Energy Strategy Reviews 64 (2026) 102179

Contents lists available at ScienceDirect

Energy Strategy Reviews

journal homepage: www.elsevier.com/locate/esr

Cross-border impacts of nuclear phase-out policies on the European power system: Economic and environmental insights for strategic energy planning

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ARTICLE INFO

Handling Editor: Dr Jesse Van Griensven Thé

Keywords:
Nuclear energy
Power system modelling
Energy Policy
European coordination
Cross-border effect

ABSTRACT

The European power system plays a strategic role in reducing dependence on fossil fuels while contributing to reaching Europe's CO2 emissions targets. The energy crisis triggered by Russia's war against Ukraine has revived interest in the role of nuclear energy in the European power system. We examine how postponing nuclear phase-out affects optimal dispatch and environmental performance of the interconnected European power system. We use ESMOD, a unit commitment model of the European electric system at the 2030 horizon, built with Antares Simulator, to assess the impact of nuclear phase-out policies in Germany and Belgium. The model accounts for 36 European countries and focuses on cross-border effects and country-level impacts. The model shows that not decommissioning 4 GW of nuclear capacity in these two countries would have reduced European CO2 emissions by 16 million tons in 2030. Strikingly, about 45% of such reductions would have occurred in other European countries and keeping nuclear power plants in operation would have increased the total European surplus by 3 billion euros heterogeneously affecting across countries. To interpret these heterogeneous effects, we analysed the load size, power mix, trader status and interconnections to explain cross-border sensitivities. Finally, we assessed the countries' sensitivity to weather variation across 34 climate years by classifying them using the K-means clustering method. The results underscore the central role of European energy policy coordination in shaping future energy strategies that prioritize climate goals and efficient system integration while challenging the economic efficiency and environmental effectiveness of solely national plans.

1. Context

The liberalization of the electricity market and the establishment of a common internal European power market are remarkable achievements of the European Institutions. The play of market forces, the solidarity-based adequacy mechanism, and the promotion of cross-border interconnectivity enabled improvements in the competitiveness, environmental effectiveness, and security of supply of the European power system. However, its effectiveness has been undermined by uncoordinated and unforeseen national initiatives at the time of its design [1] lacking a long term strategy vision, such as the premature nuclear phase-out in some countries [2]. Such national initiatives, through trade between bidding zones following power market rules, generate cross-border effects [3,4]. These cross-border effects could be amplified by unforeseen events or exogenous shocks, such as the 2008 financial and economic crisis, the Fukushima accident in 2011, the COVID-19 pandemic in 2020, or the Russia's war against Ukraine in 2022.

In 2021, nuclear power accounted for up to 25% of Europe's electricity mix. By the same year, Germany relied on nuclear power for up to 13% of its electricity and was the second-largest nuclear power producer in Europe after France [5]. In Belgium, in the same year, more than 50% of electricity was produced from nuclear power [6,7] and it was the fifth-largest nuclear power producer in Europe in 2021 [5]. Still, both countries had plans to phase out nuclear energy while simultaneously reducing carbon emissions by massively deploying renewable energy, following political decisions rooted in the preceding decades [8,9].

The Russia's war against Ukraine led to reduced Russian gas supplies triggering an energy crisis in Europe in 2022 [10], as Russia was by far

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https://doi.org/10.1016/j.esr.2026.102179
Received 8 January 2026; Received in revised form 11 February 2026; Accepted 23 February 2026

the largest gas supplier to Europe, accounting for 35% to 40% of its needs [11]. This energy crisis further led to increased electricity prices across Europe and to a renewed interest in nuclear power, especially for countries that had earlier planned to phase out nuclear facilities. Consequently, new debates emerged within the energy policy-making sphere of governments and European institutions. For example, through "Streckbetrieb'' (limited stretched-out operation), Germany postponed the planned nuclear phase-out from the end of 2022 until April 15, 2023. Belgium's parliament decided to postpone the nuclear phase-out planned for 2025 by repealing the 2003 phase-out law, intending to extend operations until 2045 and build new reactors. Furthermore, the European Commission recognized the strategic role of nuclear power in achieving European climate, security of supply, and competitiveness objectives.

The renewed interest in the nuclear sector, combined with the unexpected postponement decisions for the German and Belgian phase-outs, motivated us to conduct this study by modelling the European power day-ahead market at a bidding zone level. Thus, the study examines the potential impact of a European country's nuclear phase-out policy on the optimal dispatching mix of other European countries, and thereby, on national and European CO_2 emissions, as well as the cross-border flows that impact total surplus. The scope and magnitude of the cross-border effects under the contemporary context (the Russia's war against Ukraine and the Belgian and German phase-out) are further addressed in the following sections.

The results highlight the significant correlation between the nuclear energy policy of a European country and the rest of the countries in terms of CO_2 emissions and electricity trade; they further stress the unequal distribution of total surplus gains or losses, impacting power market competitiveness and undermining the achievement of environmental targets, underscoring the relevance of considering European Policy coordination strategies within a more interconnected European power system with a greater share of renewable energy, mostly intermittent [1 2,12,13]. These findings are essential for shaping energy policies aimed at reducing CO2 emissions, as they highlight the importance for coordinated European energy strategies and call into question the economic efficiency of purely national vision. This study also provides political insights into how country-level policies shape integrated systems, e.g., European electric system.

This paper is organized as follows: Section 2 summarizes the literature review and Section 3 outlines the methodology applied. In Section 4, the results are analysed. The policy implications and conclusions are exposed in Section 5. Finally, Section 6 presents the limitations of the study.

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 power system and analysed their implications for European Policy coordination, which has become a significant concern in the pathway towards achieving the ambitious decarbonization goals. In this section, a literature review is presented on the Belgian and German nuclear phase-out and its effects on their power systems and the rest of the European power system, whenever this topic is addressed, as well as the effects of decentralized energy decisions and the relevance of strategic European energy policy coordination.

The literature review revealed a limited number of studies examining the impact of Belgian nuclear policy decisions on the overall power system. An analysis of the impact of the Belgian nuclear phase-out on the country's economy and emissions was conducted by Soytas et al. [14] using time-series economic analysis and machine learning experiments. This investigation finds that shutting down the nuclear reactors would not affect the economy's growth nor carbon emissions in the long term because the lack of energy from nuclear would be replaced by renewable energy sources (RES) and alternative energies. These results are the outcome of analysing the electricity market, the economy and primary energy consumption [14]. Nevertheless, this finding remains valid as long as replacing the entire nuclear park with renewable and alternative energies remains technically and financially feasible, provided that access to a gas supply is cheap and guaranteed. Otherwise, Belgium would have to import electricity from the neighbouring countries, including carbon-intensive electricity, or domestically produce electricity from fossil fuels.

Kunsch and Friesewinkel [6] use system dynamics to analyse the effects of the closure of seven nuclear Belgian power plants between 2015 and 2025. They found that, given that these reactors account for more than 50% of domestic electricity production and that, to remain independent from external markets, nuclear phase-out planning should be rescheduled, allowing more time for renewables to become more competitive. Otherwise, dependency on external suppliers would increase, as well as the use of non-renewables. Another study focusing on short-term and long-term security of supply analyses the reliably available capacity and the reserve margins, shortages that could emerge from phasing-out nuclear in Belgium [15]. Laleman and Albrecht [15] conclude that for the short-term security of supply, not being able to access electricity from nuclear reactors would heavily affect the reserve margins, opposite to the effect of extending the lifetime of the reactors, which increases the reserve margins. As for in the long term, they conclude that huge investments are needed to replace electricity produced from nuclear and fossil fuels. In terms of product and market design, Höschle and De Vos [16] state that the prolongation of the nuclear fleet reduces the amount of strategic reserves contracted as a capacity mechanism, which translates into a system more adequate to ensure that supply meets demand.

Regarding Germany, the most cited effect presented in the literature is the replacement of nuclear power with more renewable energy sources (RES) and other dispatchable sources. Welsch [17] and Bruninx et al. [18] investigated the impact of the German nuclear phase-out on its power system using a partial equilibrium model and a unit commitment model, respectively. The studies show an increase in coal, lignite, and gas-based electricity generation [1718]. Similarly, De Cian et al. [19] studied the effect of nuclear phase-out on investment in new technologies using a dynamic optimal growth model. The findings suggest that this approach would stimulate investment in fossil-based technology until 2030 and in R&D and new low-carbon technologies thereafter, yielding economic benefits [19]. Additionally, Selosse et al. [20] studied the impact of developing Carbon Capture and Storage (CCS) and Bioenergy with Carbon Capture and Storage (BECCS) as solutions for replacing nuclear energy. They find that limited nuclear energy would incentivize the use of Carbon Capture and Storage technologies [20]. If these technologies are not developed, limited nuclear energy would incentivize the development of renewable energy under the assumption that electrical storage is developed to ensure the system's flexibility. 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.

De Menezes and Houllier [21] examined the impact of the German nuclear phase-out on the European electricity market using statistical tests and correlation models. 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. Beran et al. [22] corroborates these results for national results and Bode [23] and Grossi et al. [13], for neighbouring countries. Another study uses a methodological triangulation to analyse the economic impacts in Germany of nuclear phase-out or extension was done by Emblemsvåg [24]. He states that the Energiewende[1] has not only cost Germany billions of euros between 2002 and 2022 but has also prevented the country from reducing emissions

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[1] Term used to reference the energy transition in Germany.

more than it would have if it had kept nuclear power plants running or had invested more in nuclear capacity [24]. Nagl et al. [25] studied four different scenarios through simulation models, combining dispatch, investment, and optimisation for renewable energies, with varying CO_2 emission reduction targets at different horizons, and nuclear power plant lifetime extensions 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 extension of the lifetime of nuclear power plants. Moreover, a study Jafari et al. [26] focusing on Germany's net-zero emission target for 2045-2050 states that even by phasing-out coal completely, it would not be possible to reach the emission targets. To meet its peak demand, Germany would need to rely on imports, possibly from carbon-intensive sources, highlighting the need to study the cross-border effects of a national policy. The analysis in these studies is at the national level rather than system wide.

As for system-wide level, an environmental and economic study carried out by Hoster [27], using a multi-period, multi-region linear programming model simulating European power supply, investigates the impact of the German nuclear phase-out in terms of economic and environmental viability on the European power system, with a complete phase-out reached in 2005 and the ex-post effect until 2020. The model represents France as one zone, Belgium, the Netherlands, and Luxembourg as one zone, and Austria and Switzerland as one. The rest of Europe is exogenous. This aggregated geographical resolution implies an analysis that is not only concentrated on immediate neighbours but also indistinguishable by countries when analysing the aggregated neighbouring countries. The author draws that CO_2 emissions would rise in these neighbouring market zones as German imports from these zones would increase [27]. Additionally, he notes a gradual increase in costs resulting from domestic and foreign requirements for new capacities to meet demand with reduced nuclear capacity and higher fuel costs. On the other hand, Lechtenböhmer and Samadi [28] examine the German mix capability of completely replacing nuclear power with renewable electricity generation, assuming an expansion of the grid and provision of balanced power through demand adjustment.

A recent study by Glynos and Scharf [29] 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, in addition to a marginal increase in overall welfare, they found that increased nuclear power during the stated period results in reduced use of gas and coal-fired power generation at both national and European levels, as well as decreased grid congestion in Germany. Regarding the interconnected system, neighbouring countries benefit marginally from this nuclear phase-out postponement through the imports of cheaper electricity, whilst non-neighbouring countries 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.

European energy policy coordination is still a matter in progress. *Common Market – Yes, common energy policy – Never* [2]. This was the premise at the beginning of the attempts to liberalize the European power market, followed by the reform in 2007, and the setting of common European environmental goals, which opened way to the European coordination. However, several studies concentrate their efforts on understanding the divergence in the policies and their diverse effects [1]. Lindberg et al. [30] studied how energy policy and energy politics have been two camps that lead to different decarbonization pathways. The consequences of having decentralized energy policies are translated into a slower energy transition in the EU [30]. Following the same idea, Pepermans [31] described the challenges of the Integrated European Electricity Market and the importance of improving the cross-border capacities allocation. Neuhoff et al. [32] and Ringler et al. [33] joined Pepermans in concluding on the importance of having a regulatory framework that allows a better management of cross-border congestion. Their findings also point out the relevance of having clearly defined policies that take into account possible conflicts between decentralized objectives [32,33].

Bigerna et al. [34] highlighted that national policy implementation has an heterogenous impact among neighbouring countries and that their responses might be dependent on the level of regulation of each country. Additionally, Cassetta et al. [35] highlighted the need to have a better cooperation for policy and regulation between countries in order to have a better energy price convergence in both households and non-households markets across member states in the EU.

This study addresses the gap in the literature by modelling a unit commitment model of the European interconnected power system using country-detailed technologies and production capacities to analyse German and Belgian nuclear phase-out policies and their effects on power scheduling, CO_2 emissions, power trade, and total surplus at the country and system level in a 2030 market context. As most literature focuses on the impacts of a country's own energy policies and only the impacts on neighbouring countries, this study instead investigates the impacts that other countries undergo when one country changes its nuclear policy, affecting their emissions reduction objectives and the overall production efficiency in their markets, thereby revealing the importance of European coordinated energy policies.

3. Methodology

This section is divided into a brief description of the European power system unit-commitment model, the scenarios, and the indicators employed to analyse 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 [36]. The model is based on an hourly hydrothermal unit commitment paradigm within a partial equilibrium model. It complies with a merit order market configuration based on marginal costs, the hourly power trade among countries considering both physical and economic constraints, and the cycles of loading and discharging from PSPs 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, up-and-down times, planned and forced outages, start-up costs. CO_2 emissions are calculated ex-post, and the CO_2 price is included in the marginal cost calculation.

ESMOD models the European power system for 2030, covering 36 countries, constituted of 53 market-bidding zones interconnected. The interconnections are based on the net transfer capacity approach. The model incorporates coupling market dynamics into its modelling. The technical-economic data of the model is mainly based on ENTSO-e's European Resource Adequacy Assessment (ERAA) [37], which provides a dataset with the characteristics of the power system. The study spans over 34 climate years, which is essential for taking into account the sensitivity of the power system to different meteorological variations on both the supply and demand sides.

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 on the I-TESE Website [38].

3.2. Scenarios

Three scenarios for 2030 that depict the Belgian and German nuclear energy policies. In the analysis, the German and Belgian nuclear plants that were operational in 2022 are considered.

Three scenarios for Belgium and Germany were defined as follows:

Table 1

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

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

- 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 Russia's war against Ukraine. This scenario is the benchmark.
- The second scenario, *REAL*, takes into account the policies adopted in reaction to the Russia's war against Ukraine following energy crisis in 2021. For this scenario, 2 GW extra on nominal power for Belgium are considered and, for 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, a nuclear production capacity of 4 GW for each country is assumed.

Table 1 summarizes the three scenarios mentioned above.

3.3. *Analysing the results*

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

3.3.1. *Distance*

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

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

3.3.2. *Total CO_2 emissions electricity supply (TEES)*

The change in total CO_2 emissions is assessed in both absolute and relative terms, using the FUCL scenario as the benchmark.

In absolute difference, for any pair of scenarios, the difference between scenarios is simply calculated, S_1 being the FUCL scenario.

$$\Delta_{TEES_m}^{s_2\leftarrow s_1} = TEES_m^{s_1} - TEES_m^{s_2} \tag{1}$$

And in relative difference is set as follows:

$$\Delta\text{relative}_{TEES_m}^{s_2\leftarrow s_1} = \frac{TEES_m^{s_1} - TEES_m^{s_2}}{TEES_m^{s_1}} \tag{2}$$

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

3.3.3. *Consumer surplus (CS) and producer surplus (PS)*

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 [39]. However, the difference in consumer surplus between the scenarios is assessed [40] as the difference in the shadow values between the scenarios multiplied by the load.

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

The producer surplus is the difference between the shadow value multiplied by the production and the operational costs for each technology. In other words, the producer surplus is the area between the market-clearing equilibrium price and the supply curve [40].

For more information on how to calculate the PS, refer to Appendix E.

3.3.4. *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 the principles of economic dispatch. 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 congestion rent becomes a congestion surplus as it is allocated to a common fund used to enhance interconnection capacity and support broader system-level investments.[2]

Thus, the congestion surplus is the variation between the price at which consumers paid for the electricity and the price at which generators sold it, multiplied by the power traded. It occurs due to interconnection congestion; the shadow values of the importer and exporter market-bidding zones differ from each other ([40]).

For more information on how to calculate the CSP*, refer to Appendix* F.

3.3.5. *Total surplus (TS)*

The total surplus (TS) is the sum of the three prior indicators, as follows ENTSO-E [40]:

$$\Delta_{TS_m}^{s_2\leftarrow s_1} = \Delta_{CS_m}^{s_2\leftarrow s_1} + \Delta_{PS_m}^{s_2\leftarrow s_1} + \Delta_{CSP_m}^{s_2\leftarrow s_1} \tag{3}$$

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 it is used to calculate the TS indicator.

4. Results

This section explores the effect of postponing nuclear phase-out in Belgium and Germany on the European power system by 2030. Moreover, it examines the externalities, specifically the cross-border effects of the national nuclear phase-out policy in terms of CO_2 emissions and TS variations. First, these impacts are examined at the national and European levels. Second, clusters spanning the 34 climate years are identified, and the weather sensitivity of the results is assessed.

4.1. *National effects of postponing nuclear phase-out*

This first part illustrates the modifications in the power scheduling of Belgium and Germany. The postponement of nuclear reactors grants the Belgian and German power systems access to cheaper power sources. This results in modifying the cost-effective dispatching and calling fewer 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 TS than in the FUCL benchmark scenario, as presented in Table 2.

In the REAL scenario, given that the postponement occurred only in Belgium, it is normal that Germany's CO_2 emissions and TS remain almost steady. In the NUEX scenario, both countries undergo consequent changes in their emissions and savings. This analysis supports the

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[2] 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 2
Differences of CO_2 emissions and TS for Belgium and Germany.

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

extensive literature review about the direct benefits of postponing the nuclear phase-out in terms of CO_2 emissions and TS.

The study was initially planned 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 compared to the reference scenario FUCL. However, a merely linear effect was found. For most countries, the differences between REAL-FUCL and NUEX-FUCL in terms of CO_2 emissions and TS were essentially in the intensity, keeping the same trend. Therefore, the intermediate scenario (REAL) was set aside and the focus was given to assess the metrics between the benchmark scenario (FUCL) and the Nuclear Extension scenario (NUEX).

Fig. 1 shows the discrepancies in power dispatch for these two countries under the NUEX and FUCL scenarios. It illustrates two effects. First, a direct effect at the national level occurs when nuclear-based electricity replaces gas or another fossil fuel for electricity production within the same country. Second, a cross-border effect occurs through reduced electricity imports and increased electricity exports, affecting other European countries [3,4,41]. Notably, in Germany, the direct effect amounts to 14.3 TWh, which is slightly more than half of the country's nuclear production. The cross-border effect 11.6 TWh is also very significant 44%. In Belgium, the direct effect represents 10.6 TWh. The cross-border effect amounts to 14.7 TWh, which is more than 56% of the additional nuclear production. Therefore, the cross-border effect has a significant impact on the rest of the countries within the European interconnected power system, which brings us to the next section.

4.2. Cross-border effects on the European system of postponing nuclear phase-out

The cross-border 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 higher 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 set to study the effect on the rest of the countries (cf. Section 3.3), the analysis of the results was conducted.

4.2.1. Total CO_2 emissions from electricity supply (TEES)

Across 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 to 56% of the total reduction in European emissions. The remaining 44% decrease is unevenly distributed across the rest of Europe, as illustrated in Fig. 2. This corresponds to the cross-border effect, which is almost as large as the direct national impact.

Fig. 3a illustrates the variation between the NUEX and FUCL scenarios of total CO_2 emissions (TEES) in relation to the *"distance"* in absolute terms (cf. 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 chart reveals that, in general, the farther a country is located from Belgium or Germany, the less it is affected by postponing the nuclear phase-out. For example, Malta (mt), being the "farthest" (connected to Europe only 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"*. The model reveals that interconnections (the proxy is *"distance",* c. f. section 3.3) might play a central role, but they do not fully explain the variation in CO_2 emissions, as countries at the same *"distance"* experienced markedly different changes in their power scheduling. Conversely, "distant" countries might undergo changes of the same magnitude as "close" ones in relative terms (as seen in the next section). Therefore, the analysis is complemented by considering, each country's electricity consumption size (represented by the size of the dot in Fig. 3a and Fig. 3b), its trade status—net importer labels are shown in red and net exporter labels in blue—illustrated in Fig. 3a andFig. 3b, and the share of carbon-intensive technologies in its energy mix (used as a proxy for CO_2 intensity represented by the colour intensity for each dot). The darker the colour, the greater the share of carbon-intensive technologies, as shown in Fig. 3a and, Fig. 3b.

As illustrated in Fig. 3a, the "nearby" countries most affected by the nuclear phase-out postponement have carbon-intensive technologies in

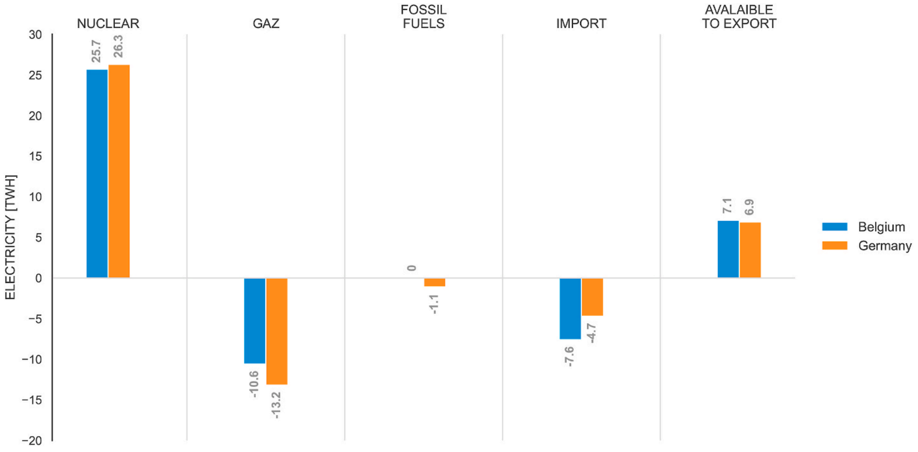

Fig. 1. Difference in power dispatching between NUEX and FUCL scenarios.

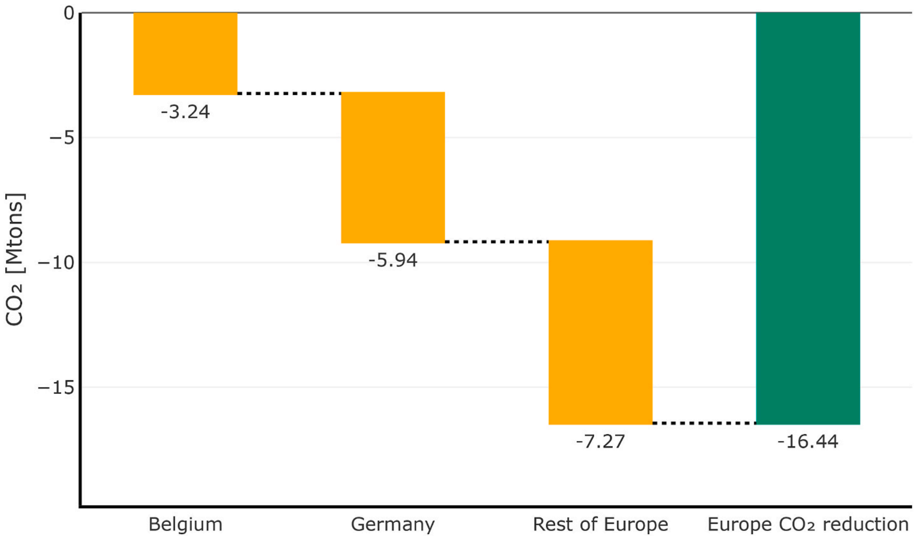

Fig. 2. European CO_2 emissions reductions in NUEX compared to FUCL.

their energy mix, whether they are importers or exporters. Poland and Italy, as importers, stand to gain significantly from a nuclear extension, as it offers 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, such as those from the Netherlands, results in a larger decrease in emissions compared to the reduction seen with low-carbon exports, like 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).

Fig. 3b illustrates the variation in total CO_2 emissions (TEES) between NUEX and FUCL in relative terms. It indicates that a greater number of countries appear to be affected. The first observation is the change in the data distribution and the nature of the effect in each country. The non-linearity between the indicator and the *"distance"* is further observed here. Countries "farther" from Germany and Belgium, like Slovenia (si), Ukraine (ua) and Hungary (hu) are nearly as impacted as those closer, such as France (fr) and the United Kingdom (uk). The cross-border effects of the German and Belgian nuclear phase-out extend far beyond the neighbouring countries, widening the scope of externalities associated with national choices and emphasizing the need for strategic European policy coordination to achieve environmental targets. Some of these countries are considerably impacted by the cross-border effects in relative terms[3] [13,30]. This rise can be attributed to two factors: the size of their electricity demand and their mix. With small or low-carbon countries, fewer tons of CO_2 can lead to substantial relative impacts. The list can be complemented with Estonia (ee), Latvia (lt), Lithuania (lt), Serbia (rs). Albania[4] (al), which is even farther, should not be affected, whilst its significant variation should be explained by other dynamics like the sensitivity to meteorological variations[5] c. f section 4.3. 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, regarding 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.

4.2.2. *Total surplus (TS)*

There is mostly a direct positive correlation between reductions in CO_2 emissions and decreases 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 improvement of the TS of 3.09 billion, compared to the FUCL benchmark scenario, for the year 2030. Fig. 4 illustrates the distribution of annual TS improvements across Europe, comparing Germany, Belgium, the countries where TS increased due to the postponement of nuclear phase-out, and the countries where TS decreased.

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.

Fig. 5 illustrates the variation in TS between the NUEX and FUCL scenarios relative to *"distance"*, revealing a different cross-border effect than that observed in TEES.

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 TS. In fact, the TS of France, the United Kingdom, and Denmark suffered a contraction. This contraction is partly due to their status as net exporters[6] and partly to the type of power traded. Since these countries trade mainly renewables and nuclear

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[3] 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, it is inferred this result is biased and it must not be taken into account the analysis.

[4] Albania holds the top position in the ranking of countries with larger share of hydropower in their energy mix see Annexes H.

[5] This accounts for Norway and explains the detachment of Norway from the group of not-affected countries mentioned in the analysis of Fig. 3a.

[6] The United Kingdom's mix is based on ERAA 2021-2022, cf. Section 3.1 model description. Therefore, the model outcomes do not account for the recent shutdowns of the United Kingdom 's advanced gas-cooled nuclear reactors.

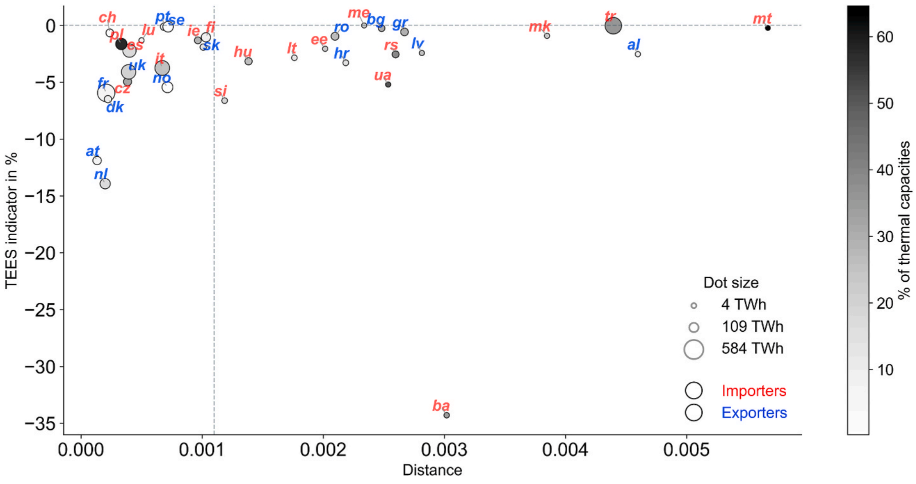

Fig. 3a. Variation between the NUEX and FUCL scenarios of total Mtons of CO_2 emissions (TEES) relative to the “distance” in absolute terms.

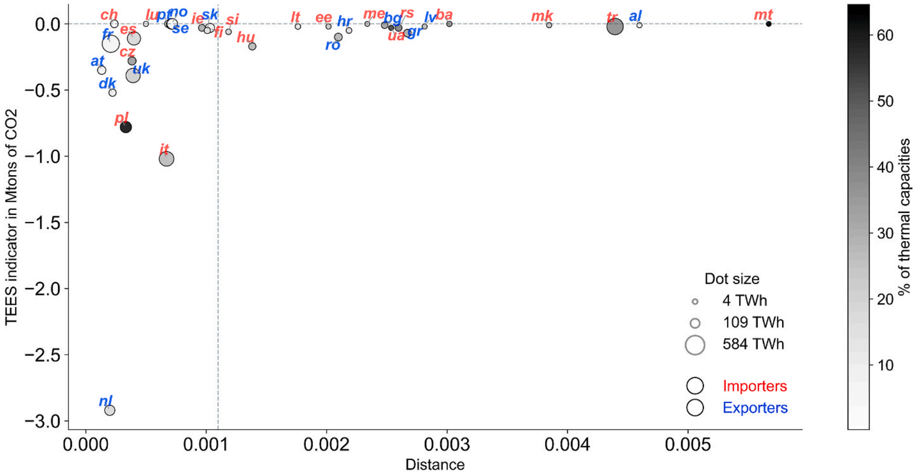

Fig. 3b. Variation between the NUEX and FUCL scenarios of total CO2 emissions relative to the “distance” in relative terms.

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, the Netherlands and Austria, see an increase in TS 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 the obligation to export, the gains in consumer surplus and changes in congestion surplus outweigh the losses in producer surplus.

Poland, Switzerland, the Czech Republic, Italy, and Luxembourg benefit from the lower-cost extra dispatchable nuclear power to reduce their costs and increase their TS, since they are already net importers. Norway benefits from the German and Belgian nuclear phasing-out as its mix is decarbonised, and it has low-carbon dispatchable power (hydraulic). The gains in consumer surplus outweigh 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. The rest of the countries placed after the dotted vertical line are overall slightly affected.

To conclude, the postponement of the nuclear phase-out creates a significant cross-border 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 TS variation. This indicates that the effect does not solely depend on the “distance”.

4.3. Sensitivity to weather through climate years

The analysis is completed by focusing on meteorological impact, analysing the results in light of the 34 climate years that were have used. Fig. 6a,Fig. 6billustrate the distribution of total CO2 emissions variation (TEES) in absolute terms and the variation of TS across all 36 countries in response to the weather sensitivity. This is important for understanding which countries are more sensitive to meteorological conditions. As shown in Fig. 6a,Fig. 6b, some countries, other than Germany and Belgium, such as the United Kingdom, Poland, Greece, and the Netherlands, show wide variation in TEES across climate years, as do Sweden, Spain, Portugal, and Norway, which show wide variation in TS.

4.3.1. Clusters

To better understand the behaviour of the results across climate years, the k-means algorithm was used to group data into distinct clusters, identify patterns, and assess sensitivity to climate years. The elbow method for distortion and inertia was used to define the k numbers of clusters, cf. Appendix G. The use of this method resulted in 7 clusters distributed as shown in Fig. 7 and, explained in Table 3.

Fig. 8 shows the number of clusters to which each country belongs.

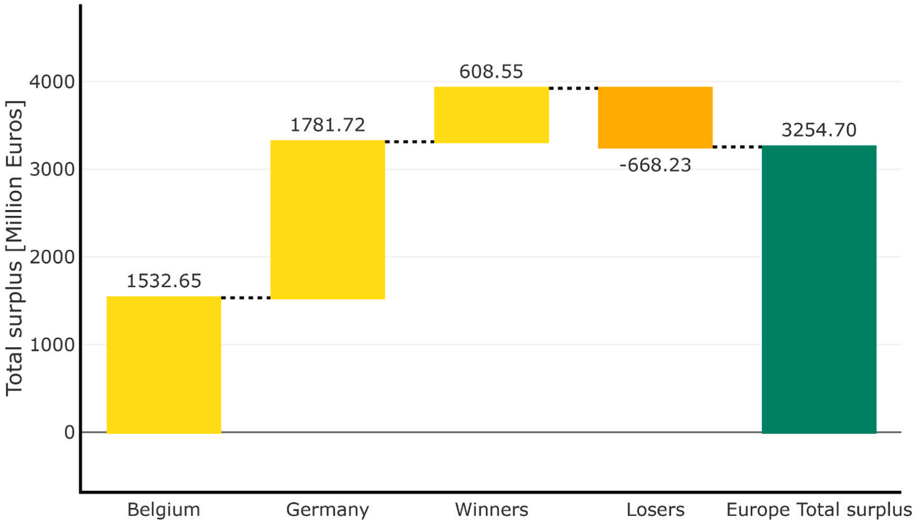

Fig. 4. *Total surplus* distribution across Europe [Million Euros].

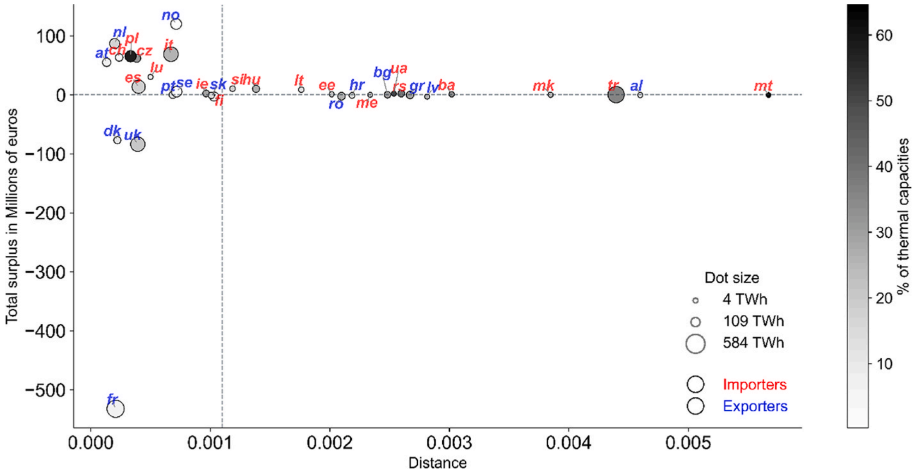

Fig. 5. Variation between the NUEX and FUCL scenarios of total surplus relative to the “distance”.

The greater the number of clusters a country belongs to, the more sensitive it is to weather, and the more varied the trends are across the analysed years. Countries like Switzerland, Norway, Poland, and Romania[7] are within the countries belonging to 2 or more clusters. For example, in rainy years, Norway belongs to the *Trade-off* group, suffering a decrease in TS, whereas in dry years it belongs to the *Total surplus growth* group. This highlights the sensitivity of these countries to nuclear policy because it provokes contrast effects, such as economic benefits (*Total surplus* growth) or economic impacts (Trade-off group), as in the case of Norway.

Table H in the appendix illustrates the share of hydro-based technology in each country's total power generation capacity. Among the top five, three countries—Switzerland, Norway, and Austria—exhibit sensitivity to weather variations, shifting between groups depending on the climate year. This highlights the cross-influence of meteorological 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 the results, belong to the neutral group and do not appear to be sensitive to meteorological variations. However, this does not contradict the previous statement, as these countries are still affected in terms of CO_2 emissions (see Section 4.3). For example, Slovenia, Slovakia, North Macedonia, and Albania experience emissions-related effects, despite the latter two being geographically distant from Belgium and Germany. The reason for its belonging to the neutral group could be related to the limitations of the clustering technique.

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

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 power system of the policy decision to phase out nuclear power in Belgium and Germany. It aims to study the effects on power dispatch and economic efficiency at the national level as well as at a system-wide level. The goal is to provide insights into how unilateral national energy policies affect the European power system in terms of CO_2 emissions and TS.

The postponement of the nuclear phase-out in Belgium and Germany

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[7] Italy and Greece are excluded from this group of countries which belongs to two groups but having only one group that is quite small (1 year out of 34) in comparison to the others. For instance, Greece: 33 years belong to the Neutral group and one year belongs to the Trade-off group.

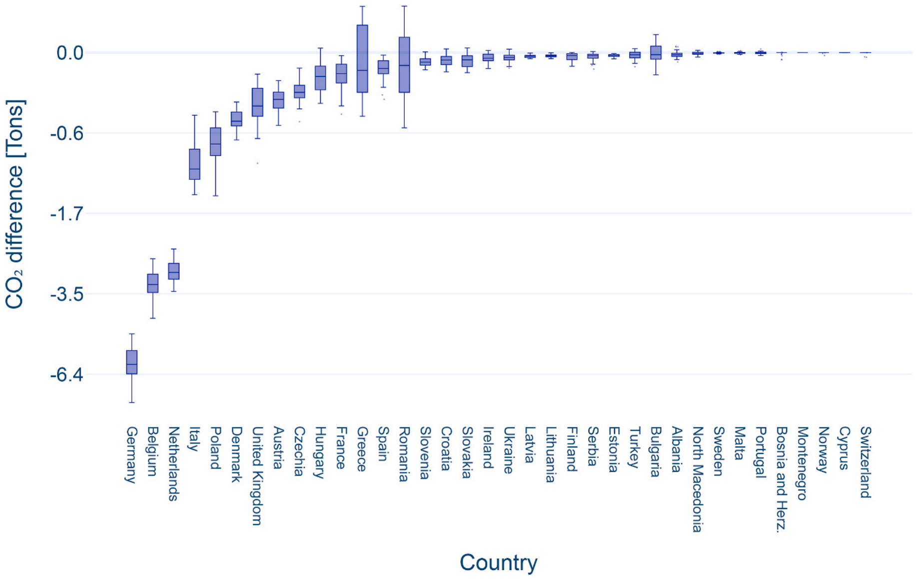

Fig. 6a. Distribution of TEES in absolute value in response to climate years.

would reduce, in 2030, European CO_2 emissions from electricity production by approximately 16,4 Mtons, which represents around 5% of total European electricity emissions. From this total, CO_2 emissions reductions of 20% come from Belgium and 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 cross-border effects through variations and substitutions in imports and exports across the rest of Europe. While previous studies refer mostly to national direct effects [6,14,15,18,19,21], this study emphasizes the magnitude of the effect suffered by neighbouring countries as well.

As the cross-border effect is considerable, metrics were established to assess the impact of the Belgian and German nuclear policies across the European power system. The interconnections evidently play a central role in determining the changes in the power scheduling. Therefore, interconnections were transformed into “*distances*”. The 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 when analysed in relative terms. The analysis was complemented by considering each country's size, trade status, and the share of carbon-intensive technologies in its energy mix.

TS in Europe increased in the nuclear extension scenario, but the change was not uniform across countries. For instance, while France would have experienced a reduction in TS, the Netherlands would have benefited from the nuclear extension. Gains in consumer surplus and congestion surplus outweigh the losses in producer surplus in the Netherlands, despite both countries being at the same *“distance,” i.e.,* well interconnected. This outcome could diminish 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 strategy, integration and coordination, and challenge the economic efficiency of solely national plans.

Political insights into how country-level policies can affect systems such as the European electricity integrated system are among 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 [13,34,35]. This is a crucial aspect to consider during energy policy discussions in order to reach common environmental targets as well as energy security goals, giving way to prioritize climate goals and security of supply rather than politically based decisions that impact a whole region [30,32,33]. This is in line with and complements the literature review on policy coordination.

The goal is to provide evidence-based insights into how the European power system reacts to national energy policies, focusing on a 2030 horizon. This analysis seeks to contribute to the ongoing debate and literature (see section 2) about the role of nuclear energy in the European energy transition [1,10]. These insights are crucial for designing future energy policies targeting CO_2 emission reduction, as they underscore the importance of strategic European energy policy coordination and challenge the economic efficiency of solely national plans [10]. Given the extent of the impacts, the analysis of the scenarios becomes a relevant question for European policy coordination analysis. In shaping Europe's energy future, policy coordination is not just desirable, it is essential.

6. Limits of the study

European power system modelling is complex, heterogeneous, and difficult to abstract without simplification due to limited computational capacity, which leads 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, evidence from the Belgian case complies with nuclear extension policy from the scenario conception, thus explaining the unevenness in installed capacity across the scenarios. The demand is inelastic to price, and its shape remains 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 [43] 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 [44]. In this case, a less sophisticated approach was applied but it was 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 [45]. This approach leads to some inefficient equilibrium for some economic actors yielding some losses or gains in the equilibrium.

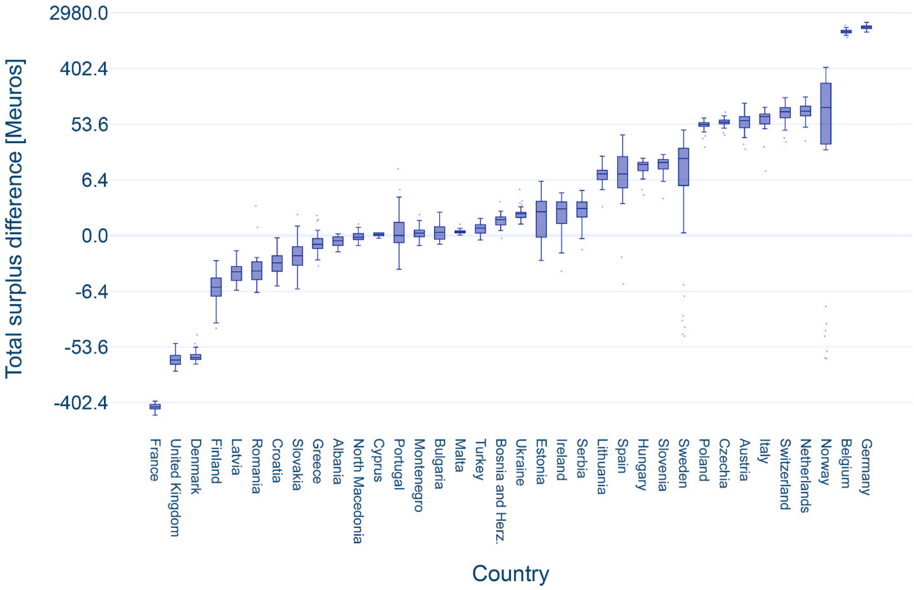

Fig. 6b. Distribution of total surplus in response to climate years.

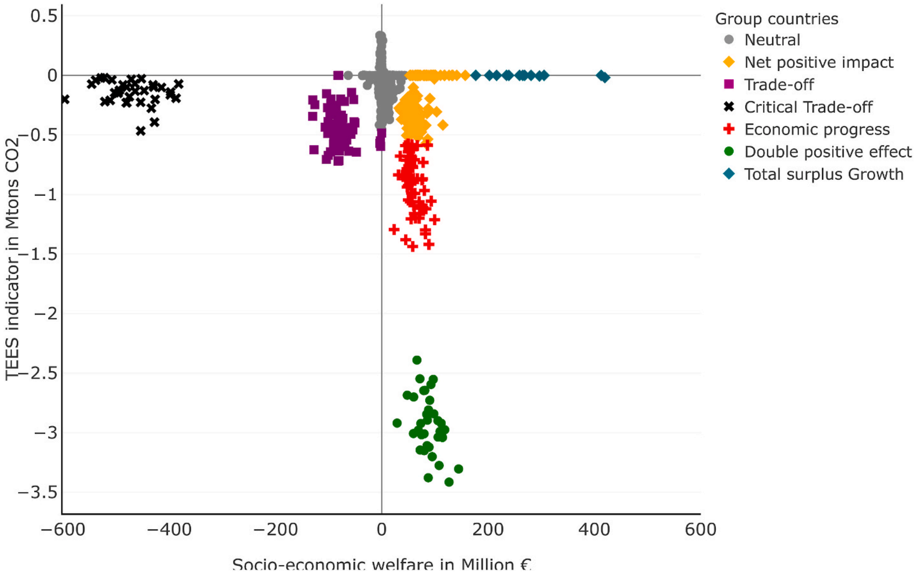

Fig. 7. CO_2 and total surplus impacts of NUEX compared to FUCL for the 34 modeled climate years.

Nevertheless, these imperfections are allowable to answer the research question.

And 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.[8] Because of all of this, results should be considered as trends and avoid taking them as absolute values or forecasting results.

Author contributions

Sergio Leo Vargas Aranda: Conceptualization, Methodology, Formal analysis, Validation, Vizualization, Writing- Original draft, Writing – review and editing.

Erica Ramirez Conceptualization, Methodology,Vizualization, Writing- Original draft, Writing – review and editing, Project administration.

Maxence Cordiez Conceptualization, Writing- Original draft, Writing – review and editing.

Bertrand Charmaison Conceptualization, Writing- Original draft, Writing – review and editing.

Emma Moulan Conceptualization, Writing- Original draft.

Declaration of generative AI and AI-assisted technologies in the manuscript preparation process

During the preparation of this manuscript, the authors used ChatGPT

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

Table 3
Cluster details.

Cluster dot mark	Name	Description
Grey circle	Neutral	In the *neutral* group there are some slight changes regarding either CO_2 emissions or TS. However, the changes between the two scenarios are not important enough relative to the other countries, making the group less impacted by the nuclear phasing-out postponement.
Orange diamond	Net positive impact	*Net positive impact* consists of a slight reduction of CO_2 emissions and/or a slight gain in TS due to the nuclear phasing-out postponement.
Tail diamond	Total Surplus Growth	*Total Surplus growth* contrasts with *Net positive impact* on the intensity of gains of TS, this group benefits similarly in CO_2 emissions reductions but harnesses the nuclear postponement to increase its TS.
Red plus	Economic progress	*Economic progress* contrasts with *Net positive impact* on the reductions in CO_2 emissions, this group benefits similarly in gains of TS but benefits from low-carbon nuclear energy to reduce further its local emissions due to power generation.
Purple square	Trade-off	In the *trade-off* group, the environmental gain in terms of CO_2 emissions is contrasted with the loss of TS; for such countries, a nuclear extension policy 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 TS. This results in a trade-off.
Black cross	Critical Trade-off	This group has a similar reduction in CO_2 emissions than *Trade-off*, however its decrease in TS is more accentuated.
Green circle	Double positive effect	While some countries weigh the benefits and drawbacks of nuclear policy, a group of countries actually undergoes a *double positive impact*, meaning they experience both a reduction of CO_2 emissions and an improvement in TS, as illustrated in Fig. 7. Analogous to the double dividend tax environmental theory [42], postponing the nuclear phase-out provides this group with the first benefit —a reduction in carbon emissions —and the second —the “double dividend” of improved TS, which can eventually be used to promote further environmental policies.

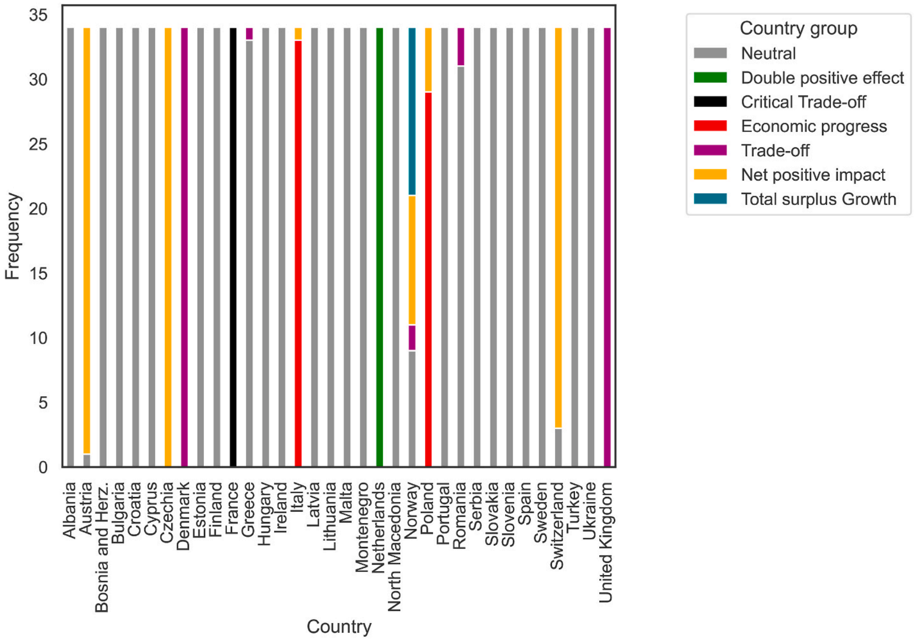

Fig. 8. Frequency of cluster per country for the 34 climate years.

in order to assist with grammar and spelling checks, improving syntactic clarity, enhancing textual cohesion and readability, and rephrasing selected paragraphs for stylistic refinement. After using this tool, the authors(s) reviewed the content as needed and take(s) full responsibility for the content of the published article.

Funding sources

This research did not receive any specific grant from funding agencies in the public, commercial or not-for-profit sectors.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The authors and the research institution they represent were all members of the research institution I-Tésé of the Atomic French Commissariat CEA during the research project. The authors gratefully acknowledge the support of researchers from I-Tésé and, LGI Central-Supelec. Notably, Stéphane Tchung -Ming for the help in the construction of indicators and Diego Cebreros for the conceptualization of the research question. This article was presented first at the conference IEAA Istanbul 2024 and several internal and international workshops.

Appendix

A) Countries with their ID

Table A.1
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
Turkey	TR
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.

Distance (DTS_m) between two zones m are set as the inverse of its NTC,$DTS_m \Leftrightarrow dts = \frac{1}{ntc}$. Then, the shortest path is calculated between each market zone m and Belgium and Germany by applying Dijkstra's algorithm. The results are sets of short paths $SP_n, n \in M \text{ and } \{Germany \text{ and } Belgium\} \notin SP_n$. Figure B.1 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, the graph of the European power network is designed 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 $ntc \in NTC_m$.

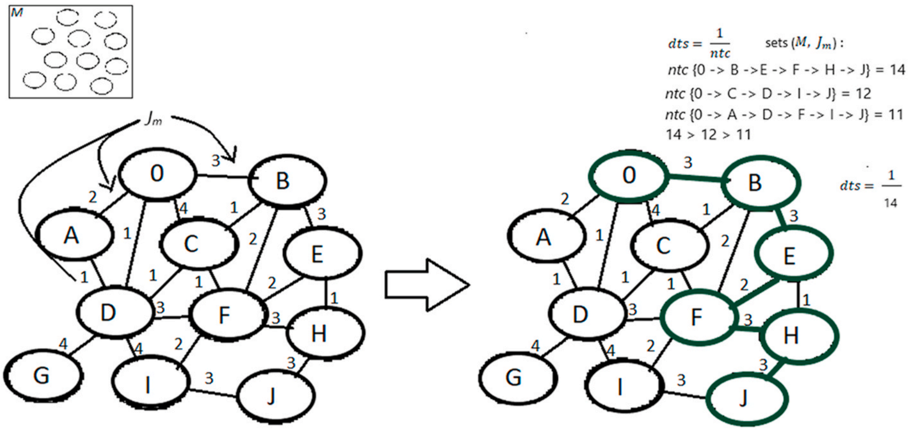

Fig. B.1. Exemple of Short Path for Dijkstra's algorithm for distance between nœud 0 and nœud J

C) Total CO_2 emissions electricity supply (TEES)

Emissions by country were calculated in absolute and relative differences between scenarios as follows: A set of $S = \{FUCL, REAL, NUEX\}$ scenarios was created; then, the scenario index $s \in S$ is omitted from the equations for simplicity. On any market zone $m \in M$, there is a set of P_m producing units, for which commitment is tracked at the hourly level over a year, $h \in H = [1, 8760]$. Then parameters and model outcomes are defined:

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

Total emission of electricity supply for each market zone m is defined as:

$$TEES_m = \sum_{h \in H} \sum_{p \in P_m} er_p {}^* Q_{p,h} \qquad \text{Eq. (C.1)}$$

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

$$\Delta_{TEES_m}^{s_2 \leftarrow s_1} = TEES_m^{s_2} - TEES_m^{s_1} \qquad \text{Eq. (C.2)}$$

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

$$\Delta_{TEES_m}^{s_2 \leftarrow s_1} = \frac{TEES_m^{s_2} - TEES_m^{s_1}}{TEES_m^{s_1}} \qquad \text{Eq. (C.3)}$$

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

D) Consumer Surplus (CS)

- Parameters:
  - o $L_{m,h}, \forall m \in M, \forall h \in H$: load of a market zone m at hour h ;
- Model results (optimal values)
  - o $\lambda_{m,h}, \forall m \in M, \forall h \in H$: the marginal value of the demand constraint in market zone m at hour h. Based on the marginal value pricing principle, it is assumed that this shadow value represents the market clearing price of market m at hour h [46].

The consumer surplus is the difference of the shadow values between the scenarios multiplied by the load.

$$\Delta_{CS_m}^{s_2 \leftarrow s_1} = \sum_{h \in H} \left(\lambda_{m,h}^{s_2} - \lambda_{m,h}^{s_1} \right) {}^* L_{m,h} \qquad \text{Eq. (D.1)}$$

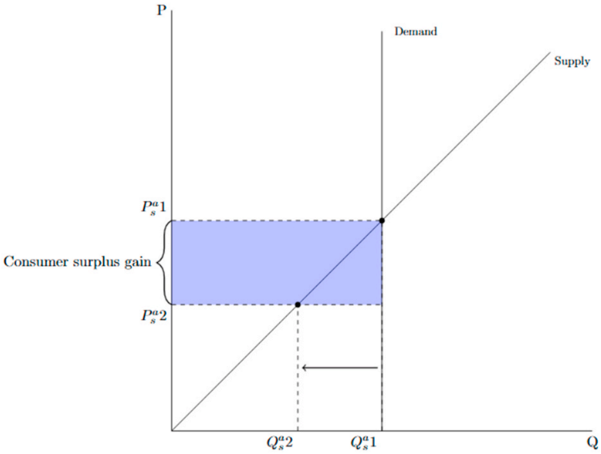

Fig. D.1. Gain in consumer surplus

In Figure D. the purple area represents the gain in the consumer surplus of a country '*a*' when comparing reference scenario at P^a_{s1} to another scenario when importing electricity at price P^a_{s2}.

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;

The producer surplus is the difference between the shadow value multiplied by the production and the operational costs for each technology.

$$PS^s_m = \sum_{h \in H}\left[\lambda_{m,h}, {}^*Q_{m,h} - \sum_{p \in P_m}\left(FC_{p,h} + VOM_{p,h}\right)Q_{p,h}\right] \quad \text{Eq (E.1)}$$

$$\Delta^{s_2 \leftarrow s_1}_{PS_m} = PS^{s_2}_m - PS^{s_1}_m \quad \text{Eq (E.2)}$$

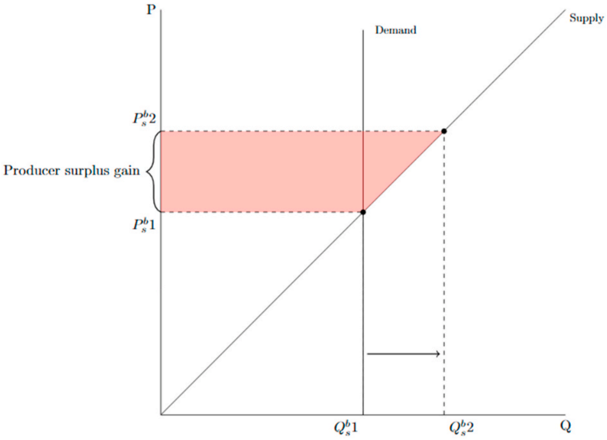

Fig. E.1. Producer surplus

In Figure E.1 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)

- Parameters:
  - $tc^j_m, \forall m \in M, \forall j \in J_m$: the unit transmission cost between two connected zones;
- Model results (optimal values)
  - $T^j_{m,h}, \forall m \in M, \forall j \in J_m, \forall h \in H$: the net electricity transfer between markets m and j at hour h;

o $\lambda^{j}_{m,h}, \forall m \in M, \forall h \in H, j \in J_m$:The marginal value of the demand constraint in the interconnected market zone j with respect to m at hour h; it is assumed that 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, $\lambda_{m,h} = \lambda_{j,h} \pm tc^{j}_{m}$, depending on the direction of the flow.[9]

The congestion surplus is the absolute value of the shadow value between the importer zone and the exporter zone multiplied by the power traded

$$CSP^{s}_{m} = \sum_{h\in H}\sum_{j\in J_m}\left|\lambda_{m,h} - \lambda^{j}_{m,h}\right| {*} T^{j}_{m,h} \qquad \text{Eq (F.1)}$$

$$\Delta^{s_2 \leftarrow s_1}_{CR_m} = CR^{s_2}_{m} - CR^{s_1}_{m}$$

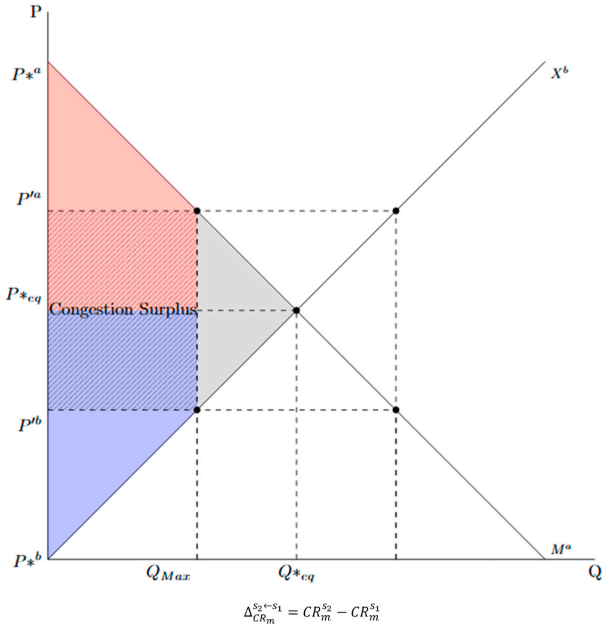

Fig. F.1. Illustration for the congestion surplus

To 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, the strayed area represents the congestion surplus

G) The elbow method for defining K number of clusters

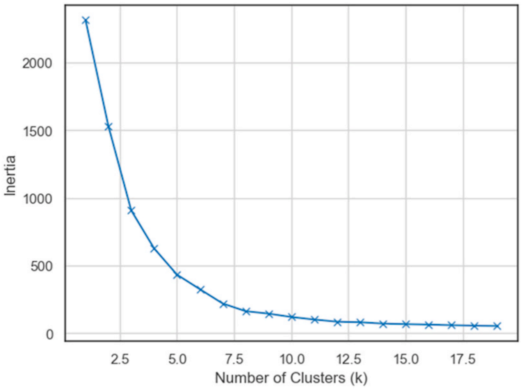

Fig. G.1. Elbow method using Inertia

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[9] See e.g. Samuelson [44].

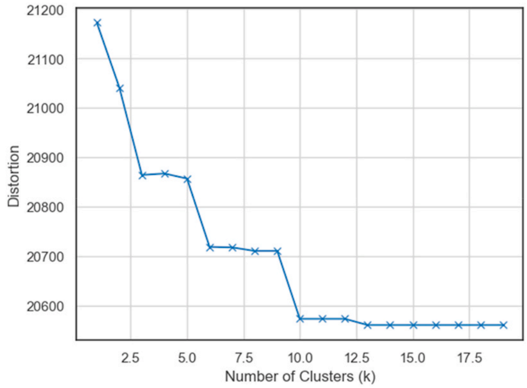

Fig. G.2. Elbow method using Distortion

H) The ranking of share of hydro based technology

Table H.1
The ranking of the percentage of hydro-based technology share in European power mixes

	Country	Hydro_capacity[10]	Total capacity installed	% of hydro-based technology
1	Albania	2691	3691	73
2	Norway	33361	46780	71
3	Montenegro	1198	1983	60
4	Switzerland	16304	30460	54
5	Austria	31100	62373	50
6	Bosnia and Herz,	2494	5496	45
7	Latvia	1699	4134	41
8	North Macedonia	1136	2860	40
9	Slovenia	2652	7022	38
10	Slovakia	3745	10096	37
11	Croatia	2678	7881	34
12	Turkey	39675	124340	32
13	Sweden	16447	52076	32
14	Romania	9093	29556	31
15	Portugal	9275	30951	30
16	Serbia	4210	14996	28
17	Bulgaria	3606	14556	25
18	Lithuania	1120	5476	20
19	Czechia	3645	20953	17
20	Spain	26674	159177	17
21	Italy	29755	181215	16
22	France	29738	194585	15

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

Data availability

Data will be made available on request.

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