limited rather than universal.

Moreover, in 2021, the European Commission adopted the EU taxonomy regulation. The EU taxonomy regulation classifies economic activities based on their environmental sustainability to guide investments towards climate change mitigation and environmental objectives. It covers sectors such as energy, transportation, agriculture, manufacturing, and more, and establishes criteria and disclosure requirements to determine if an activity is environmentally sustainable. The inclusion of natural gas in the EU taxonomy has sparked debate due to its status as a fossil fuel. Advocates argue that natural gas can serve as a transitional fuel towards a low-carbon future, as it emits less carbon dioxide and air pollutants compared to coal and oil.

<sup>9</sup> <https://www.dw.com/en/germany-shuts-down-its-last-nuclear-power-stations/a-65249019>.

<sup>10</sup> <https://www.bbc.com/news/world-europe-64309628>.

<sup>11</sup> <https://www.reuters.com/business/environment/german-police-drag-away-activists-protesting-coal-mine-expansion-2023-01-10/>.

They believe it can reduce greenhouse gas emissions in the short term and provide backup to intermittent renewable energy sources, ensuring energy security and grid stability. However, critics express concerns about methane leaks during extraction and distribution, as methane is a potent greenhouse gas. They emphasize the need to prioritize investments in renewable energy sources to achieve long-term climate goals. The EU is actively working on criteria to determine the sustainability of different activities, including natural gas, in the taxonomy.

In response to these debates, the EU has been working to establish criteria and thresholds for including or excluding different economic activities, including natural gas, in the EU taxonomy. The aim is to ensure consistency with climate objectives and avoid greenwashing. The decision on whether natural gas will be classified as a sustainable investment in the EU taxonomy will depend on the outcome of these ongoing discussions and assessments of its environmental impact throughout its life cycle.

Even though once again the European Energy Commission has met and suggested goals and directives for a cleaner, more sustainable, and safer generation, the doubt will always remain as to which will be the guiding processes for the fulfillment of these directives. Will it really be, that this time, the bloc will move towards a cleaner, independent and safe electric mix or will the economic and individual interests of some countries once again overcome all the others?

Based on the analysis of the OECD Europe's electricity generation data from 2010 to 2022, and extensive literature review, it is evident that the transition of the European electricity mix to a cleaner and more sustainable mix has not occurred as anticipated. The notion that natural gas is a cleaner solution compared to coal or oil, is flawed.

In fact, this is a solution that, even when analyzing the entire life cycle, according to many authors, has a lower impact on the concentration of greenhouse gases in the atmosphere. But that is only if compared to burning coal or oil, and even then, this lower emission of GHGs may depend on the country, technology, and transportation of natural gas, among others [80].

But the reality is that the entire process of extracting, transporting, and burning natural gas emits a large amount of GHGs into the atmosphere, and does influence climate change and the entire climate imbalance experienced by Europe and much of the planet in recent years [9, 81–84].

In 2021, the use of natural gas for power generation in OECD Europe resulted in approximately 1010 millions tones of CO<sub>2</sub> eq into the atmosphere, compared to 794 Millions tones of CO<sub>2</sub> eq from the use of coal. Is this the migration to a clean electric and energy mix?

Many researchers have asked this same question, raising concerns about the bloc's progress towards a clean energy mix. The lack of political interest and public understanding regarding renewable energy sources, such as solar and wind, has hindered their implementation [85, 86].

Apparently, many studies using robust tool methodologies and more current technical capacity estimates on Europe's potential for really cleaner and renewable energy generation, such as solar and wind, and their advantages, e.g. [87–90], have not aroused enough political interest for their implementation. As well as investment in new technologies for the conversion of solar energy based, for example, on natural dyes, which would have a lower environmental impact in their disposal phase [91] are not always encouraged and developed on an industrial scale.

Just the opposite, some protests the installation of even wind farms have been observed in regions of the bloc<sup>12 13 14 15</sup>. This illustrates how the lack of understanding and clarification of the population in relation to the impacts of the electricity mix on the climate, the economy and society as a whole, can lead to totally erroneous interpretations.

Decisions made by influential countries within the bloc, driven by economic interests, have contributed to the expansion of natural gas-based energy generation and increasing the dependence on countries like Russia [21, 72]. This dependence may have influenced Russia's invasion of Ukraine, leading to rising energy prices, inflation, and economic challenges across Europe [92, 93].

<sup>12</sup> <https://www.ejatl.org/conflict/popular-and-institutional-opposition-to-the-serra-morena-and-la-macana-wind-farms-in-lanoia-spain>.

<sup>13</sup> <https://edition.cnn.com/2023/03/01/europe/greta-thunberg-wind-farm-norway-sami-climate-intl/index.html>.

<sup>14</sup> <https://www.reuters.com/world/europe/norway-wind-farms-heart-sami-protest-violate-human-rights-minister-says-2023-03-02/>.

<sup>15</sup> <https://renewablesnow.com/news/anti-renewables-protesters-from-rural-spain-descend-on-madrid-757820/>.

## 6 Summary

First and foremost, it is essential to acknowledge that the expansion of an electricity mix within a globalized world, should not solely prioritize economic interests. The environmental must be a central consideration and the population should be adequately informed and engaged in transparent and objective discussions about energy generation sources. Environmental education plays a vital role in fostering informed decision-making and raising awareness about the impacts of the electricity mix on climate, the economy, and society as a whole.

The authors emphasize the need for transparent and objective communication, free from manipulation, regarding energy generation sources. This involves collaboration between the public and private sectors, as well as the active participation of the scientific community. Additionally, reflection on consumption patterns and modes of society are necessary to ensure a sustainable future and reduce greenhouse gas emissions associated with power generation.

These reflections and discussions are necessary so that the expansion of the electric matrix in Europe and in any bloc or country does not repeat past actions that had, and still have, major global repercussions. In this sense we can list:

- The European community's reactions to the Fukushima disaster only occurred practically on "discourse", with the most effective shutdown of nuclear plants occurring only 10 years after the incident. This is because safety involving generation conditions also has to be weighed against the safety of energy supply;
- The decarbonization of an electric matrix from the use of natural gas is a fallacy, as can be observed when one evaluates the emissions and concentrations of CO<sub>2</sub> eq;
- The expansion using hydrogen, even "green" hydrogen (the only environmentally viable option), should still be carefully analyzed because of the costs and the environmental impact of the whole process;
- The solution for decarbonization of the electric matrix already exists and should be, at this moment, based on wind (on shore and offshore) and solar generation, as described in the most recent IEA Report, called "Renewable Energy Market Update Outlook for 2023 and 2024"<sup>16</sup>. However, this expansion must be done in a coordinated manner with the climatic potential of each region, so that there is no excess generation at one time and deficit at another, and always seeking new conversion technologies with less environmental impact;
- The life cycle and the operation risk must always be analyzed when thinking about a source of energy generation. A nuclear power plant, for example, emits, in its operating phase, practically no gram of CO<sub>2</sub> eq; however, it has a high operational risk, in addition to the production of radioactive waste. A hydroelectric power plant has a low environmental impact during its operation; however, it has a high impact during its construction, which is also perpetuated during its operational phase, unless the vegetation suppression is restored.

The lack of a broad and efficient environmental education, allied to fake news and a certain manipulation of reality due to political and economic interests, often leads the population itself to not ask the right questions, as for example:

- Couldn't small hydroelectric plants (with their due environmental compensation) and nuclear plants (investing more and more in their operational safety) be part of the expansion of an electric matrix thinking about its decarbonization?
- Although burning coal emits to the atmosphere other pollutants that are harmful to human health, besides GHG, such as CO<sub>2</sub>, in a period of war and humanitarian crisis, knowing that natural gas generation contributes to the greenhouse effect in a similar way to coal, is it unthinkable to reactivate coal plants to create greater independence for the invading country (a natural gas exporter)?
- Are protests against the installation of wind farms valid for local reasons linked to landscape change, bird routing (which is quite questionable) and some noise? Are these factors worse than crises associated with climate extremes such as prolonged droughts, large forest fires, hailstorms, floods, etc. that can occur on a local as well as a global scale?

Finally, the authors hope that with this work they are contributing to a greater dissemination of knowledge, based on real data and reliable sources, with in-depth analysis and free of any kind of passion. Future work can be done using remote sensing tools to better understand the spatial and temporal distribution of emissions from the electricity matrix of OECD Europe.

<sup>16</sup> [https://iea.blob.core.windows.net/assets/63c14514-6833-4cd8-ac53-f9918c2e4cd9/RenewableEnergyMarketUpdate\\_June2023.pdf](https://iea.blob.core.windows.net/assets/63c14514-6833-4cd8-ac53-f9918c2e4cd9/RenewableEnergyMarketUpdate_June2023.pdf).



## 7 Conclusions

The transition of the electricity matrix of OECD Europe was going on a path, until 2016, prioritizing the decrease in coal and gas generation and the increase in the insertion of renewables, such as wind and solar. However, this path apparently also had changed by political decisions, placing natural gas as belonging to this transition to a cleaner matrix, which is observed to be not true, when evaluating, for example, the CO<sub>2</sub> eq emissions associated with power generation.

In relation to the security of electricity supply, this study also discussed that Europe's electricity matrix could rely on hydroelectric generation, in addition to thermoelectric generation, to meet peak periods of high demand that require rapid and secure dispatch, since the variability of hydroelectric generation is small on the continent, due to its spatial complementarity. In this way, the need for conventional thermoelectric and nuclear generation, added together, could be around 15 to 20%, to make up, together with hydroelectric generation, 30% of electrically stable generation. This figure is much lower than the 58% of thermoelectric generation applied in 2022.

This decision has brought consequences that go beyond the delay in the transition of the electricity matrix and, consequently, the worsening of the changing climate process. In fact, it made Europe "hostage" to Russian gas exports, which, in a way, may have been a decisive element for Russia's invasion of Ukraine, creating a war that has already exceeded 500 days, with accusations of crimes against humanity, and that has reactivated tensions regarding a possible nuclear conflict.

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**Author contributions** MC—Articulating the ideas in the text, drafting the main text and processing the data. NE—Proofreading the text, describing sustainability topics and the history of the EE Mix. SJ—Proofreading the text and describing studies on EE Mix projections in changing climate scenarios. JPM—Proofreading the text and helping with statistical analysis. LS—Proofreading the text and helping to prepare the discussions on CO<sub>2</sub> Equivalent. JD—Proofreading the text and describing the topics on hydrogen energy generation. MT—Proofreading the text.

**Data availability** The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

## Declarations

**Competing interests** The authors declare no competing interests.

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