Working paper.

Modelling the sensitivity of the European power system to Belgian and German nuclear policies

Authors :

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Abstract

Reaching carbon neutrality in the European energy sector requires a profound transformation of energy production and consumption. In this context, electricity is expected to take a more significant share in replacing the direct use of fossil fuels in industry, mobility, and heating. The role of nuclear power is debated, with policies differing among the various Member States. The European power system will play a central role in accomplishing Europe's energy transition towards lower dependence on fossil fuel imports and CO_2 emissions reduction objectives. Through ESMOD, a model presenting the 2030 European integrated power system that we developed with Antares Simulator, we present the direct (national-level) and indirect (system-level) effects of a total nuclear phase-out in two countries, Germany and Belgium, in terms of CO_2 emissions and variations in the socio-economic welfare. General results show that postponing nuclear phase-out would have (or have had) a considerable indirect impact. This impact expands not in a homogenous fashion and reaches the entirely European power system, creating a spillover effect. Indeed, the proximity to Belgium and Germany is a crucial factor. However, nearby countries experienced different effects. Hence, the impact of nuclear extension depends on the context described by the load size, power mix, trader status, and interconnections. Finally, we crossed the two indicators to classify the countries into 7 groups: by using K-mean clustering method and assessing the climate year sensitivity. These results illustrate some consequences of phasing out low carbon generating power capacities while the electricity system still depends on fossil-fired power plants. They also show the sensitivity of European countries to national nuclear policy in an integrated system and highlight the relevance of having coordinated energy policies throughout countries served by the system.

Keywords: Nuclear energy, Electricity system, Energy Policy, Modelling, European coordination

1) Context

The European electricity system will play a central role in accomplishing Europe's energy transition, as it is an integrated power system through a mutualisation of production units and demand aggregation. It enables cost-effective electricity production by optimising marginal capacities and enhancing the security of the power supply (Amprion connects, 2023). Likewise, the grid fosters the development of renewable energy sources (RTE, 2023). These resources, however, bring greater instability to the system due to their production intermittency, leading to a greater need for flexibility (Buongiorno et al., 2019).

Nuclear energy can be used as a dispatchable source of electricity, hence contributing to the flexibility of the power system (intraday to weekly flexibility through load-following and seasonal flexibility through the positioning of refuelling and maintenance). On the other hand, nuclear power also contributes to improving the European security of energy supply through the nuclear fuel inventories (Euratom Supply Agency, 2023) and the low price dependence of the nuclear kWh on the price of uranium (Nuclear economy 1 chapter 4 the costs of Nuclear fuel, ISTE, 2023). Another significant feature of this power source is its very low net CO_2 emissions (Gibon and Hahn Menacho, 2023). Despite these interesting features to support decarbonization and the significant share in its production mix, by 2021 two countries had committed to completely phase-out nuclear energy, following decisions taking their roots in the preceding decades (FPS Economy, 2023)

In 2021, electricity from nuclear production represented up to 25% of the electricity mix in Europe. By the same year, Germany relied on nuclear power up to 13% and was the second biggest producer after France at the European level (ERPRS, 2023). Despite the large renewable electricity production (45.9%), Germany was still highly dependent on fossil fuels for its power generation (41%).

In Belgium, for the same year, more than 50% of the electricity was produced from nuclear power (Energy-Charts, 2023) and Belgium was the fifth biggest producer at the European level in 2021 (ERPRS, 2023). Regardless of the efforts to incorporate and use renewable energy, Belgium still significantly relied on fossil fuels, which accounted for more than 25% of the power mix (Energy-Charts, 2023). Still, both countries had plans to phase-out nuclear energy, following political decisions taking their roots in the preceding decades (FPS Economy, 2023).

Table 1 summarizes the share of fossil fuels, nuclear energy, and renewable energy in electricity production mix and the percentages for both countries, in 2021.

	Fossil fuels*	Nuclear	Renewable Energy
Germany	204.47 TWh *(41%)*	65.44 TWh *(13.1%)*	229.13 TWh *(45.9%)*
Belgium	25.73 TWh *(27.8%)*	47.96 TWh *(51.8%)*	18.84 TWh *(20.4%)*

*Takes into account coal and coal products, oil and oil/petroleum products and natural gas

Table 1 Electricity production mix in Germany and Belgium in 2021. Data taken from Energy-Charts

Until 2021, Russia was by far the largest gas supplier to Europe, supplying about 35% to 40% of its needs (Council of the European Union, 2023). In the summer of 2022, following the Russo-Ukrainian conflict, the EU had to import large quantities of LNG[1] at a very high price, triggering energy crises in other parts of the world dependent on LNG. The Russian invasion of Ukraine has been eye-opening for Europe's dependence on Russian energy imports, principally regarding fossil gas, indicating a lack of energy sovereignty and security (Buck et al., 2022). The skyrocketing prices of gas and, to a lesser extent, oil encouraged European countries to accelerate their transition towards less CO_2-emitting and more independent energy production.

For Germany and Belgium, it raised significant questions on whether or not they should review their nuclear phase-out policy. Indeed, they were deeply committed to phasing out nuclear, while trying to reduce carbon emissions by massively deploying to renewable energy and phasing out nuclear at the same time, resulting in an a policy leading to an increased reliance on gas (Thompson, 2022)

In this study, we delved into the systemic effects imposed by the nuclear policy decisions of these two countries at the European level for 2030. We focused on the repercussions of nuclear policy decisions on CO_2 emissions, electricity trade, and socio-economic welfare. Unexpected policy implications in the European interconnected system motivate this study. To carry it out, we used a Unit Commitment and Economic Dispatch model that represents the European electric interconnected system and include 34 climate years.

Our paper is organized as follows: literature is reviewed in section 2, followed by the methodology applied in section 3. In section 4, we analyse our results and expose the limits of our study. Finally, we conclude in section 5.

[1] Liquefied Natural Gas

2) Literature

Since the German and Belgian nuclear phase-out was announced, several studies have examined the impact of this decision across neighbouring European countries. However, only a few have examined the effects on the entire European system. In this section, we review the literature concerning the Belgian and German nuclear phase-out and the consequences for their power system and the rest of the European power system whenever this topic is approached.

Our literature review, as far as we know, led us to very few studies related to the impact of the Belgian nuclear policy decisions when analysing the overall power system. An analysis of the Belgian nuclear phase-out impact on the country's economy and emissions was conducted by Soytas et al. (2022). This investigation finds that shutting down the nuclear reactors would not affect the economy's growth nor carbon emissions in the long term when analysing the electricity market and the economy (in terms of GDP) and primary energy consumption (Soytas et al., 2022). Nevertheless, this finding is valid as long as replacing the whole nuclear park with alternative renewable energies is technically and financially feasible (and effectively done). Otherwise, Belgium would have to import electricity from the neighbouring countries, including carbon-intensive electricity, or domestically produce electricity from fossil fuels.

Concerning Germany, the first effect is the replacement of nuclear power with more renewable energy sources (RES) and other dispatchable sources. Welsch (1998) and Bruninx et al. (2013) study the effects of German nuclear phase-out on its power system. The study shows an increase in coal, lignite, and gas-based electricity generation (Bruninx et al., 2013; Welsch, 1998). Similarly, De Cian et al. (2014) studied the effect of nuclear phase-out on the investment in new technologies, finding that it would stimulate investment in fossil-based technology until 2030 and in R&D and new low-carbon technologies after that, bringing with it economic benefits, the timing of which depends on the ambition of climate policies adopted (De Cian et al., 2014). These new power sources caused a logical impact on prices. De Menezes and Houllier (2015) studied the impact of the German nuclear phase-out on the European electricity market. Given a greater penetration of RES, price volatility in the day-ahead and intra-day markets increases in Germany but also at the European level (de Menezes and Houllier, 2015).

Another study that concentrates on the economic impacts in Germany of nuclear phase-out or extension was done by Emblemsvåg (2024). He states that the Energiewende[2] has not only cost Germany billions of euros between 2002 and 2022 but has also prevented the country from reducing more emissions than it would have if they had kept nuclear power plants running or had invested more in nuclear capacity (Emblemsvåg, 2024). (Nagl et al., 2011) study through four different scenarios with variation of CO_2 emission reduction target at different horizon crossed with a nuclear power plant life time extension of 4, 12, 20 or 28 years. They found that one of the main reasons for the reduction of CO_2 emissions and a positive impact on end consumer electricity prices in Germany is the life-time extension of nuclear power plants.

Moreover, environmental and economic studies carried out by Hoster (1998) investigate the impact of the German nuclear phase-out in terms of economic and environmental viability on the European integrated power system, with a complete phase-out reached in 2005 and the ex-post effect until 2020. This model represents France as one zone, Belgium, Netherlands and Luxembourg as one zone, and Austria and Switzerland as one. The rest of Europe is exogenous. The author draws that CO_2 emissions would rise in these neighbouring market zones as German imports from these zones would increase

[2] Term used to reference the energy transition in Germany

(Hoster, 1998). Additionally, he finds a soft increase in costs caused by domestic and foreign requirements for new capacities to satisfy demand with less nuclear capacity and increased fuel costs. Similarly, Bode (2009) concludes that a German nuclear phase-out results in an increment in prices and CO_2 emissions (Bode, 2009).

In addition to the directly related impacts on the power system, the development of new technologies to counterbalance the absence of dispatchable power plants, the expansion of new renewable power sources with high rates of intermittency and mild predictability and the deep electrification become a significant concern in the pathway towards achieving the ambitious transition goals. Selosse et al. (2012) study the impact of developing Carbone Capture and Storage (CCS) and Bioenergy with CCS (BECCS) as a solution for replacing nuclear energy. They find that limited nuclear energy would incentivise the use of CCS technologies (Selosse et al., 2012). If CCS technologies are not developed, limited nuclear energy would incentivise the development of renewable energy under the assumption that electrical storage is developed to ensure the flexibility of the system. Otherwise, the use of gas and coal would be as important as the use of renewable energy dragging out the achievement of energy transition goals. On the other hand, Lechtenbohmer and Samadi (2013) examine the German mix capability of completely replacing nuclear power with renewable electricity generation under the premise of expanding the grids and provisioning balanced power through demand adjustment (Lechtenböhmer and Samadi, 2013).

A recent study by Glynos and Scharf (2024) examines the effects of the German nuclear phase-out in the context of the 2022-2023 energy crisis in Germany and Europe. This study focuses on the period from January to April 2023, stating the positive effects that the German decision to postpone the nuclear phase-out during this period brought with it. Among these effects, other than a marginal increase in the overall welfare, they found that more nuclear power during the state period results in less use of gas and coal-fired power generation at national and European levels and reduced grid congestion in Germany. Regarding the interconnected system, neighbouring countries benefit marginally of this nuclear phase-out postponement through the imports of cheaper electricity, whilst non-neighbouring are disadvantaged. Indeed, for the latter countries, the gain of consumer surplus is eclipsed by the loss in producer surplus, resulting in a negative effect on their welfare (Glynos and Scharf, 2024).

Moreover, a study (Jafari et al., 2023) concentrating in German's net zero emission target for 2045-2050, states that even by phasing out completely coal, it would not be possible to reach the emission targets. To satisfy its peaks in demand, Germany would need to rely on imports possibly based on carbon intensive sources.

Our contribution to the literature includes modelling the impact of German and Belgian nuclear phase-out policies and analysing their effects on power scheduling, CO_2 emissions, power trade and socio-economic welfare at the country and system level in a 2030 market context, including a sensitivity test to analyse the effect of climate years in our results. This study addresses the gap in the literature regarding the German and Belgian nuclear phase-out going further than previous studies by incorporating a unit commitment model of the European power system using country-detailed production capacities and dispatch of the whole European interconnected electric system. As literature usually focuses on the impacts of the country's own energy policies, we instead study the impacts that other countries have to undergo, affecting their emissions reduction objectives and the overall efficiency of their markets. The following section depicts the methodology, hypotheses, and scenarios used for this study. We then present the results and the analysis and conclude with a few points for discussion on the subject.

3) Methodology

We divided this section in order to give a complete insight into the methodology used to realize the study and the method employed to analyse and present the results

3.1) Model description

In order to carry out this study, we used the "European Electric System Modelling", *ESMOD* model, developed within CEA *I-Tésé* research institute. *ESMOD* model is built on Antares-Simulator, an open-source software developed by RTE (RTE, 2022). The model is based on an hourly hydrothermal unit commitment paradigm within a partial equilibrium model. It complies with merit order market configuration based on marginal costs, the hourly power trade among the countries following physical and economic constraints and the cycles of loading and taking-off from PSP and batteries. Through this calculus, the operating ranges of the various means of production are determined to minimise the power system's annual operating cost. Among the constraints considered are variable costs, minimum time for a unit of production to be switched on/off, planned and forced outages, start-up costs, and CO_2 emissions and costs.

ESMOD models the European power system for 2030, covering 37 countries constituted of 53 market-bidding zones interconnected. The interconnections are based on net transfer capacity approach. We point out that the model considers coupling market dynamics in its modelling. The technical-economic data of the model is mainly based on ENTSO-e's European Resource Adequacy Assessment (ERAA) (ENTSO-E, 2022), which provides in a dataset the characteristics of the power system. Our study comprises 34 climate years which we consider essential to take into account the sensitivity of power system to different climate risks dependencies in both supply and demand side.

For a more detailed description of the model and the dataset used in this study as well as the mathematical formulation of the model, refer to ESMOD description in ITESE Website.

3.2) Scenarios

We built three scenarios for 2030 that depict the Belgian and German nuclear energy policies. In our analysis, we considered the German and Belgian nuclear plants in operation in 2022.

Three scenarios for Belgium and Germany were defined as follows:

- The scenario *FUCL*, for *Full Closure,* considers all nuclear power plants in Belgium and Germany to be closed by 2030. As mentioned, this was the initial policy of both countries, which planned a nuclear phase-out long before the Russian invasion of Ukraine. This scenario is our benchmark.
- Our second scenario, *REAL*, takes into account the policies adopted in reaction to the Russian invasion of Ukraine following energy crisis in 2021. For this scenario, we consider the lifetime extension of Doel 4 and Tihange 3 reactors that Belgium enacted in 2023, representing 1.039 GW and 1.038 GW, respectively. We rounded down to 2 GW extra on nominal power for Belgium. Regarding Germany, no nuclear reactor is prolonged, leaving the country with zero nuclear power in 2030.
- The third scenario, *Nuclear Extension (NUEX)*, assumes that both countries would have continued to produce nuclear energy without shutting down the nuclear plants that remained in April 2023 before Germany's last reactors were phased out. Thus, we assume a nuclear production capacity of 4 GW for each country.

Table 2 summarizes the three scenarios mentioned above.

Country\Scenario	FUCL	REAL	NUEX
Belgium	0GW	2GW	4GW
Germany	0GW	0GW	4GW

Table 2 Hypotheses of nuclear-installed capacity in 2030 in Belgium and Germany for the three scenarios.

3.3) Analysing the results

This section states the metrics to analyse the outcomes of our model as follows:

Distance

We define the interconnections between market-bidding zones as "*distances*", meaning that the greater the interconnection between two zones, the "closer" the country is located.

For more information on how we calculate the *"distance"* refer to Appendix B.

Total CO_2 emissions electricity supply (TEES)

We assess the change in total CO_2 emissions in absolute and relative terms using the FUCL scenario as the benchmark scenario.

In absolute difference, for any pair of scenarios we just make the difference between scenarios, S_1 being the FUCL scenario.

$$\Delta_{TEES_m}^{S_2 \leftarrow S_1} = TEES_m^{S_1} - TEES_m^{S_2}$$

And in relative difference is set as follows:

$$\Delta\text{relative}_{TEES_m}^{S_2 \leftarrow S_1} = \frac{TEES_m^{S_1} - TEES_m^{S_2}}{TEES_m^{S_1}}$$

For more information on how we calculate the total emissions refer to Appendix C.

Consumer Surplus (CS) and Producer Surplus (PS)

We suppose that electricity behaves as an inelastic good and that the day-ahead market model emulates a perfect competition market, meaning equal access to information, no barriers to entry and no market power. Such conditions make the consumer surplus, by definition, unlimited (Elsner et al., 2015). However, we can assess the difference in the consumer surplus between the scenarios (ENTSO-E, 2024) as the difference of the shadow values between the scenarios multiplied by the load.

For more information on how we calculate the *CS* refer to appendix D.

We define the producer surplus as the difference between the shadow value multiplied by the production and the operational costs for each technology. In other words, we set the producer surplus as the area between the market clearing equilibrium price and the supply curve (ENTSO-E, 2024).

For more information about on we calculate the *PS* refer to appendix E.

Congestion surplus (CSP)

As bidding zones are interconnected but limited by a maximum available transfer capacity—defined by the Net Transfer Capacity (NTC)—electricity demand and supply between countries might exceed these limits, leading to cross-border congestion. In such cases, electricity flows from the lower-priced market to the higher-priced one, following economic dispatch principles. This results in an apparent arbitrage gain for the importing country, which acquires electricity at a lower marginal cost and supplies it to its consumers at a higher internal price. However, this gain is offset by the payment of a congestion rent, derived from the price differential between zones. This congestions rent becomes a congestion surplus as it is allocated to a common fund used to enhance interconnection capacity and support broader system-level investments[3].

Thus, the congestion surplus is the variation between the price to which consumers paid for the electricity and the price for which generators sold it, times the power traded. It occurs due to interconnection congestion, the shadow values of the importer and exporter market-bidding zones differ from each other (ENTSO-E, 2024).

For more information on how we calculate the CSP refer to appendix F.

Socio-economic welfare (SEW)

The socio-economic welfare is the sum of the three prior indicators, as follows (ENTSO-E, 2024):

$$\Delta_{SEW_m}^{S_2 \leftarrow S_1} = \Delta_{CS_m}^{S_2 \leftarrow S_1} + \Delta_{PS_m}^{S_2 \leftarrow S_1} + \Delta_{CSP_m}^{S_2 \leftarrow S_1}$$

The revenues from the congestion surplus are typically used to finance grid investments, such as increasing interconnection capacity or maintaining existing infrastructure, in order to improve cross-border electricity flows, network reliability and support the integration of the energy market. This allows consumers and producers to profit from it hence used to calculate the SEW indicator.

4) Results

This section explores the effect of postponing nuclear phase-out in Belgium and Germany on the European power system by 2030. Additionally, it examines how CO_2 emissions, day-ahead power scheduling, and socio-economic welfare are sensitive to national energy transition plans. First, we study the national and European power system effects of the postponement of the nuclear phase-out. Second, we carried out an analysis for 34 climate years in order to assess the climate sensitivity of the results.

4.1) National effects of postponing nuclear phase-out

This first part is devoted to showing the modifications of the Belgian and German power scheduling. The postponement of nuclear reactors grants the Belgian and German power systems access to cheaper power sources. This results in modifying the cost effective distpaching and calling less fossil-based sources. Under these circumstances, it is expected that Belgium and Germany, in the REAL and NUEX scenarios, experience lower CO_2 emissions, and greater socio-economic welfare SEW than in FUCL benchmark scenario, as presented in Table 3.

	REAL vs FUCL	**NUEX vs FUCL**
Germany		
CO_2 emissions [Mton CO_2]	0,04 (0,11%)	-5,37 (-14,1%)
Socio-economic welfare Gains [Meuros]	50	1932
Belgium		
CO_2 emissions [Mton CO_2]	-2,22 (-27,87%)	-3,9 (-49,08%)
Socio-economic welfare Gains [Meuros]	852	1628

[3] Transmission System Operators (TSOs) earn congestion revenues when there are price differences between interconnected bidding zones. These revenues help cover some of the TSOs' costs, which means they don't need to rely as heavily on charging consumers through network tariffs

Table 3 Differences of CO_2 emissions and SEW for Belgium and Germany

In the REAL scenario, given that the postponement takes place only in Belgium, it is normal that Germany's CO_2 emissions and social economic welfare remain almost steady. In the NUEX scenario, both countries undergo consequent changes in their emissions and savings.

This analysis comforts the literature review by quantifying the advantages for Germany and Belgium of postponing the nuclear phase-out regarding CO_2 emissions and socio-economic welfare confirming the direct positive repercussions. Figure 1 shows the discrepancies in power dispatch for these two countries under the NUEX and FUCL scenarios.

Figure 1 illustrates two effects. First, a direct effect with nuclear based electricity replacing gas or another fossil fuel to produce electricity in the same country. Second, an indirect effect through the reduction in electricity imports and increase in electricity exports affecting other European countries. Notably, if we look at Germany, the direct effect represents 14.3 TWh, slightly more than half of nuclear production. The indirect effect (11.6 TWh) is very significant as well. In Belgium, the direct effect represents 10.6 TWh. The indirect effect arises to 14.7 TWh, more than half of the extra nuclear production. Therefore, the indirect effect has significant impact on the rest of the countries within the European interconnected electricity system, which brings us to the next section.

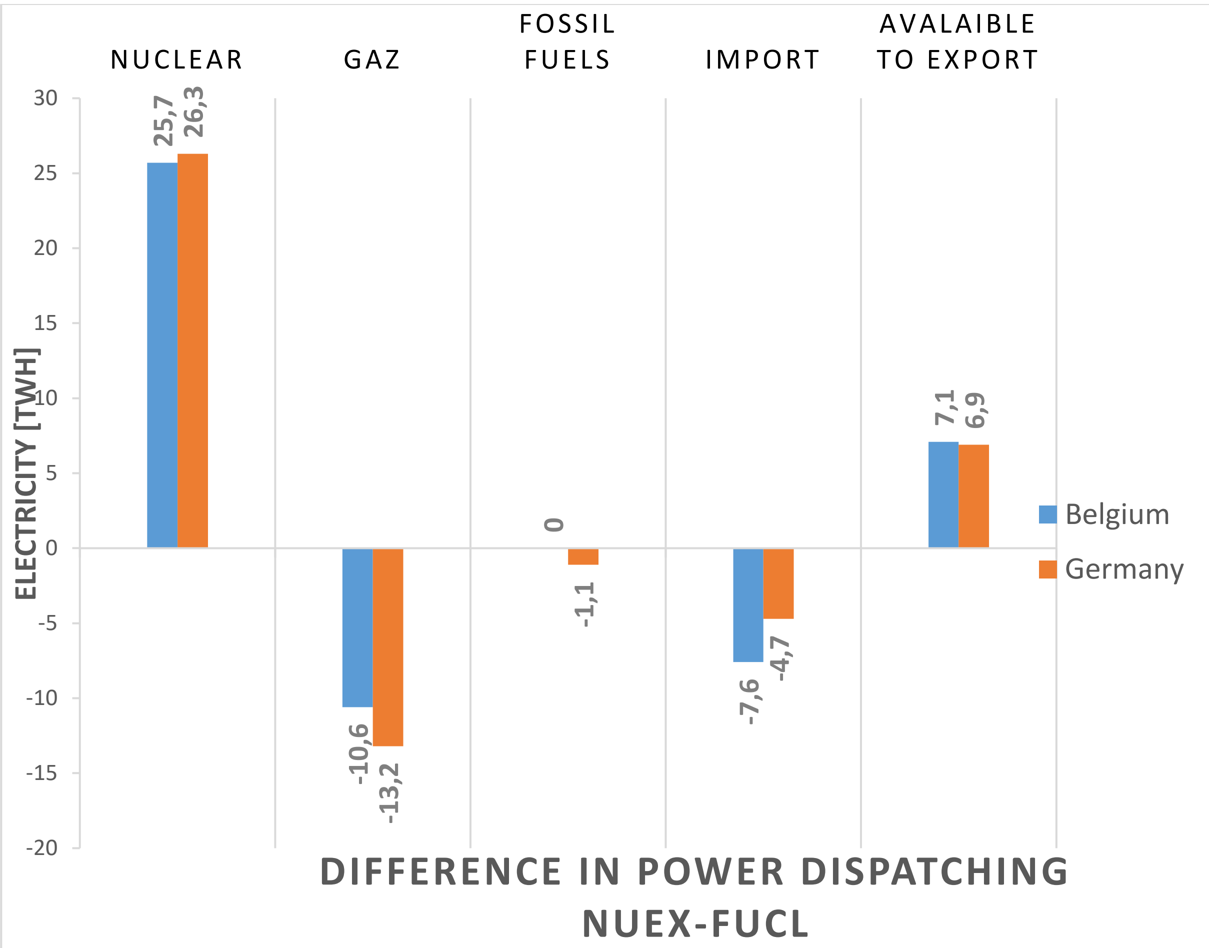

Figure 1 Difference in power dispatching (NUEX-FUCL)

Source: authors' elaboration

4.2) Effects on the European system of postponing nuclear phase-out

The indirect effect of postponing the nuclear phase-out spreads across the European power system depending on factors such as network location, interconnections, power mix, and load curve. The optimal power scheduling of countries closer to Belgium and Germany is more likely to be affected. These countries are better positioned to reduce their operational costs during peak periods — typically characterized by high costs due to the activation of fossil-based technologies — either by importing the extra nuclear power or by reducing their exports to meet Belgian or German demand. Following the metrics that we set to study the effect on the rest of the countries (cf. section 3.3), we proceed to analyse the results.

We initially planned the study with an intermediate scenario, REAL, representing the current situation, and a hypothetical scenario, NUEX, representing the nuclear extension, expecting to observe non-linear effects in the differences related to the reference scenario FUCL. However, we found merely a linear effect. For most countries the differences were essentially in the intensity, meaning reducing or increasing further the CO_2 emissions when comparing the differences between the REAL-FUCL and NUEX-FUCL. Therefore, we decided to set aside the intermediate scenario (REAL) and focus on assessing the metrics between the benchmark scenario (FUCL) and the Nuclear Extension scenario (NUEX).

<u>Total CO_2 emissions electricity supply (TEES)</u>

Throughout Europe, CO_2 emissions decreased by 16.4 Mtons per year, equivalent to a 5% total reduction between FUCL and NUEX. Germany and Belgium alone account for 9.2Mtons of this decrease contributing 56% of the total reduction in European emissions. The remaining 44% decrease is unevenly distributed among the rest of Europe, illustrated in Figure 2. This corresponds to the indirect impact which is almost as large as the direct impact.

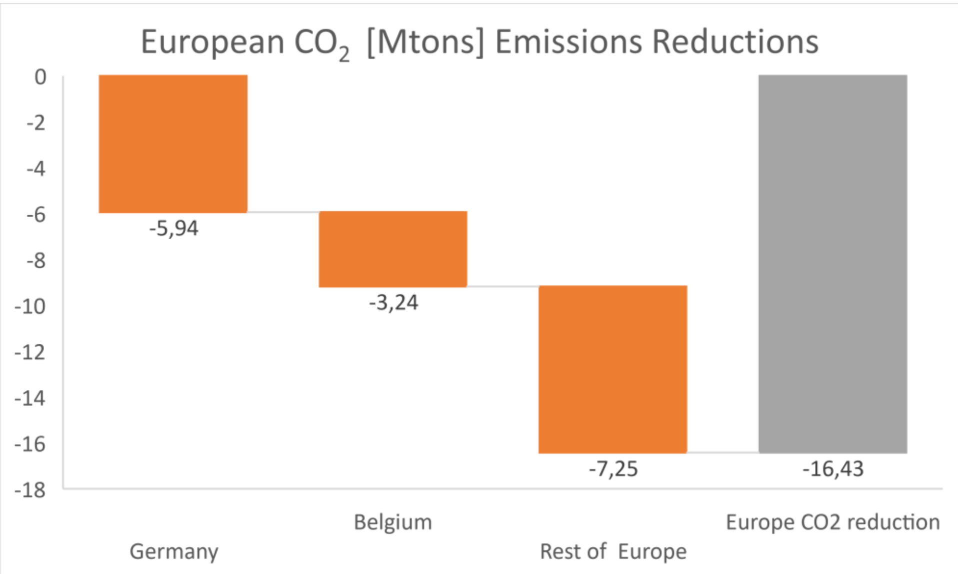

Figure 2 European CO_2 emissions reductions in NUEX compared to FUCL

Figure 3 illustrates the variation between the NUEX and FUCL scenarios of total CO_2 emissions (TEES) in relation to the *"distance"* in absolute terms (cf. the appendix A to see correspondence with country ID). The dotted vertical line shows the median "*distance"* (cf. section 3.3), which defines arbitrarily whether a country can be considered "close" or "far". The graphic reveals that the "farther" a country is located from Belgium or Germany, the lesser it is affected by postponing the nuclear phase-out. For example, Malta (mt) being the "farthest" (connected to Europe through a 200 MW line to Sicily), is slightly affected; while Austria (at), being the "closest", avoids approximately 0.3 Mtons of CO_2 emissions. However, this intuitive trend is not consistently observed: for instance, Switzerland (ch), Norway (no), and Sweden (se), which are "closer" than Hungary (hu), Romania (ro), or Croatia (hr), remain unaffected, while the latter countries do avoid carbon emissions. Similarly, Poland (pl) and Italy (it), avoid more CO_2 emissions, even though they are "farther" than Austria (at). This leads us to conclude that the effect is not strictly linear with respect to *"distance"* and depends on other factors. These aspects will be further analysed.

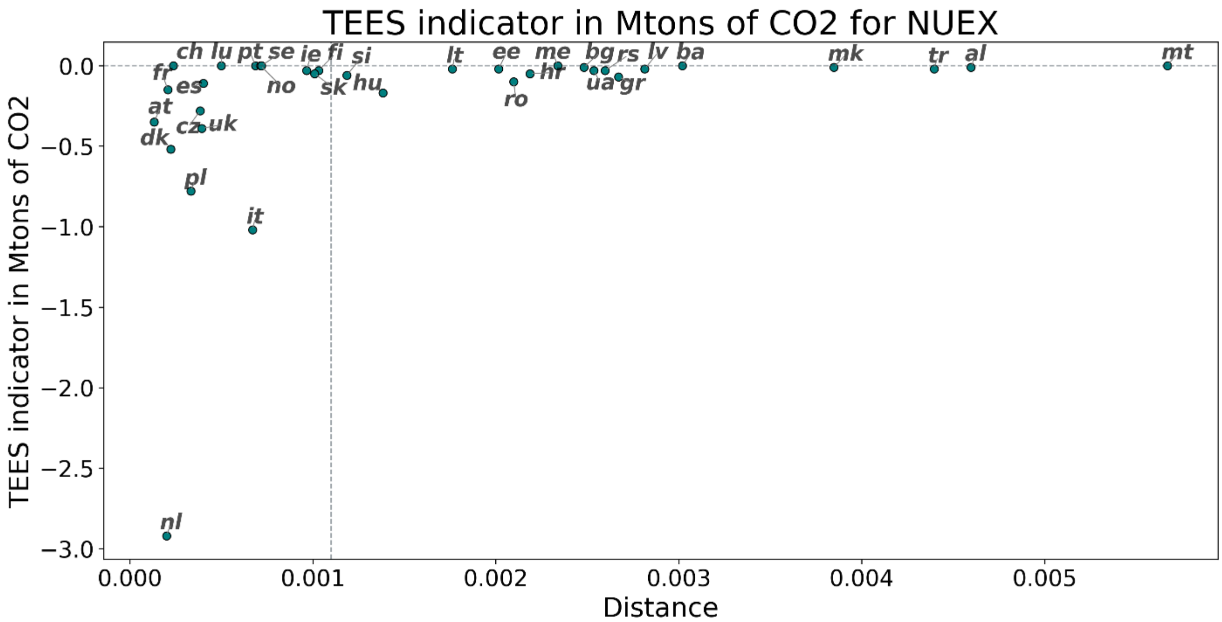

Figure 3 TEES_NUEX – TEES_FUCL relative to the *"distance"*

Source: authors' elaboration

Erreur ! Source du renvoi introuvable. illustrates the variation in total CO_2 emissions (TEES) between NUEX and FUCL in relative terms. The first observation is the change in the disposal of the data and the nature of the effect in each country. The non-linearity between the indicator and the *"distance"* here is further highlighted. Countries "farther" from Germany and Belgium, like Slovenia (si), Ukraine (ua) and Hungary (hu) are nearly as impacted as those closer, such as Austria (at) and the Netherlands (nl). Some countries have reduced their impact, like Italy and Poland.

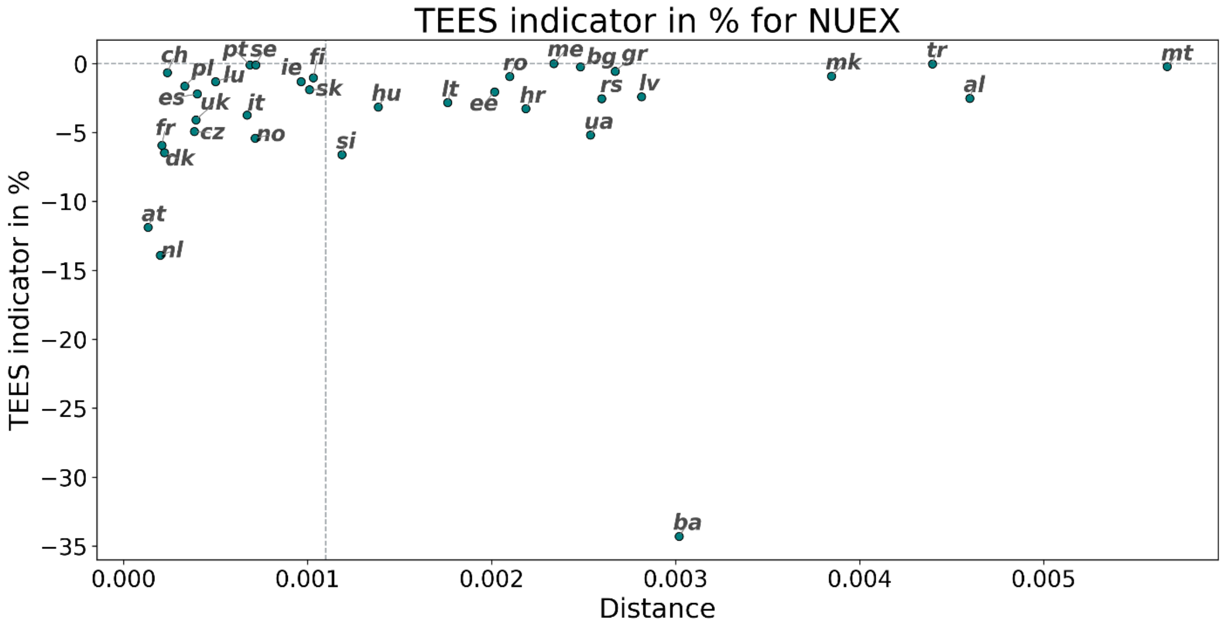

Figure 4 (TEES_NUEX – TEES_FUCL)/TEES_FUCL relative to the "distance"

Source: authors' elaboration

While *"distance"* plays a significant role in determining the impact intensity, other factors also seem to contribute, leading to the non-linearity that we observe. To better understand the countries which deviate from the expected trend of decreasing impact with increasing *"distance"*, we added complementary information to the plot as follows:

- Total electricity annual consumption of the country, normalized between the extreme values, represented by the size of the dot.
- Trader border status based on the annual balance of each country, resulting in net importers (in red) and net exporters (in blue) of electricity labelling in the function of the country label colour.
- The share of thermal capacity installed as a proxy for CO_2 intensity in the mix of each country designed by the colour intensity for each dot. The darker the colour, the greater the share of carbon-intensive technologies.

Figure 5 (TEES_NUEX – TEES_FUCL) relative to the "distance" with additional information

5 illustrates the previous **Erreur ! Source du renvoi introuvable.**3 with the added context elements.

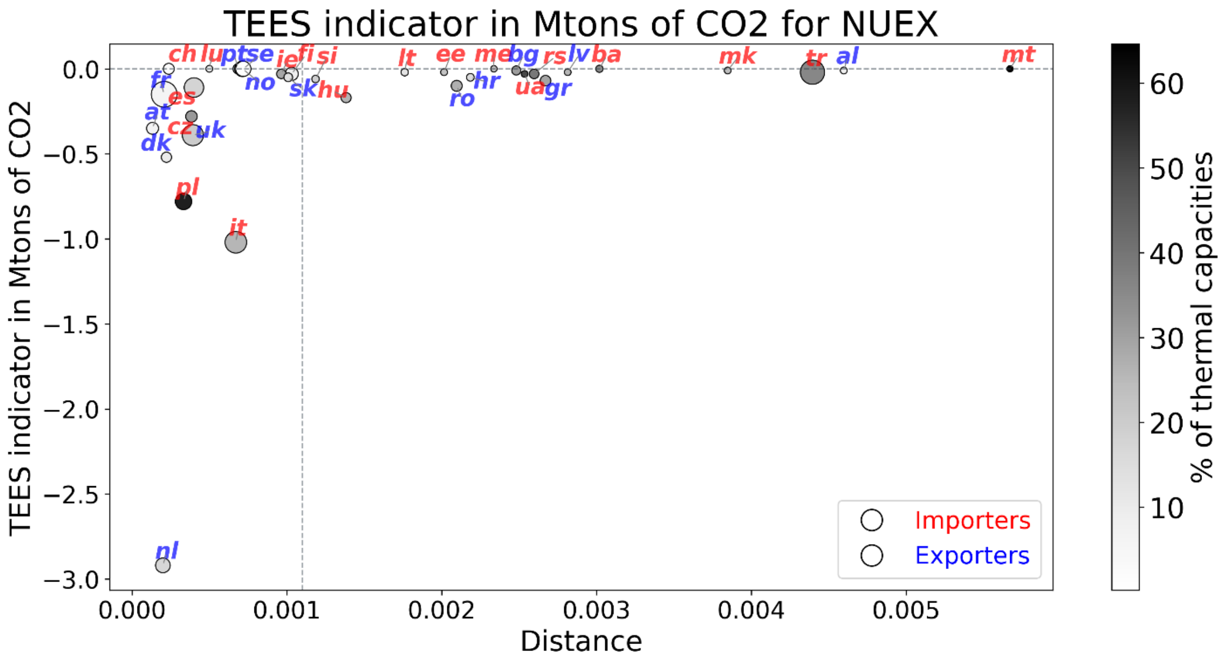

Figure 5 (TEES_NUEX – TEES_FUCL) relative to the "distance" with additional information

As shown in Figure 5 (TEES_NUEX – TEES_FUCL) relative to the "distance" with additional information

, the *"nearby"* countries most affected by the nuclear phase-out postponement contain carbon-intensive technologies in their mix, whether they are importers or exporters. Poland and Italy, as importers, stand to gain significantly from the opportunity to access cheaper, low-carbon imports. In contrast, the Netherlands and France, both exporters, will see their export obligations reduced, allowing for a decrease in CO_2 emissions. The difference in impact between these two countries is due to the type of electricity they export—mostly gas in the Netherlands and mostly nuclear in France. A reduction in carbon-intensive exports, like those from the Netherlands, results in a greater decrease in emissions compared to the reduction seen with low-carbon exports, such as those from France. Conversely, *"nearby"* countries that remain unaffected all contain low-carbon mixes. Whether they are importers or exporters, their mix shields them from major impact. The group of countries to the right of the dotted line (the median *"distance"*) experienced slight reductions in carbon emissions except for Romania (ro) and Hungary (hu). We will return to these countries below when we calculate the relative difference in TEES.

Although Romania is *"farther"* away than some unaffected countries, it experiences a similar level of impact as countries with a shorter *"distance"*. Its carbon-intensive mix drives a strong demand for cheaper low-carbon electricity and in terms of *"distance"* is still close enough to benefit from the available nuclear power. Countries neighbouring Romania that are *"closer"* to Germany and Belgium have low-carbon mixes and will, therefore, prioritize the transit of nuclear electricity to Romania. In contrast, despite having a carbon-intensive mix, Malta and Turkey are too distant to take advantage of this opportunity. Nonetheless,

6 indicates that, in relative terms, a greater amount of countries appear to be impacted.

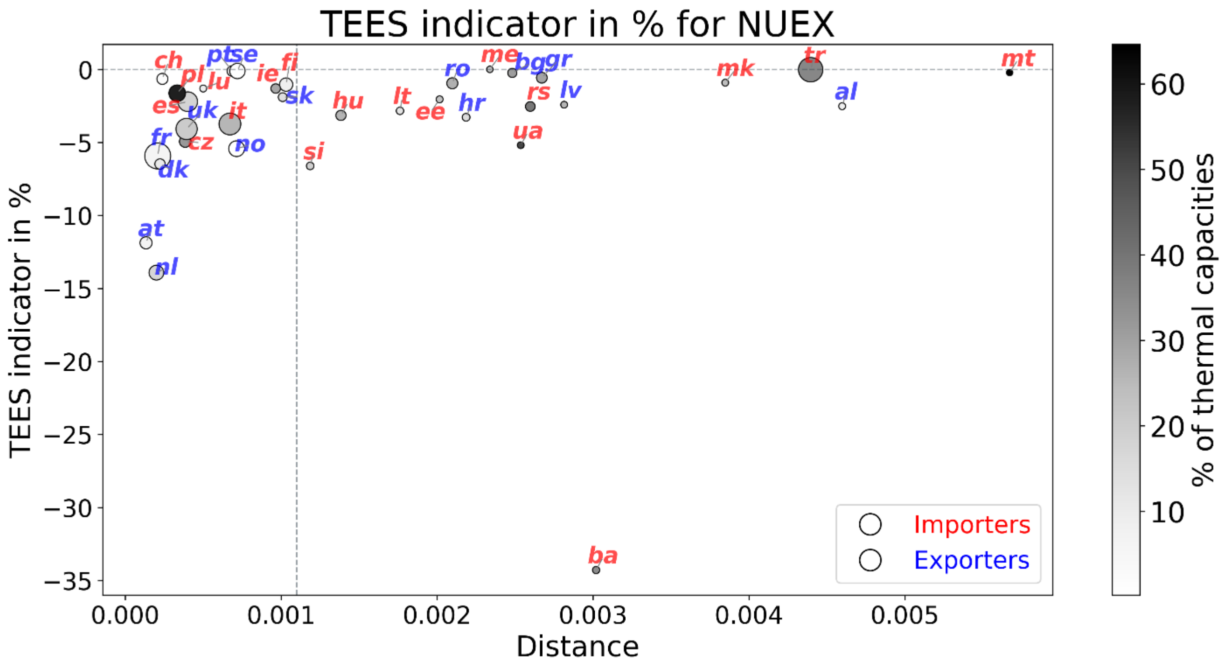

Figure 6 (TEES_NUEX – TEES_FUCL)/ TEES_FUCL relative to the "distance" with additional informations

Source: authors' elaboration

As illustrated in

, several countries ascend to high levels of impact in relative terms[4]. This rise can be attributed to two factors: their size of electricity demand and their mix. With small or low-carbon countries, the slightest change in emissions can lead to substantial relative impacts. Slovenia (si), Albania (al) and Lithuania (lt) see, therefore, an increase in their TEES indicator in relative terms. Taking into consideration those factors is thus crucial to understand how some decisions can have major repercussions in small and distant countries.

On the other hand, for relatively large countries or those with carbon-intensive mixes, significant changes are needed to experience a substantial relative impact. As a result, countries like Poland and Italy experience a milder relative impact. Despite varying levels, most countries experience a decrease in CO_2 under this nuclear expansion scenario, both in absolute and relative terms.

Socio-economic Welfare (SEW)

There is mostly a direct positive correlation between reduction of CO_2 emissions and decreasing in operational costs. Therefore, decreasing carbon emissions due to postponing the nuclear phase-out directly translates into economic savings by reducing the operational costs of carbon-intensive technologies. The postponement of nuclear phasing-out in NUEX scenario leads to a European annual

[4] ba stands for Bosnia and Herzegovina. Its TEES absolute indicator is affected in 4 years of 34 climatic years. Due to its mix and size of the demand a very slight modification could yield a high TEES indicator change in relative terms. Therefore, we infer this result is biased and we don't take into account our analysis.

improvement of the SEW of 3.09 billion, compared to the FUCL benchmark scenario, for year 2030. Figure 7 illustrates the distribution of annual SEW improvements across Europe, comparing Germany, Belgium, the countries where SEW increased due to the postponement of nuclear phase-out and the countries where SEW decreased.

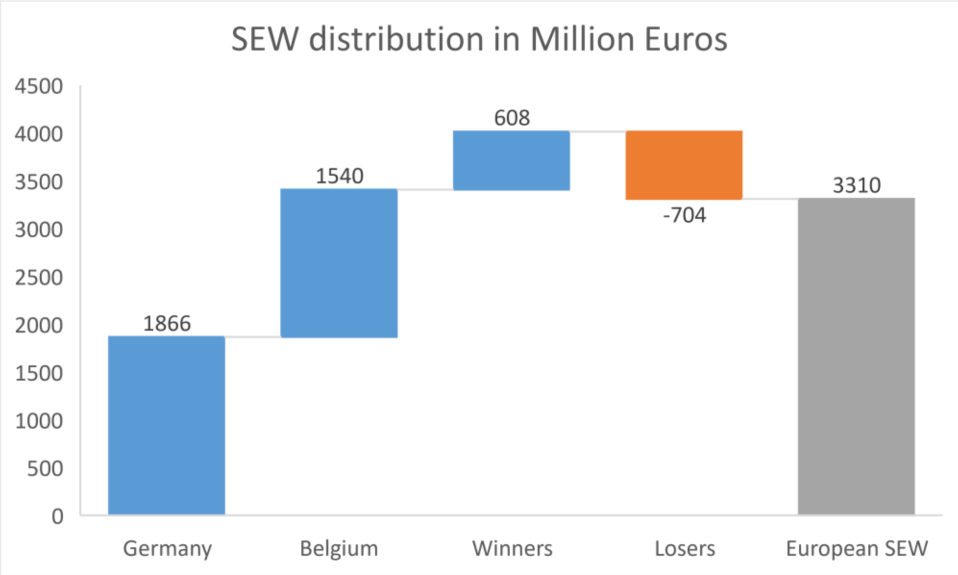

Figure 7 Distribution of SEW across Europe

The optimal power scheduling in NUEX modifies the equilibrium exchanges between market zones, the occurrence of electricity congestion between two market zones, and the equilibrium quantity and price within a given market zone.

Figure 8 (SEW_NUEX – SEW_FUCL)) relative to the "distance"

8 illustrates the variation in SEW between the NUEX and FUCL scenarios relative to *"distance"*, revealing a different effect than that observed in TEES.

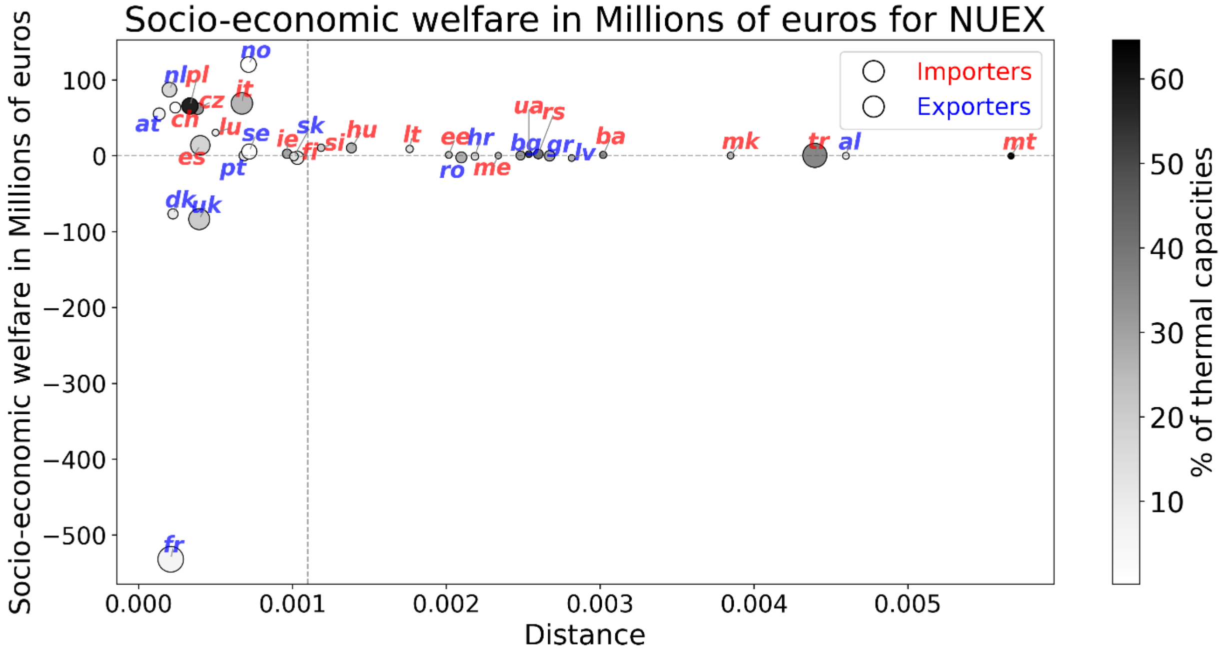

Figure 8 (SEW_NUEX – SEW_FUCL)) relative to the "distance"

Source: authors' elaboration

While all bidding zones near Germany and Belgium reduced their carbon emissions by decreasing fossil-fuel-based generation in NUEX, not all experienced an increase in SEW. In fact, the SEW of France, the United Kingdom and Denmark suffered a contraction. This contraction is partly due to their status of net exporting countries and partly due to the type of power traded. Since these countries trade mainly renewables and nuclear power, the losses in producer surplus and congestion surplus caused by reduced equilibrium prices and trading volumes outweigh the gains in consumer surplus. Conversely, the exporting bidding zones, Netherlands and Austria, see an increase in SEW due to the type of power traded. They have a partially decarbonized mix, and a great share of their fossil-fuel-based generations is dedicated to export. Since the postponement of the nuclear phase-out would release the Netherlands and Austria from exporting, the gains in consumer surplus and changes in congestion surplus outweigh the losses in producer surplus.

Poland, Switzerland, Czech Republic, Italy and Luxembourg profit from the cheaper extra dispatchable nuclear power to reduce their costs and increase their socio-economic welfare since they are already net importers. Norway benefits from the German and Belgium nuclear phasing-out as its mix is decarbonized and it has low-carbon dispatchable power (hydraulic). The gains in consumer surplus outweighs the losses in producer surplus. Regarding Portugal, Spain, Sweden, Ireland, Slovakia and Finland, the variations of consumer surplus, producer surplus and congestion surplus nearly balance out remaining almost unaltered to postponing nuclear phase-out. For the rest of the countries placed after the dotted vertical line are overall slightly touched.

We conclude that the postponement of the nuclear phase-out creates a significant spillover effect. This effect influences neighbouring countries, but not with the same intensity nor in a uniform manner. Additionally, distant countries might be affected either regarding TEES or SEW. This indicates that the effect does not solely depend on the "distance".

4.3) Sensitivity to climate years

We now complete our analysis by focusing at climatic impact, analysing our results in light of the 34 climate years that we have used. Figure 9 Distribution of TEES in absolute value in response to climate years

illustrates the distribution of the variation of total CO_2 emissions (TEES) in absolute terms for all the 37 countries in response to the sensitivity of the climate years. This sensitivity is important in order to take into account climatic uncertainties in the response of each country and to understand which countries are more sensitive to meteorological conditions. Some countries, other than Germany and Belgium, such as United Kingdom, Poland, Greece and Netherlands have a wide range of response in the variation of TEES depending on the climate year.

Figure 10 zoom in on TEES values between [-1; +0.5]

provides a closer examination of other countries exhibiting a more limited range of responses such as Spain, Finland, Ireland and Portugal, which pass from positive to negative impact depending on the climate year. These charts corroborate that the results are dependent on the climate year.

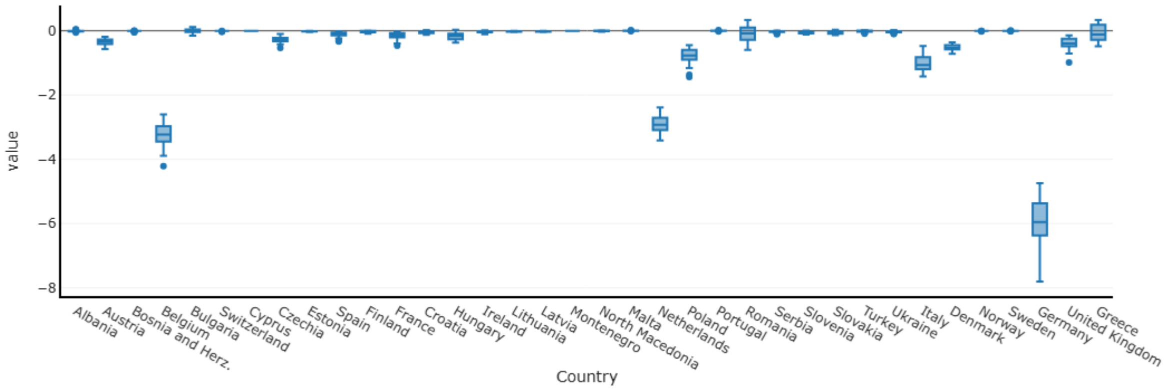

Figure 9 Distribution of TEES in absolute value in response to climate years

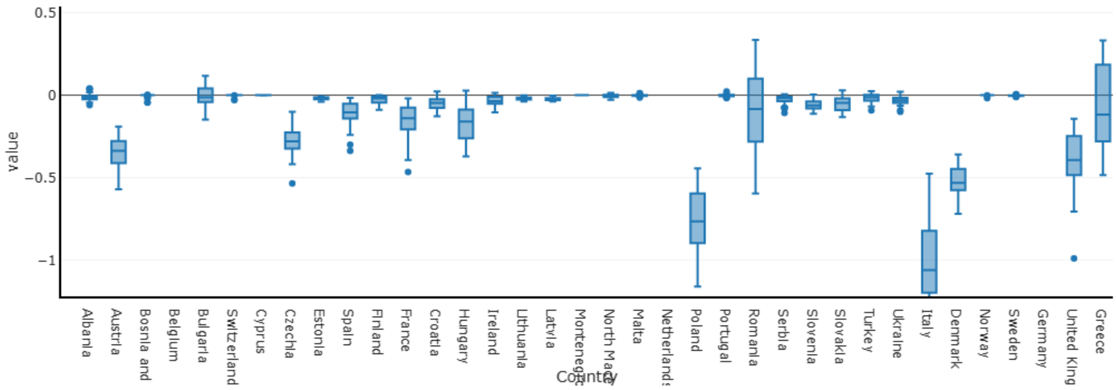

Figure 10 zoom in on TEES values between [-1; +0.5]

4.3.1) Clusters

In order to further understand the behaviour of our results depending on climate years, we proceeded with a k-means cluster method. We decided to use a k-means algorithm to group data into distinct clusters with the purpose of finding patterns and asses the sensitivity to climate years. We use the elbow method for distortion and inertia to define the k numbers of cluster, c.f Appendix G. The use of this method resulted in 7 clusters distributed as shown in Figure 11 and explained in Table 4.

Cluster dot mark	Name	Description
Gray circle	Neutral	In the *neutral* group there are some slight changes regarding either CO_2 emissions or SEW. However, the changes between the two scenarios are not important enough relative to the other countries making it the group less impacted by the Belgium and Germany nuclear phasing out postponing.
Orange diamond	Net positive impact	*Net positive impact* comprises a defined impact on the reduction of CO_2 emissions and gain in SEW due to nuclear postponement, detaching from neutral group in the distance from the coordinate origin.
Tail diamond	Welfare Growth	*Welfare growth* contrasts from *Net positive impact* on the intensity of gains of SEW, this group benefits similarly in CO_2 emissions reductions but harness the nuclear postponement to increase its SEW.
Red plus	Economic progress	*Economic progress* contrasts from *Net positive impact* on the reductions on CO_2 emissions, this group benefits similarly in gains of SEW but take advantage of low-carbon nuclear energy to reduce further its locals emissions due to power generation.
Purple square	Tradeoff	In the *trade-off* group, the environmental gain in terms of CO_2 emissions is contrasted with the loss of SEW; for such countries, a nuclear extension policy in Germany and Belgium would reduce the fossil-fuel-based generation either by importing more low-carbon power or exporting less carbon-intensive power. Yet, there is a decrease of SEW. This results in a trade-off. Although postponing nuclear phase-out certainly reduces the overall cost of the system, the distribution of economic gains is not homogenous.
Black cross	Critical Tradeoff	This group has a similar reduction in CO_2 emissions than *Tradeoff*, however its decrease in SEW is more accentuated. Nuclear postponement would reduce fossil fuel-based generation at expense of great losses in SEW. France is the big SEW loser in the case of a nuclear extension in Belgium and Germany, hence the sole member of this *Critical Tradeoff* group.
Green circle	Double positive effect	While some countries weigh the benefits and drawbacks of nuclear policy, there is a group of countries that actually undergo a *double positive impact*, meaning that they experience both a reduction of CO_2 emissions and an improvement in SEW, illustrated by blue circle in Figure 11. Analogous to the double dividend tax environmental theory (Allan et al., 2020), postponing the nuclear phase-out generates for this group the first benefit of reduction of carbon emissions and the second one, “double dividend” of improving SEW, which can eventually be used to promote further environmental policies.

Table 4 Cluster details

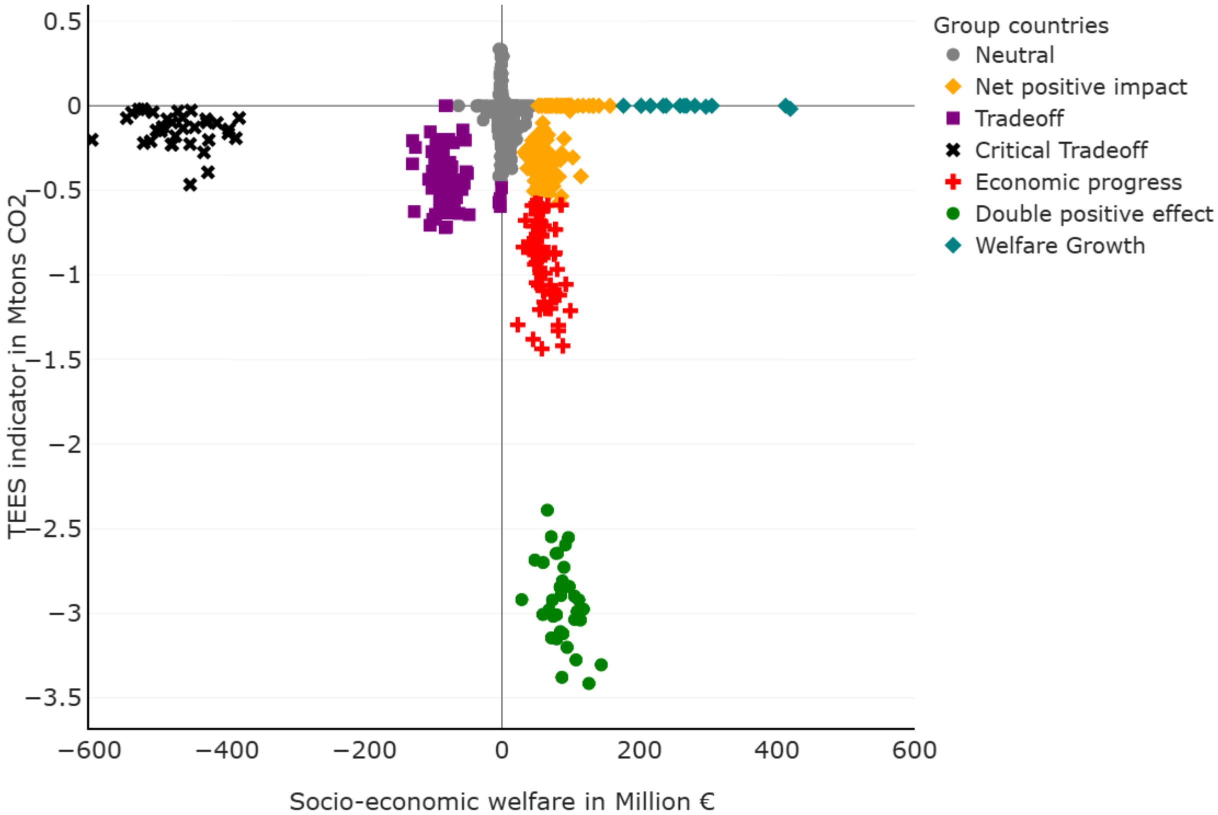

Figure 11 CO2 and SEW impacts of NUEX compared to FUCL for the 34 modelled climate years

Figure 12 shows the number of clusters to which each country belongs. The greater the number of cluster a country belongs, the more sensitive it is to the climate, presenting different trends depending on the analysed year. Countries like Switzerland, Norway, Poland, Romania and Greece[5] are within the countries belonging to 2 or more clusters. For example Norway in rainy years belongs to trade-off group suffering a decrease in the SEW in contrast to dry years belonging to Welfare growth group. This highlights the sensitivity of these countries to the nuclear policy because it provokes contrast effects such as economic benefits (Welfare growth) or economic impacts (Trade-off group) like the case of Norway.

Table H in the appendix illustrates the share of hydro-based technology in the total power generation capacity for each country. Among the top five, three countries—Switzerland, Norway, and Austria—exhibit sensitivity to climatic variations, shifting between groups depending on the climate year. This highlights the crossed influence of climatic conditions and nuclear policy for countries with a high share of hydropower generation.

The remaining countries, including those ranked up to the top ten in our results, belong to the neutral group and do not appear to be sensitive to climatic variations. However, this does not contradict our previous statement, as these countries are still impacted in terms of CO_2 emissions (see Section 4.3). For example, Slovenia, Slovakia, North Macedonia, and Albania experience emissions-related effects,

[5] We excluded from this group countries which belong to two groups but having one group that is quite small (1 year out of 34) in comparison to the other. For instance Italy (Greece also): 33 years belong to Balance transition group and one year belongs to Trade-off group.

despite the latter two being geographically distant from Belgium and Germany. The reason of its belonging to neutral group could be related to the limitations of the clustering technique.

This may also explain why Bosnia and Herzegovina was excluded from our analysis (see Section 4.3). As for Montenegro, it appears to be unaffected.

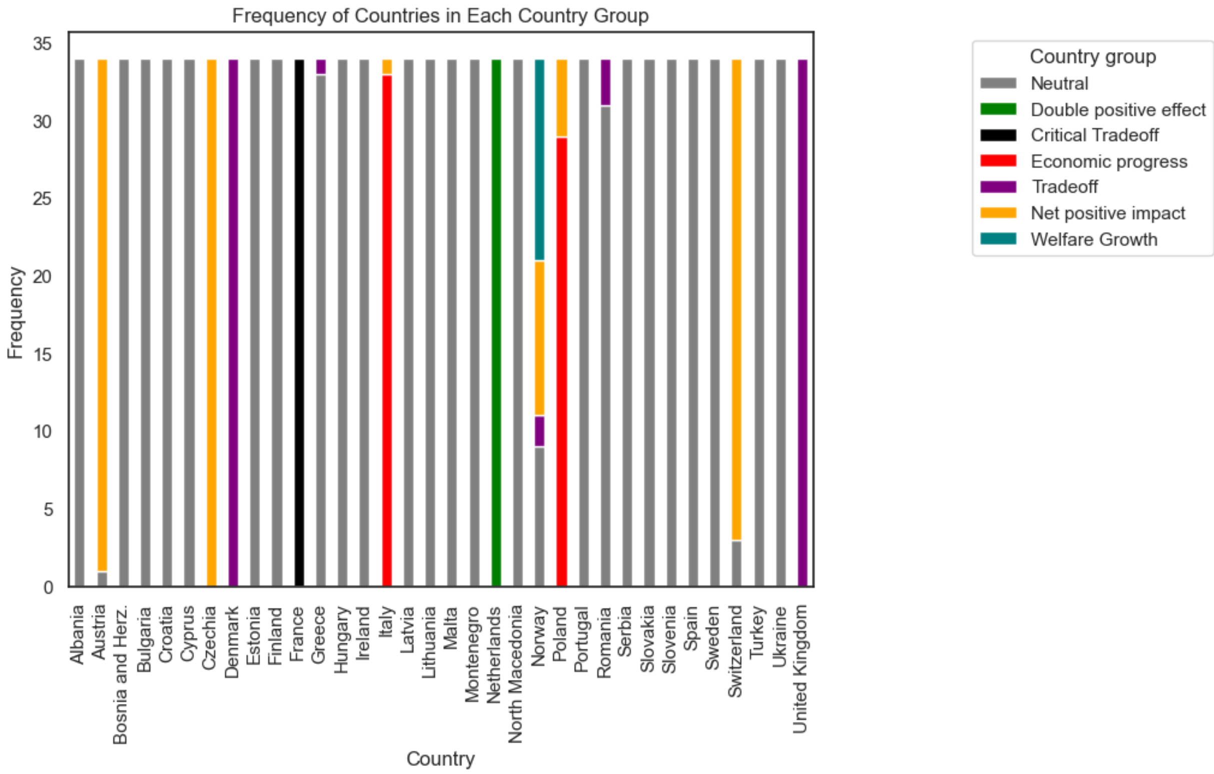

Figure 12 Frequency of cluster per country for the 34 climate years

The rest of the countries belonging to a single cluster will have the same trend throughout the 34 climate years, meaning their results are less sensitive to weather.

5) Policy implications and conclusion

This paper analyses the impacts on the European electricity system of the policy decision to phase-out nuclear power in Belgium and Germany. It aims to study the direct effects on power dispatch and economic efficiency at the national level as well as the indirect effects caused by changes in imports and exports throughout the rest of the European system. The goal is to provide evidence-based insights into how the European electricity system reacts to national energy policies, focusing on a 2030 horizon. This analysis seeks to contribute to the ongoing debate about the role of nuclear energy in the European energy transition.

The postponement of the nuclear phase-out in Belgium and Germany would reduce in 2030 the European CO_2 emissions coming from electricity production by approximately 16,4 Mtons which represents around of 4% of total electricity European emissions in 2024. From this total CO_2 reductions 20% come from Belgium, 36% from Germany, through the direct substitution of nuclear power in the merit order, primarily replacing gas and coal-based power plants. The remaining 44% is the result of the spill over effect through the variation and substitution in imports and exports in the rest of Europe. Since there is an impact all over Europe and common CO_2 emissions decrease targets are shared, the analysis of our scenario becomes a relevant question for policy analysis.

Having realized that the indirect effect is considerable, we established metrics to assess the impact of Belgian and German nuclear policy across the European power system. The interconnections evidently play a central role in determining the changes in the power scheduling. Therefore, we transformed the interconnections into "*distances*". Our model reveals that "*distance*" from Germany and Belgium does not fully explain the variation in CO_2 emissions as countries at the same *"distance"* experienced markedly different changes in their power scheduling. Inversely, "distant" countries might undergo changes of the same magnitude as "close" ones. We complemented our analysis by considering the size of each country, its trading status, and the share of carbon-intensive technologies in its energy mix.

We also observed that the total SEW in Europe increased in our nuclear extension scenario but the variation is not uniformly positive for all countries. For instance, while France would have experienced a reduction in socio-economic welfare, the Netherlands would have benefitted from the nuclear extension. Gains in consumer surplus and congestion surplus outweigh the losses in producer surplus, despite both countries being at the same *"distance"* and well interconnected.

This outcome could distort the incentives for countries negatively affected by nuclear extensions to support global carbon emission reductions, especially if CO_2 prices rise. These insights are crucial for designing future energy policies, as they underscore the importance of European energy policy integration and coordination, and challenge the economic efficiency of solely national plans.

Political insights into how country-level policies can affect a system such as the European electricity integrated system are one of the main outcomes of this study. Because of the interdependence of European countries' electrical systems, political decisions and mix choices in one country do affect other countries, mostly neighbouring countries but also countries with no direct connexions. This is a crucial aspect to consider during energy policy discussions in order to reach common environmental targets, giving way to prioritize climate goals rather than political-based decisions that impact a whole region.

A conclusive aspect of the present study is that interconnections are the arteries of the European electricity system. These interconnections make it possible to mutualize either the advantages or drawbacks of energy political decisions made elsewhere than in one's country. This emphasizes the interest in coordinating policies throughout European countries in order to reach energy security goals as well as climate targets.

6) Limits of the study

European electricity system modelling is complex, heterogeneous and difficult to abstract without simplification, posing restrictions to the computational capacity for doing calculations which lead to modelling limitations, outlined below.

The high dimensionality of the European power system is simplified through only one representative technology per fuel-based source grouping all power plants of the same type. The total installed capacity of the system is unequal across the scenarios. However, the scenarios' conceptions comply with short-term nuclear phase-out policy decisions, making up for the installed capacity unevenness and validating the comparison across the scenarios. Because the modelling tool used for this study consists of minimizing the cost function to obtain an optimal scheduling, we don't take into account the complexity of all the market rules. In addition, the indicators used do not distinguish between the impact per economic sector[6] but rather a global impact on the system. Moreover the demand is inelastic to price and its shape remain fixed through the scenarios. One another well-known downside of day-ahead power market is the non-convexities caused by the start-up costs, minimum output levels at which the plant can operate, the minimum up-and-down time. (Madani and Van Vyve, 2015) analysed this drawback and contrasted with other techniques such as convex hull optimisation or quadratic optimisation so that the shadow prices might represent the efficient costs of an equilibrium market, accomplishing the strong duality theorem (Samuelson, 1952). In our case, we applied a less sophisticated approach but suitable for large scale models – the fix and relax approach. It consists simply in resolving in two steps the optimisation problem, relaxing the binary variables in the first step and fixing them in the second so that the second step solves a linear problem totally convex (G´omez et al., 2025). This approach leads to some inefficient equilibrium for some economic actors yielding some losses or gains in the equilibrium. Nevertheless, these imperfections are acceptable to answer our research question.

Following to this downside, as European power system is well interconnected, when simulating the inter-zonal exchanges, the resulted primal values might be quite sensible to small inputs perturbations. This raises concerns about the robustness and interpretability of the results. To deal with it, we performed sensitivity analyses, as a part of the results in section 4.2, we varied the ENR and load generation, and the main outcomes stand steadily. To complement, we varied the generation costs of fuel-based technologies by increasing proportionally to the distance from Germany and Belgium, and the main outcomes remain the same.

Last but not least, due to computationally limits, the carbon emissions generation is not considered as an endogenous variable, so by extension, the carbon price is settled exogenously[7]. Because of all of this, results should be considered as trends and avoid taking them as absolute values or forecasting results

[6] Primary, secondary and tertiary sectors suffer heterogeneous impacts regarding the energy policies

[7] Although the reduction of 16.1 $MtCO_2$ may influence the carbon price, carbon emissions cannot be modeled as an endogenous variable

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8) Appendix

A) Countries with their ID

Country	ID
Albania	AL
Austria	AT
Bosnia and Herzegovina	BA
Belgium	BE
Bulgaria	BG
Switzerland	CH
Cyprus	VY
Czech Republic	VZ
Germany	DE
Denmark	DK
Estonia	EE
Spain	ES
Finland	FI
France	FR
Greece	GR
Croatia	HR
Hungary	HU
Ireland	IE
Italy	IT
Lithuania	LT
Luxembourg	LUB
Latvia	LV
Montenegro	ME
Republic of North Macedonia	MK
Malta	MT
Netherlands	NL
Norway	NOM
Poland	PL
Portugal	PT
Romania	RO
Serbia	RS
Sweden	SE
Slovenia	SI
Slovak Republic	SK
United Kingdom	UK

B) Distances

Let M be the set of market zones and C the set of countries.

Let the set of the interconnection between two market zones $m \in M$ as net transfer capacity (NTC). Hence, for each market zone, there is a set of interconnected zones J_m compliant with a set of net transfer capacities values NTC_m.

We set the distance (DTS_m) between two zones m as the inverse of its NTC, $DTS_m \Leftrightarrow dts = \frac{1}{ntc}$. Then, we calculated the shortest path between each market zone m and Belgium and Germany by applying Dijkstra's algorithm. The results are sets of short paths $SP_n, n \in M$ and $\{Germany\ and\ Belgium\} \notin SP_n$. Figure 12 presents an example of the SP by applying Dijkstra's algorithm for distance between *node 0* and *node J* showing the optimal path in green.

Combining the sets M, J_m, NTC_m, we define the graph of the European power network as a pair of sets (M, J_m) where M are the vertices and J_m are the edges. Each edge is defined as a pair {m,j} $\forall m \in M$; $\forall j \in J_m$,and the weight for each edge is $ntc \in NTC_m$.

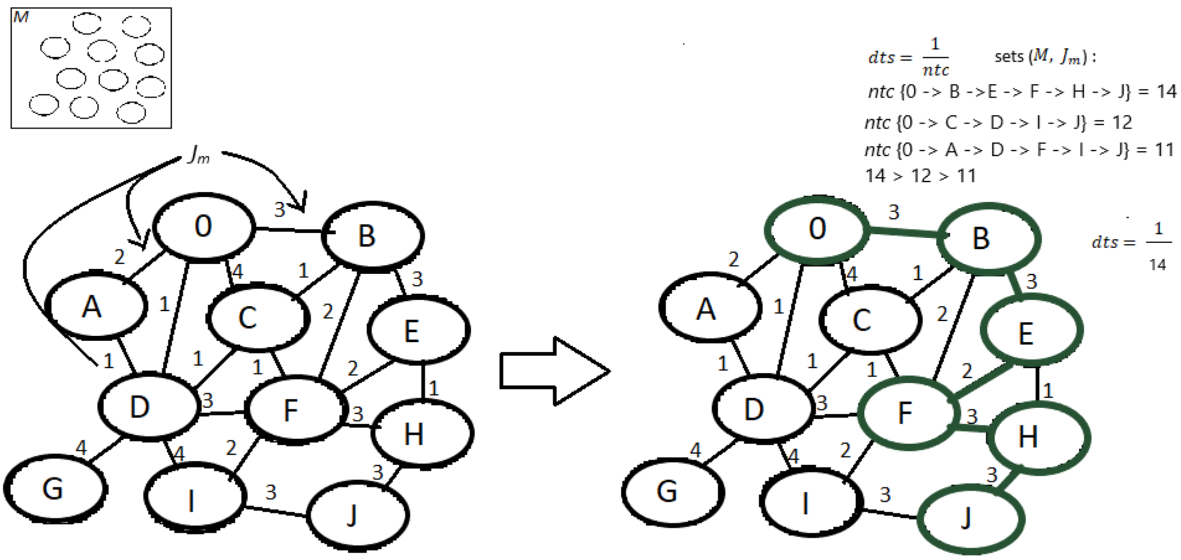


Figure 12 Exemple of Short Path for Dijkstra's algorithm for distance between nœud 0 and nœud J

C) Total CO_2 emissions electricity supply (TEES)

We calculate emissions by country and then we calculate absolute and relative differences between scenarios as follows: we ran a set of $S = \{FUCL, REAL, NUEX\}$ scenarios; in the following, we omit the scenario index $s \in S$ from the equations for simplicity. On any market zone $m \in M$, there is a set of P_m producing units, for which we track commitment at the hourly level over a year, $h \in H = [1,8760]$. We then defined parameters and model outcomes:

- Parameters :
  - $er_p, \forall p \in P_m, \forall m \in M$: the CO_2 emission rate of plant p in market zone m
- Model results (optimal values)
  - $Q_{p,h}, \forall p \in P_m, \forall m \in M, \forall h \in H$: the output of plant p in market zone m at hour h ;

We set the total emission of electricity supply for each market zone m as:

$$TEES_m = \sum_{h \in H} \sum_{p \in P_m} er_p * Q_{p,h}$$

Then, to get TEES indicator in absolute terms of any pair of scenarios $(s_1, s_2) \in S^2$, we just make the difference.

$$\Delta_{TEES_m}^{s_2 \leftarrow s_1} = TEES_m^{s_2} - TEES_m^{s_1}$$

The CO_2 emissions coming from the power traded between countries is not counted down in the CO_2 emission calculation. We set to the relative difference as follows:

$$\Delta_{TEES_m}^{s_2 \leftarrow s_1} = \frac{TEES_m^{s_2} - TEES_m^{s_1}}{TEES_m^{s_1}}$$

Remark: for the sake of illustration, we set the difference $\Delta_{TEES_m}^{s_2 \leftarrow s_1}$ as the amount of CO_2 emissions avoided between scenarios. In other words, a positive value means the reduction of CO_2 emissions, and a negative value means the increase of CO_2 emissions.

D) Consumer Surplus (CS)

- Parameters :
  - $L_{m,h}$, $\forall m \in M, \forall h \in H$: load of a market zone m at hour h ;
- Model results (optimal values)
  - $\lambda_{m,h}, \forall m \in M, \forall h \in H$: the marginal value of the demand constraint in market zone m at hour h. Based on the marginal value pricing principle, we assume that this shadow value represents the market clearing price of market m at hour h (Munasinghe, 1990).

We set the consumer surplus as the difference of the shadow values between the scenarios multiplied by the load.

$$\Delta_{CS_m}^{s_2 \leftarrow s_1} = \sum_{h \in H} (\lambda_{m,h}^{s_2} - \lambda_{m,h}^{s_1}) * L_{m,h}$$

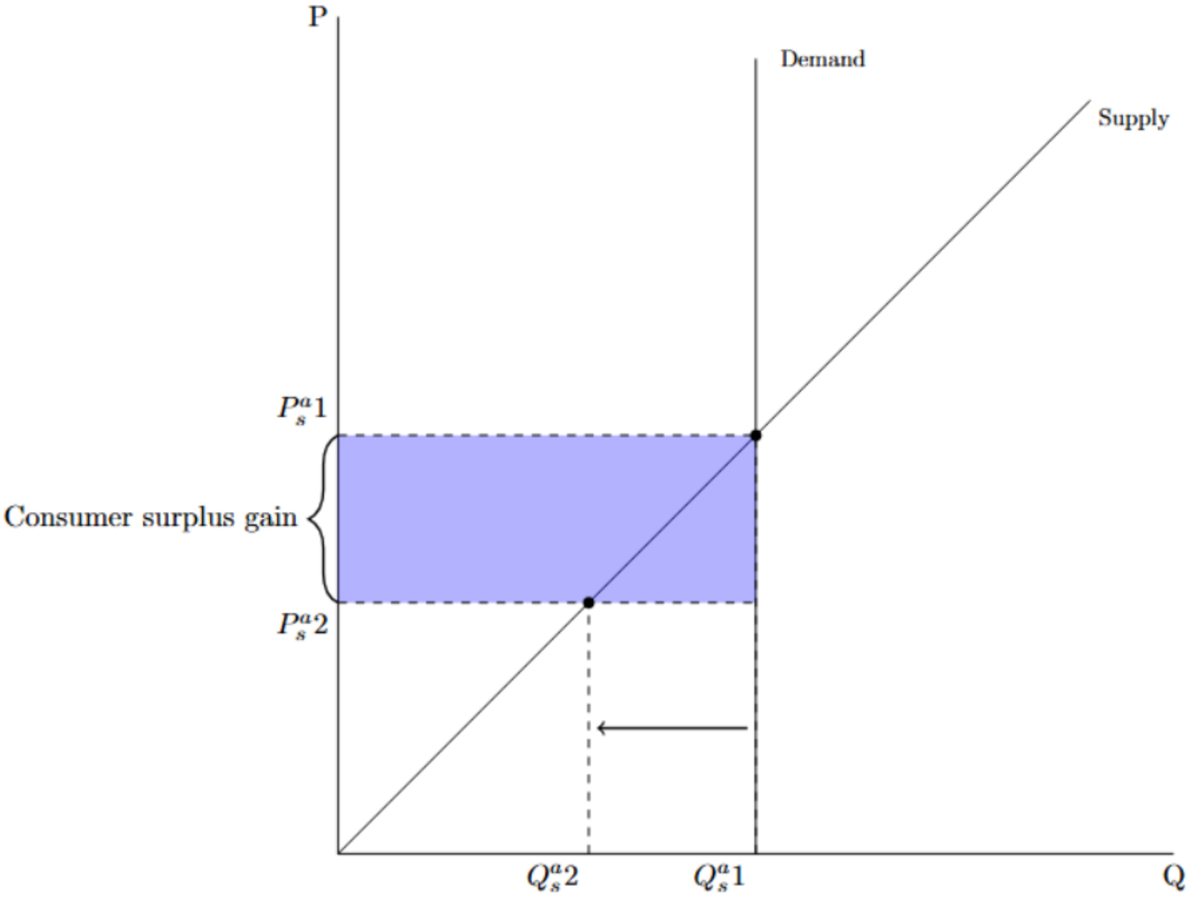


Figure 13 Gain in consumer surplus

In Figure 13 the purple area represents the gain in the consumer surplus of a country 'a' when comparing reference scenario at P_{s1}^a to another scenario when importing electricity at priceP_{s2}^a.

E) Producer surplus (PS)

- Parameters :
  - $FC_{p,h}, \forall p \in P_m, \forall m \in M, \forall h \in H$: the unit fuel cost of plant p in market m at hour h. The carbon tax and the efficiency are already included ;
  - $VOM_{p,h}, \forall p \in P_m, \forall m \in M, \forall h \in H$: the unit variable O&M cost of plant p in market m at hour h;
- Model results (optimal values)
  - $Q_{m,h}, \ \forall m \in M, \forall h \in H$: the equilibrium electricity amount in market m at hour h ;

We set the producer surplus as the difference between the shadow value multiplied by the production and the operational costs for each technology.

$$PS_m^s = \sum_{h \in H} \left[\lambda_{m,h}, * \, Q_{m,h} - \sum_{p \in P_m} \left(FC_{p,h} + VOM_{p,h} \right) Q_{p,h} \right]$$

$$\Delta_{PS_m}^{s_2 \leftarrow s_1} = PS_m^{s_2} - PS_m^{s_1}$$

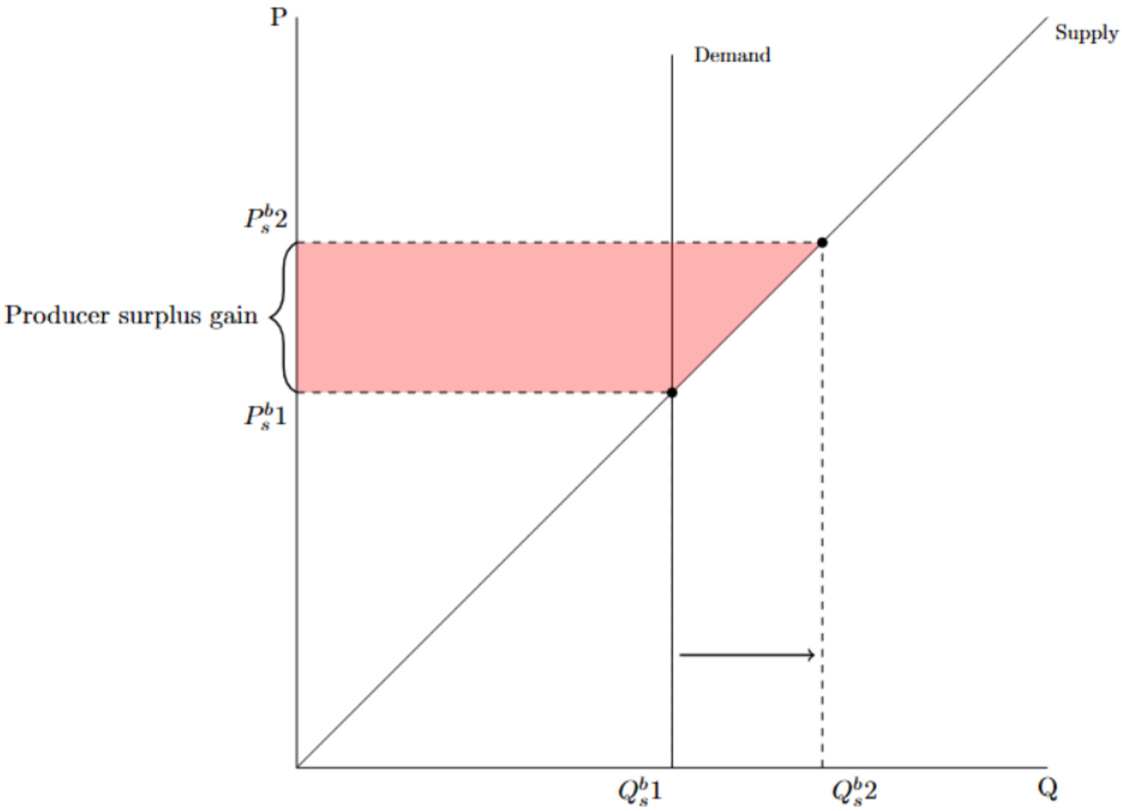


Figure 14 Producer surplus

In Figure 14 the red area represents the producer surplus of a country '*b*' when comparing the reference scenario at P_{s1} to another scenario when exporting electricity at price P'_{s2}

F) Congestion surplus (CSP)

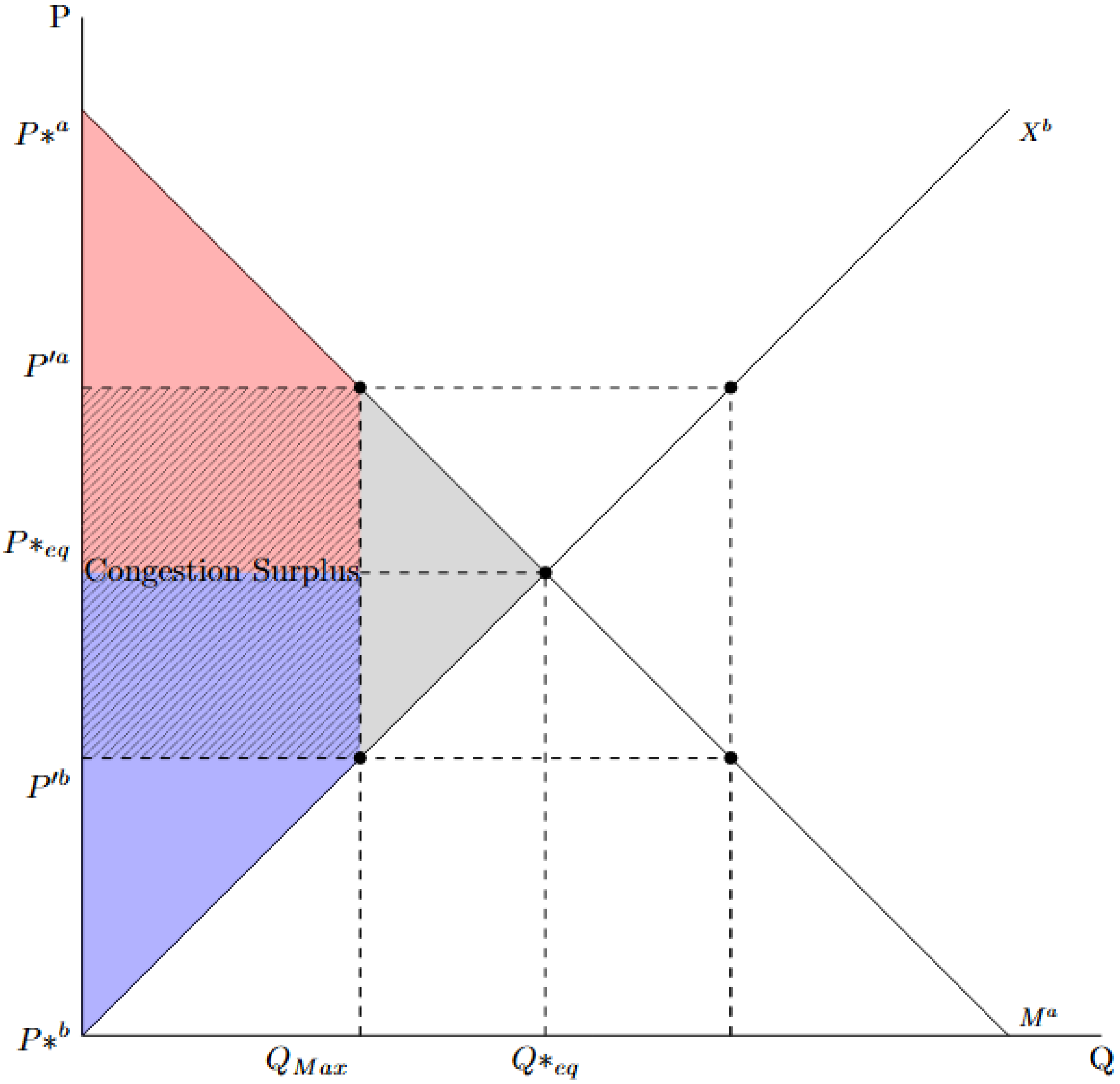
We set:

- Parameters :
  - $tc_m^j, \forall m \in M, \forall j \in J_m$: the unit transmission cost between two connected zones ;
- Model results (optimal values)
  - $T_{m,h}^j, \forall m \in M, \forall j \in J_m, \forall h \in H$: the net electricity transfer between markets m and j at hour h;
  - $\lambda_{m,h}^j, \forall m \in M, \forall h \in H, j \in J_m$: The marginal value of the demand constraint in the interconnected market zone j with respect to m at hour h; we assume this shadow value represents the market-clearing price. Remark that unless the transmission capacity between m and $j \in J_m$ is saturated, there is no arbitrage opportunity between the two zones; therefore, market clearing prices differ only by transmission costs, $\lambda_{m,h}$=$\lambda_{j,h} \pm tc_m^j$, depending on the direction of the flow[8].

[8] See e.g. Samuelson (1952).

We set the congestion surplus as the absolute value of the shadow value between the importer zone and the exporter zone multiplied by the power traded

$$CSP_m^s = \sum_{h \in H} \sum_{j \in J_m} \left|\lambda_{m,h} - \lambda_{m,h}^j\right| * T_{m,h}^j$$



$$\Delta_{CR_m}^{s_2 \leftarrow s_1} = CR_m^{s_2} - CR_m^{s_1}$$

Figure 15. Illustration for the congestion surplus

If we illustrate the willingness of country *a* to import as the curve M^a and the willingness of country *b* to export and restrain the flow of electricity by a Q_{Max}, the congestion surplus is defined by the difference of prices of country *a* and *b* times the quantity of electricity exchanged. In Figure 15, the strayed area represents the congestion surplus

G) The elbow method for defining K number of clusters

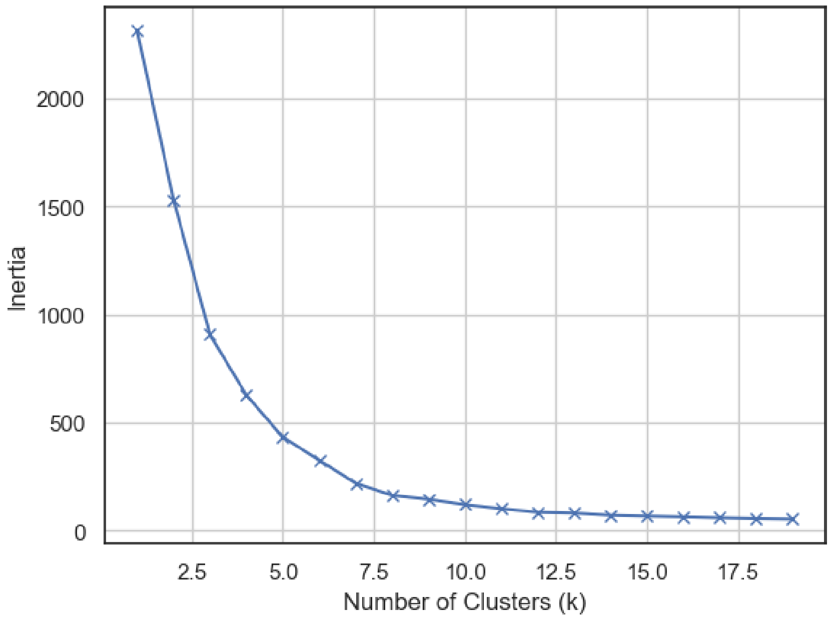


Figure 16 Elbow method using Inertia

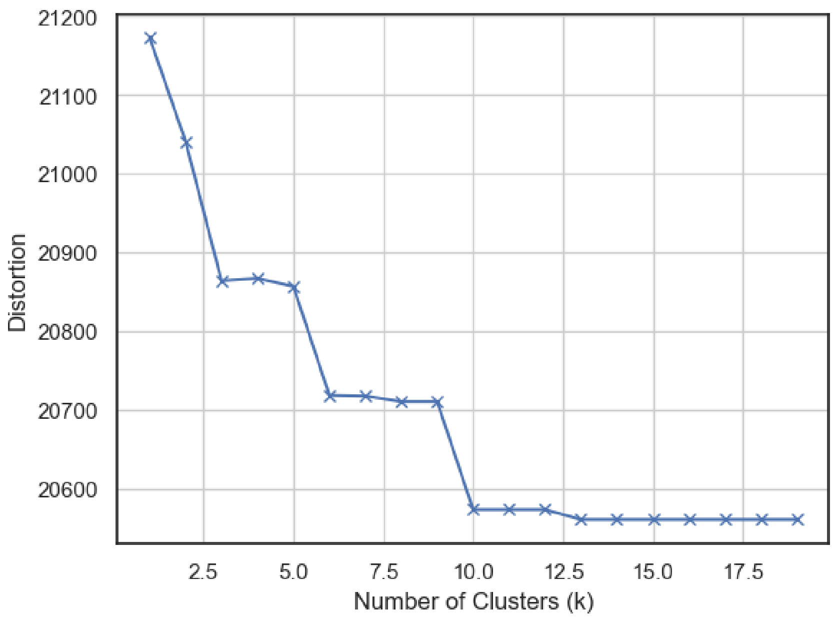


Figure 17 Elbow method using Distortion

H) The ranking of share of hydro based technology.

	Country	Hydro_capacity[9]	Total capacity installed	% of hydro-based technology
1	Albania	2691	3691	72,9
2	Norway	33361	46780	71,3
3	Montenegro	1198	1983	60,4
4	Switzerland	16304	30460	53,5
5	Austria	31100	62373	49,9
6	Bosnia and Herz,	2494	5496	45,4
7	Latvia	1699	4134	41,1
8	North Macedonia	1136	2860	39,7
9	Slovenia	2652	7022	37,8
10	Slovakia	3745	10096	37,1
11	Croatia	2678	7881	34
12	Turkey	39675	124340	31,9
13	Sweden	16447	52076	31,6
14	Romania	9093	29556	30,8
15	Portugal	9275	30951	30
16	Serbia	4210	14996	28,1
17	Bulgaria	3606	14556	24,8
18	Lithuania	1120	5476	20,4
19	Czechia	3645	20953	17,4
20	Spain	26674	159177	16,8
21	Italy	29755	181215	16,4
22	France	29738	194585	15,3

[9] Hydro_capacity : it spans reservoir storage (dams), run-of-the-river, pumped storage power type open and closed c.f the technical note of ESMOD to further details.