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# Electricity market relationship between Great Britain and its neighbors: distributional effects of Brexit

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## Abstract

**Background:** Beyond Great Britain, Brexit could also have ripple effects on the electricity systems of certain other EU member states. This paper investigates the possible effects of reduced growth in interconnectivity between Great Britain and mainland Europe by 2030 on the electricity system in GB and across other EU member states in addition to the effects of Pound depreciation. Effects are analyzed across a “Green Scenario” and “Blue Scenario” in 2030, based on the ENTSO-E (European Network of Transmission System Operators-Electricity) 10-year development plans. There is a greater expansion of nuclear and renewables in Green than in Blue and, in Blue, the British CO<sub>2</sub> price is higher than in the EU. Within each scenario, there are four variants: full vs. reduced expansion of interconnection capacity, in combination with no devaluation and 10% depreciation of the British Pound. The EMME (Electricity Market Model for Europe) is used to model these impacts across the different scenario variants.

**Results:** Interconnector utilization is more volatile in the Green Scenario variants, leading to concerns about investor incentives, especially given the increased uncertainty under Brexit. In terms of electricity prices, GB consumers lose out across both Blue and Green scenario variants, whereas EU and GB producers both gain and lose in different variants. Across the Green Scenario variants, EU neighbors’ trade balances with GB deteriorate slightly, but the impact is far stronger in Blue due to a loss of opportunities to export power. GB sees significant increases in electricity costs across scenario variants. Green scenario variants offer potential for modest emission reductions in certain EU nations, whereas Blue Scenario variants lead to greater emission reductions in the EU neighbors which contrasts with a sharp rise in GB emissions.

**Conclusions:** There is a significant link between NTC expansion and wholesale prices. Delayed or cancelled NTC expansion could negatively affect the GB power system’s low-carbon transition. Pound depreciation and reduced expansion of NTCs lead to shifts in generation-related CO<sub>2</sub> emissions. A higher cost burden for electricity is a risk for GB, whereas, for EU neighbors, their trade position with the UK risks deteriorating.

**Keywords:** Brexit, Interconnectors, Electricity system, Pound depreciation, Distributional effects

## Background

The Brexit vote of 2016 represents a turning point in Britain’s position in Europe, with wide-ranging economic and political ramifications. Since energy and climate policies of GB (Great Britain) and the EU are interlinked, it is important to study the effects of Brexit on the energy system and emissions in both GB and its EU neighbors. As

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regards the EU's objectives for energy and climate, these are based around a common energy policy encompassing 'solidarity between member states' and greater integration of energy systems, enabled by a European grid [1]. A target has been set to increase net transfer capacities (NTCs) to 15% of all installed capacity across member states by 2030 [2], with such cross-border transmission possibilities important in systems with increasing shares of renewable power [3]. The redesign of electricity systems has major implications for markets and infrastructure [4] and for economic, social and political structures [5]. Brexit runs counter to the trend towards greater integration, albeit principally concerning one country—GB—and may, through creating greater uncertainty, lead to lower than expected integration of the British grid with the grids of its EU neighbors [6–9]. In 2021, the EU–UK Trade and Cooperation Agreement was reached, setting out principles for post-Brexit cooperation between GB and the EU in a number of areas, including energy and climate. Within the agreement, it is reiterated that GB is leaving the *Internal Energy Market (IEM)*, EU ETS (Emissions Trading) scheme and *EURATOM* (European Atomic Energy Community), but GB also commits to 'non-regression' on climate change action and carbon pricing [10]. In relation to electricity interconnectors, a specific market coupling mechanism has been established which will determine interconnector capacity allocation—this mechanism is based on a separate algorithm which is only used for trades between the grids of Great Britain and those of other EU bidding zones. This agreement represents efforts to continue cooperation in energy and climate matters, however, there is a clear implication that GB is an external partner as opposed to an integral part of the Energy Union and this leads to wider questions about future British divergence and participation within the IEM.

Adam [11] is interested in creating "a framework for thinking about the impacts of Brexit" (P.9) on the British economy. This article's goal is similar, seeking to explore implications of possible scenarios from Brexit in terms of the electricity system of GB and, crucially, its neighbors. Our interest is not the short-term effects of Brexit, but the long-term implications for the electricity systems based on uncertainties about (i) the trajectory that the British power system will follow to 2030; (ii) the continued success of joint projects between the UK and EU (i.e., interconnectors) and (iii) the evolution of the Euro vs. the GBP. We focus on two potential consequences of Brexit that may have a significant impact on electricity market developments: (i) a reduced expansion of Net Transfer Capacities (NTC) and (ii) a depreciation of the GBP against the Euro. In our conception, a soft Brexit implies no reduction to NTC expansion, whereas a hard

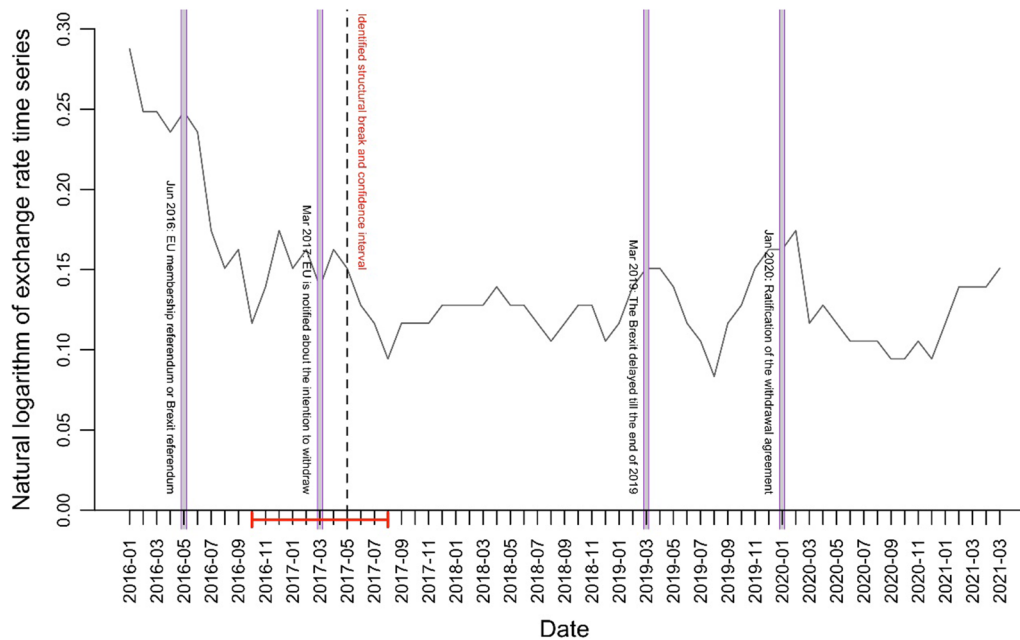
Brexit implies an expansion of NTC capacity of 65% of the planned level to 2030. No depreciation constitutes the "default" exchange rate (def), whereas depreciation of 10% in the Pound constitutes inflation (infl). We identify possible effects of Brexit on electricity prices, electricity flow structures, the utilization rates of the relevant interconnectors, shifts in CO<sub>2</sub> emissions, and a monetary assessment of potential costs for the electricity system. This study adds value to existing literature in that it considers the impact of exchange rate effects and the implications of Brexit for the electricity systems of GB's neighbors.

This analysis is organized as follows: initially, we provide a critical insight into the observable effects of Brexit to date on NTC expansion projects and on the Pound-to-Euro exchange rate. This is done, in particular, with a view to the two scenario assumptions regarding NTC expansion and the exchange rate of the British Pound. Subsequently, we deal with the relevance of Brexit for the electricity systems of neighboring countries. We then explain the methodological approach and present the employed bottom-up model of the European electricity market. Finally, results and conclusions arising from the analysis are discussed.

### Current status and critical assessment of the advancing Brexit

Broadly, two possible outcomes of Brexit are described, namely a 'soft' Brexit, in which GB remains in close alignment with EU institutions, and a 'hard Brexit', corresponding to GB leaving the IEM [12]. Although Brexit has already been the subject of several studies [6, 7, 9], little attention has been paid so far to the general potential impact of Brexit not only on GB itself, but also on neighboring countries and thus on the entire European electricity market. The present study contributes to closing this gap. Newbery's [12] and Geske et al.'s [13] distinction between a hard and soft Brexit, in electricity terms, is based on whether or not the UK leaves the IEM. This is a good guide, although GB could still reach a robust and efficient trading relationship with its neighbors outside of the IEM.

We take a critical look at the two Brexit scenario assumptions regarding the development of the NTC and the exchange rates of the Pound. Brexit has led to complications with interconnector projects. Notably, the French Regulatory Commission's decision that it would have to suspend decisions as to whether to support future interconnector projects between Britain and France has led to delays according to the FAB (France–Alderney–Britain) interconnector project [14]. Likewise, according to a report by the French Regulatory Commission, a soft Brexit could lead to a 10% fall in the value of



**Fig. 1** GBP to Euro Exchange Rate 2016–2021

interconnection between Britain and France, whereas, a hard Brexit, leading to market decoupling, could lead to a fall in value of as much as 30% [15]. In the practitioner literature, there is the suggestion that growth in interconnection is likely despite Brexit, due to increasing opportunities in GB's balancing market [16, 17]. However, with the end of the transition period on January 1st 2021, GB left the Internal Energy Market (IEM) [18]. Thus, in terms of international electricity trade, GB is treated as a third party with trades no longer being aided by EU single market tools. As a result, electricity trade between the EU and GB became less efficient and reports predicted a drop in the value of interconnection [17] and, more specifically, complications arising from the loss of access to the current market coupling arrangements [19].

The development of interconnectors between GB the neighboring EU states are listed as Projects of Common Interest (PCI). On the one hand, these projects receive an accelerated permitting process and, on the other hand, they are eligible for public funding. Between 2014 and 2020, 21 projects directly related to GB received funding, according to the EC's PCI database [18, 21]. Of these projects, 15 involved research and development of NTCs. Three others relate to interconnection between France and Ireland. The maximum committed financial support for these projects is approximately €646 million. According to a British Government White Paper, published in 2020, GB plans to realize 18 GW of NTC by 2030, which is three times the current capacity [22]. In the event that

some or all of the future interconnector projects are stripped of the PCI status, funding for these projects could be jeopardized [23]. Mathieu, Deane [20] argue that Norway as a full member of the IEM, for example, could take advantage of the situation in order to receive stronger support from the EU for their interconnector projects. In addition to the loss of EU funding, Brexit has also increased uncertainties regarding investments in the energy sector. This may have a negative impact on the financing costs of interconnector projects [20, 24].

In addition to the reduced expansion of the NTC, this study also looks at the consequences of a devaluation of the Pound. Various studies already identified a link between Brexit and devaluation [25–28]. Nabarro and Schulz [29] estimate, that the value of Sterling could fall between 5 and 10% in trade weighted terms. Plakandaras, Gupta and Wohar [27] argue that a major part of the depreciation of Sterling is due to the uncertainty associated with Brexit. Moreover, Stoupos and Kiohos [28] found that a further depreciation of the Pound is likely, which may lead to a decline in value especially against the Euro and the Dollar.

Although it is unclear how long this effect will persist, an examination of the time series of the GBP and Euro exchange rate shows that no recovery to a pre-Brexit level has taken place so far. Figure 1 displays the Pound-to-Euro exchange rate from January 2016 to March 2021. A sharp fall in the value of the Pound occurs following the Brexit vote in June 2016 and the value of the Pound has

never regained its mid-2016 level, although there have been substantial fluctuations. This sustained lower value is reflective of perceptions about a more difficult trading relationship between GB and the EU [30]. Moreover, this depreciation of the GBP against the euro occurred during the Eurozone crisis, affecting Portugal, Greece, Italy and Spain, with the euro declining seriously against the dollar in April 2014 and only gaining significant ground in early 2018 [31]. The decline of GBP against the euro despite the Eurozone crisis indicates that the effect of Brexit on the GBP was substantial. The structural break in the exchange rates possibly falls in the period between November 2016 and July 2017, close to the date when the EU was notified about GB decision to withdraw. The structural change identified is the period after which there is a consistent change in the Pound-to-euro exchange rate.<sup>1</sup> For the purposes of this study, we assume that, in certain scenarios, this depreciation persists in 2030, whereas, in other scenarios, there is no depreciation. The notes on the estimation of the structural break are given in the Appendix (Fig. 1).

The above analysis indicates that, in the short-term, Brexit has had significant structural effects on the Pound and that, in the longer-term, the smooth running of interconnector projects could be jeopardized by the uncertainty created.

### Why Brexit is relevant to the power system of GB and its EU neighbors

Studies have been published about the implications of Brexit on energy and climate policy [33–35] while there has also been research relating to economic and financial market analysis around Brexit [36–39].

Geske, Green [6] analyze the economic consequences for GB and France if GB were to leave the EU's IEM. Lockwood, Froggatt [7] contrast advantages and disadvantages of Brexit by identifying and evaluating potential tradeoffs between market integration and political freedom of action. Mayer, Ball [8] investigate the impact at the actor level in GB by considering both a reduced NTC expansion and devaluation of the British Pound. By applying a model for the European Electricity System, MacIver, Bukhsh [40] examine the implications of increased interconnectivity of the GB electricity market with Europe and conclude, among other things, that unilateral CO<sub>2</sub> taxation in GB can lead to local reductions in CO<sub>2</sub> emissions, which are offset by additional emissions in the rest of Europe. Employing a coupled modeling approach [35], examine the sectoral implications

of Brexit for the United Kingdom, Europe, and the rest of the world. They found that a positive or negative outcome of Brexit for GB depends heavily on its relationship with the rest of the world. In contrast, the picture for Europe was more pessimistic. In only one of a total of eight scenarios can Europe achieve positive gross value added as a result of Brexit. Other studies suggest more modest impacts from Brexit for the UK's electricity system, thanks to the TCA's (EU–UK Trade and Cooperation Agreement) focus on maintaining cooperation in the energy sector, highlighting minor increases in trade barriers [41] and a minimal value of an additional GW of interconnector capacity with France for UK consumers in 2025 [42]. Guo and Newbery [43] estimate the social costs of uncoupling to be substantially lower than other projections in the literature at €28 million per year. Furthermore, the marginal value of interconnector capacity with the UK could be more significant for French, Dutch and Belgian consumers [42], indicating that it is interesting to study the effects on the UK's neighbors. Costs from uncoupling the UK from the Single Electricity Market arise from increases in inefficient trading, with estimates by Gisse, Guo [44] of a 3% and 2% increase in the price differential between the UK and France and the Netherlands, respectively.

The EU's IEM involves markets clearing at the same time and transmission capacity to be allocated automatically and this minimizes the errors in electricity trading [12]. Geske, Green [6] argue that uncoupled markets may weaken incentives for investors to expand interconnection capacity between GB and EU grids, due to lower trading efficiency. Mathieu, Deane [20] argue that the welfare losses of an exclusion of GB would be all the greater the further European market integration progresses.

GB is a net importer of electricity, with France being the most significant trading partner, followed by Belgium and the Netherlands [22]. The commercial value of Britain's interconnectors with France and the Netherlands is estimated at €500 million annually, since gains can be made from trading electricity from low-cost to high-cost markets, with the social value from contributions to energy security adding an additional €25 million in social value [45]. The imposition of a unilateral carbon price in the GB market causes losses in welfare [46], as it has reversed the direction of electricity trade flows between GB and the continent, with GB importing from the Netherlands and France despite having lower generation costs and carbon intensity [45]. While there is high private and social value from interconnection, the asymmetric carbon price imposed by GB on its own generation is arguably harmful to the social value of interconnection.

<sup>1</sup> The analysis for structural change is based on the normal linear regression model and capture parameter instabilities in both regression coefficients and error variance (see [32]).



Costs of British withdrawal from the IEM are estimated by Newbery, Gissey [45] at €300 million annually for Britain by 2030, whereas the welfare losses, according to Geske, Green [6] amount to €700 million per year by 2030 for both Britain and France. The economic effects are distributed very differently among stakeholders. Geske, Green [6] find that wholesale costs for British consumers increase by 4%, whereas they fall slightly for French consumers. In contrast, they estimate that British producers benefit, whereas French producers lose out from a loss of access to trading opportunities, through a stymied expansion of interconnection capacity between the British and French grids to 5 GW (rather than 10 GW). There will also be implications for GB's energy security, especially at peak times and the loss of access to the EU's shared electricity balancing system, currently in development, will entail very large costs [47].

Negative consequences may result not only from a possibly costly coupling process of the EU ETS (EU Emissions Trading System) with the GB ETS, introduced in January, 2021, but also from insufficient interconnection at the power sector level. This could have an impact, especially with regard to the integration of high shares of intermittent renewables, both on the expansion of these and on security of supply. The transition to a low-carbon system involves high investments (both in terms of generation facilities and grid expansion). Investments of up to €130 to €330 billion could be required by 2030 [48]. The political and regulatory uncertainties associated with Brexit could have a negative impact on willingness to invest, leading to delays in innovation and the transformation of the energy sector and ultimately to insufficient progress on climate protection [20, 34, 49, 50]. The UK established its own Emissions Trading Scheme upon leaving the EU in January 2021. While there are signs of convergence between the UK and the EU ETS prices [41], there has also been divergence, with the spread between the UK and the EU ETS price reaching a high of 50% (UK price of £90 over the EU price of £60 per ton) in September 2021 [51]. While there has been talk of linking the UK ETS with the EU ETS, this would make the UK a rule-taker [52] and the process could take time [53]. While the UK and the EU have both committed themselves to Net Zero targets, indicating a similar trajectory towards more ambitious decarbonization, the UK is experimenting with its ETS system—integrating provisions for carbon dioxide removal technologies, for example [54]. This indicates that a certain degree of uncertainty about convergence on UK and EU carbon prices persists.

A common oversight of existing literature in the field of electricity market analysis is the role of exchange rates. While these have been considered in empirical studies [26, 55] and more aggregate modeling approaches such as

input–output [56], or CGE models [57], they have been mostly neglected in a bottom-up electricity market analysis. Mayer, Ball [8] consider a possible fall in the value of the Pound relative to the Euro, due to greater trade barriers between GB and the EU following Brexit. Yet, their study focuses on the implications for GB, largely omitting effects for the rest of Europe. Exchange rate effects could amplify the effect of reduced NTCs on consumers and producers in GB and connected countries while changing flows of electricity could influence carbon emissions across these countries. This paper will explore the possible implications of these fluctuations for the power system of both GB and its EU neighbors.

## Methods

### Bottom-up electricity market model

The Electricity Market Model for Europe (EMME) is a bottom-up electricity dispatch model [58], consisting of 28 European countries. It applies a linear optimization method to minimize total system costs  $Z$  under the transmission and operational constraints. Total system costs comprise electricity generation costs, imports and exports of electricity between countries as described by the objective function in Eq. 1:

$$\min Z = \sum_{h,i,d} [\text{Pr}(h,i,d) \bullet \text{Cst}(i,d)] + \sum_{h,d,k} \text{Im}(h,d,k) \bullet T \quad (1)$$

subject to:

$$\sum_i \text{Pr}(h,i,d) + \sum_k \text{Im}(h,d,k) - \sum_k \text{Ex}(h,d,k) = \text{Dm}(h,d) \forall h,d, \quad (2)$$

$$\frac{\text{Pr}(h,i,d)}{y} \leq \text{Cp}(h,i,d), \quad (3)$$

$$\frac{\text{Im}(h,d,k)}{y} \leq \text{NTC}(d,k), \quad (4)$$

with  $i$ : index for generation technology type;  $h$ : specific hour of the year  $[-]$ ;  $d$ , and  $k$ : countries indexes  $[-]$ ;  $\text{Cst}$ : variable generation costs [Euro/MWh];  $\text{Pr}$ : electricity production [MWh];  $\text{Cp}$ : generation capacity [MW];  $\text{Im}$ : electricity imports from country  $k$  to country  $d$  [MWh];  $\text{Ex}$ : electricity exports from country  $d$  to country  $k$  [MWh];  $T$ : transport costs for imports and exports (Euro/MWh);  $\text{Dm}$ : electricity demand [MWh];  $\text{NTC}$ : net transfer capacity between two markets [MW]; and  $y$ : conversion factor (MWh to MW) [unit: hours].



**Fig. 2** Geographical scope of the EMME model

Equation 2 is the central constraint that represents the energy balance. It ensures that the given hourly electricity demand is balanced by the supply side at every hour in each modeled country. The model comprises the detailed representation of the electricity generation mix: power plants, their capacities, vintage structure and respective variable costs for each country. Imports and exports between the neighboring countries are constrained by net transfer capacities (NTCs). Generation capacities, energy commodity prices, CO<sub>2</sub> certificate prices, NTCs and power demand are exogenous model input parameters. Diverse sets of input parameters represent assumptions about the future of the system and are combined in the scenarios. The production, imports, exports and electricity prices in each country result from the modeled economic dispatch. Based on these model results, we estimate emissions, consumer and producer surpluses across various scenarios.

Geographic coverage includes the EU-28 countries, with each country treated as a single node, which are linked via NTCs. Figure 2 provides an overview of the geographical scope.

The calculation of CO<sub>2</sub> emissions takes into account the vintage structure of a power plant  $i$  and the type of fuel used:

$$\text{CO}_2(d) = \sum_i \left( \text{sec}_i \bullet \sum_h \text{Pr}(h, i, d) \right), \quad (5)$$

with CO<sub>2</sub> : emissions in country  $d[t]$  and  $\text{sec}_i$  : specific emission coefficient  $\left[ \frac{\text{tCO}_2}{\text{MWh}_{\text{el}}} \right]$ .

Equation 6 below shows the trade balance comprising the difference between the value of imports and exports for each country:

$$\begin{aligned} \text{TB}(d) = & \sum_{h,k} (\text{Im}(h, d, k) \bullet X(h, k)) \\ & - \sum_{h,k} (\text{Ex}(h, d, k) \bullet X(h, d)), \end{aligned} \quad (6)$$

with  $X$ : the electricity price in the country-importer  $k$  or -exporter  $d$  [Euro/MWh]—the marginal electricity price in the respective region (shadow price of the demand constraint in Eq. 2).

The total expenses for the provision of electricity in each region can give a general overview of the costs pertinent to the described electricity system. We focus on the variable costs and do not regard the overnight costs for present generation capacities, as we do not regard investments in the electricity generation fleet. The effects of the GBP devaluation on generation costs (through e.g., increasing the cost of imported natural gas) are built into the model. The total expenses for the provision of electricity are as follows:

$$\begin{aligned} \text{TE}(d) = & \sum_{h,i} (\text{Pr}(h, i, d) \bullet X(h, d)) \\ & + \sum_{h,k} (\text{Im}(h, d, k) \bullet (X(h, k) + T(k, d))) \\ & - \sum_{h,k} (\text{Ex}(h, d, k) \bullet (X(h, d))). \end{aligned} \quad (7)$$

### Scenario assumptions

The possible distributional impacts on EU countries are investigated under the two scenarios Blue and Green (see Table 1) and these are both based on the 10-year development plans found within the ENTSO-E documentation [59]. Brexit is a cause of uncertainty in the realm of multilateral agreements, such as NTC expansion and climate policy, especially since GB will no longer be subject to the EU Renewables Directive. Both Green and Blue scenarios describe GB following strict unilateral climate policies, represented by a high GB carbon price. The Blue scenario sheds light

**Table 1** Scenarios and scenario assumptions

Scenario	Blue				Green			
	soft_def <sup>a</sup>	soft_infl	hard_def	hard_infl	soft_def *	soft_infl	hard_def	hard_infl
Increases in interconnectivity	As planned [100%]		Reduced [65%]		As planned [100%]		Reduced [65%]	
Devaluation of currency	No (0%)	Yes (10%) <sup>b</sup>	No (0%)	Yes (10%)	No (0%)	Yes (10%)	No (0%)	Yes (10%)
Certificate price [Euro/t CO <sub>2</sub> ] <sup>c</sup>	GB: 90, EU: 30				GB: 90, EU: 90			
Annual electricity demand GB [TWh]	330				355			
RES-E (GW)	41				83			
Nuclear (GW)	4.5				9			
Fossil Fuel (GW)	46				37			

<sup>a</sup> Baseline Green and Blue scenarios in the respective scenario family<sup>b</sup> 10% devaluation compared to mid-2016 level<sup>c</sup> From ENTSO-E scenarios**Table 2** Total imports of electricity to GB and exports from GB in GWh to neighbors in 2030 in default Blue and Green Scenarios

Neighboring country	Blue_soft_def		Green_soft_def	
	Imports to GB	Exports from GB	Imports to GB	Exports from GB
NL	6124	259	64	5577
BE	2625	481	25	5130
FR	48,098	7	5558	8250
DK	12,925	0	1256	1205
NO	13,103	0	11,867	0
IE	8666	0	2281	2

on the developments between GB and EU countries, in the context of a high GB carbon price and a lower EU ETS price. In contrast, under the Green Scenario, the ETS and GB carbon prices are equal, i.e., the EU ETS price is increased to match the high GB carbon price. Under the Green scenario, there is a far greater expansion of renewable and nuclear capacity than in the Blue scenario—this is based on the details of the development plans described by ENTSO-E. Details of the Blue and Green scenarios are given in Table 1 below. Effects

from reduced NTC expansion and the depreciation of the Pound on electricity prices and CO<sub>2</sub> emissions are differentiated across the Blue and Green scenarios.

## Results and discussion

In this section, the changes in power flows arising from the different variants of Brexit alongside the impacts for the utilization of NTCs, economic effects and the impacts on emissions in GB and the EU are presented.

### Changes in power flows and electricity prices

Examining the changes in power flows between GB and its European neighbors helps to understand the underlying impacts of Brexit on other European countries' power systems. The changes induced across the variants of the Blue scenario and Green scenario are discussed below. All changes are relative to the default variant of the Blue and Green scenarios in which there is no reduced expansion of NTCs and no devaluation of the Pound (Table 2).

Since, in the scenario variants of Blue, GB follows a policy of a unilaterally high carbon price combined with lower expansion of low-carbon generation alternatives, GB's domestic generation is less competitive than the

**Table 3** Changes in imports to GB from EU neighbors and exports from GB to EU neighbors in blue scenario variants compared to variant soft\_def (GWh)

GB	NL		BE		FR		DK		NO		IE	
	Im	Ex	Im	Ex	Im	Ex	Im	Ex	Im	Ex	Im	Ex
soft_infl	− 1680	26	− 1648	11	− 1283	7	− 31	3	3		− 39	0
hard_def	1113	− 86	− 67	− 311	− 16,195	− 1225	− 4485	0	− 4584		− 2983	0
hard_infl	− 454	− 70	− 1482	− 309	− 16,685	5	− 4502	0.4	− 4583		− 2983	0

**Table 4** Changes in imports to GB from EU neighbors and exports from GB to EU neighbors in green scenario variants compared to variant *soft\_def*

GB	NL		BE		FR		DK		NO		IE	
	Im	Ex	Im	Ex	Im	Ex	Im	Ex	Im	Ex	Im	Ex
<i>soft_infl</i>	− 3	2019	1	1336	− 1458	1658	− 595	196	63		− 729	3
<i>hard_def</i>	55	− 204	23	− 1840	− 924	− 2167	~0	− 189	− 4260		− 603	− 1
<i>hard_infl</i>	56	1878	23	− 937	− 2228	− 842	− 584	− 92	− 4229		− 1196	− 1

domestic generation of its European counterparts. This means that GB is a net importer under the Blue scenario and the scenario variants overwhelmingly influence the imports of power to the GB grid from the EU; see Table 3. Effects on flows in the Blue scenarios can be differentiated between Belgium and the Netherlands, for whom the depreciation effect is stronger, and the others, where the NTC effect is dominant. The falls in imports to the GB grid from Belgium and the Netherlands indicate that, under depreciation of the Pound, these countries' power exports face a substantial loss of competitiveness in relation to Britain's domestic generation. It is possible that Belgian and Dutch generation provides GB with a relatively small amount of peaking power which is no longer worthwhile, as its relative cost increases through depreciation. Curiously, under a reduced expansion of NTCs, GB imports more Dutch power, suggesting these imports are displacing those from France and the other nations. Exports from France, Denmark, Ireland, and Norway to GB are minimally affected by the depreciation, but there are substantial drops under a reduced NTC expansion. This indicates that, under the Blue Scenario, imports to GB from Belgium and the Netherlands fulfill a different function than those from France, Denmark Norway, and Ireland. It is suggested that the power flows from France, Denmark, Norway, and Ireland to GB are more constant and stable, whereas the British grid only has recourse to Belgian and Dutch power occasionally to meet peak demand needs (Table 4).

Under the Green scenario, GB's position in the EU electricity market is different, in that it is now much more of an exporter of power to the continent thanks to its expansion of nuclear and renewable capacity. In this case, the effects are stronger on the export-side for the Netherlands, Belgium and France and stronger on the import side for Denmark and Norway (i.e., imports to GB). Across the Netherlands, Belgium, France and Denmark, exports from GB are strongly boosted by a depreciation of the Pound, as would be expected, given the enhanced competitiveness of British power exports. In contrast, a fall in NTC expansion leads to considerable reductions in exports from GB to these countries. In the case of France, imports to GB behave in the expected way, but

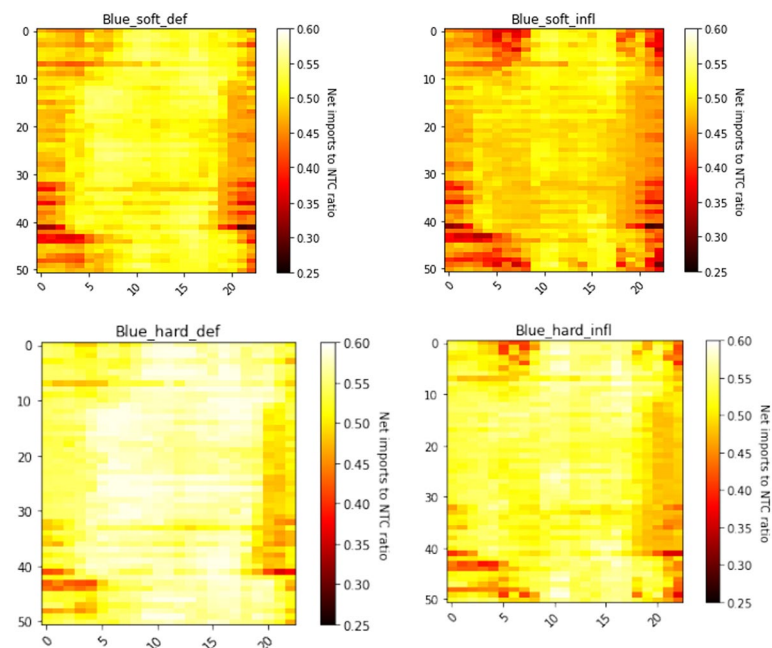
they do not in the case of the Netherlands and Belgium, although the effects are very small in the latter cases. In the case of Denmark, imports to GB fall sharply in the case of depreciation, whereas exports from GB rise, as would be expected. Under a fall in NTC expansion, there are no effects on imports to GB, but exports from GB fall significantly. For Norway, imports to GB grid fall substantially under a reduced NTC expansion, but there is little impact from the depreciation of the Pound. In the case of Ireland, imports to GB are affected strongly by both effects. In summary, Belgium and the Netherlands experience substantial changes in terms of their exports from GB, whereas, in France, the picture is mixed and, in Denmark, Norway, and Ireland, their imports to GB are strongly affected.

The changes in the flows under the different scenarios and their variants help to understand the reasons underlying changes in the utilization of NTCs, the electricity-related costs of Brexit and the impacts of Brexit on emissions. Figure 3 shows NTC utilization as the ratio of electricity flows from and to GB in relation to the NTC. The calendar weeks of the scenario year 2030 are plotted on the Y-axis, the X-axis shows the hours of a day. Light areas indicate a high, dark areas a low utilization of the NTC (Fig. 3).

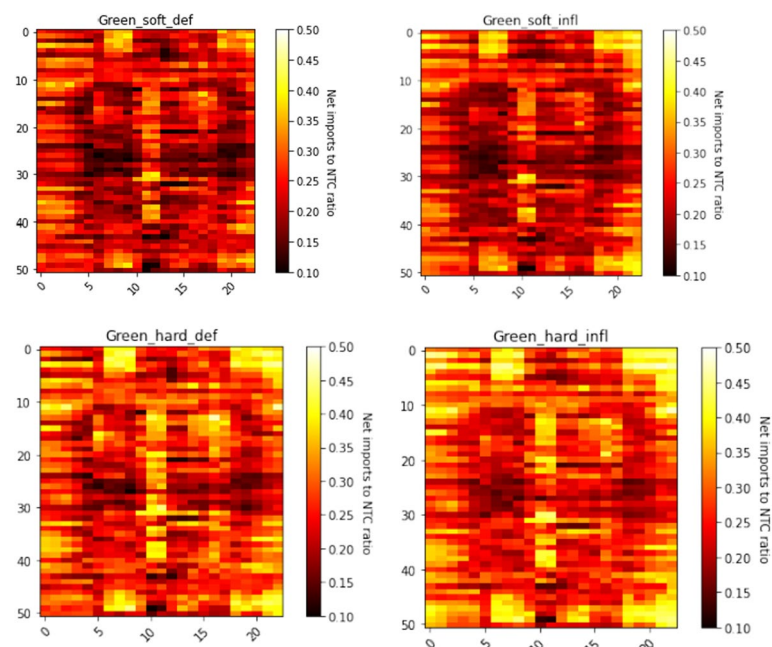
A comparison of the pattern of GB's net electricity imports shows that there is a structural difference between the Green and Blue scenario groups. All scenario groups of Blue show a relatively constant high utilization. At the same time, a slight seasonal shift can be seen with regard to the hours with the highest utilization rates. Interestingly, it seems that the combination of both a reduction in NTC and a devaluation of the British Pound lead on average to a lower utilization rate of the transfer capacities, than the reduction of NTC alone.

Although the effect is less pronounced, it can be seen that, in the Green scenario variants, the exchange rate effect tends to show an opposite trend. Here, the devaluation of the Pound leads to an increase in the utilization rate. This can be seen in the top right hand picture of Fig. 4, where, under a soft Brexit (*soft\_infl*), implying full NTC expansion, a devaluation leads to more utilization in the early weeks of the year (0–10) and the final weeks





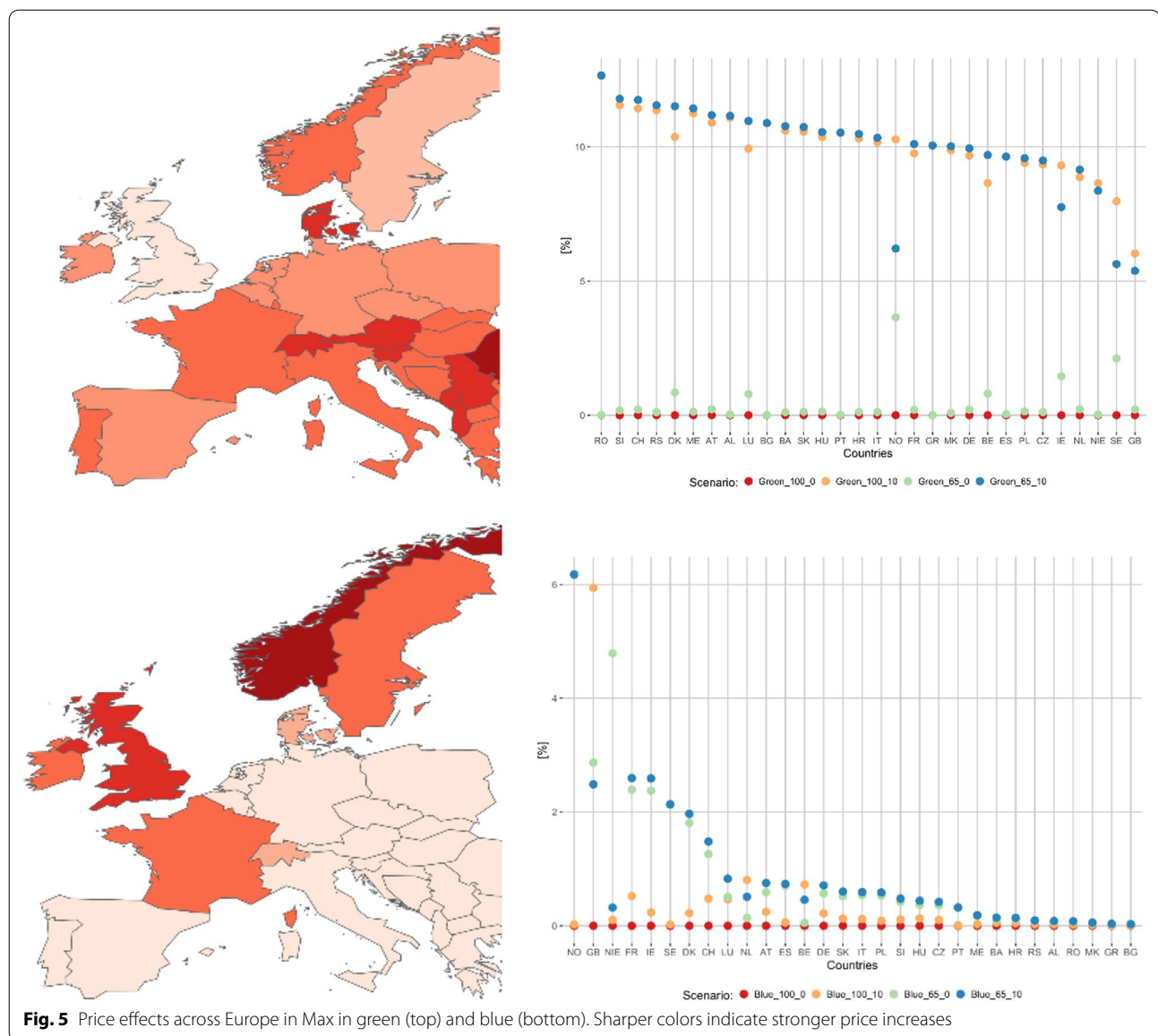
**Fig. 3** Utilization of NTCs across Blue Scenario Variants (weeks of year on y axis, hours of day on x axis)



**Fig. 4** Utilization of NTCs across Green Scenario Variants (weeks of year on y axis, hours of day on x axis)

of the year (45–50) at night, shown by the greater amount of yellow at those periods (reflecting higher utilization). Devaluation has similar effects under a hard Brexit in Green, with greater amounts of yellow during those periods. In general, Green shows a more fragmented picture,

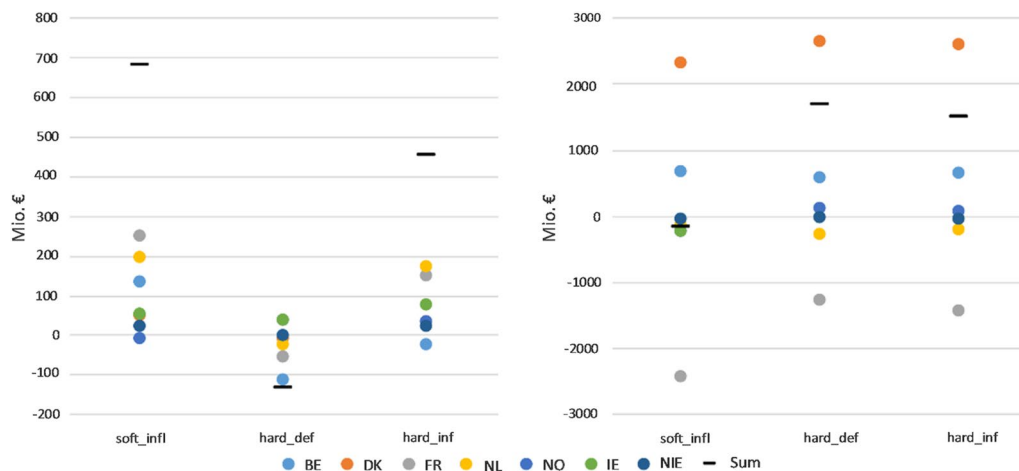
with hourly rapid shifts between high and low rates of utilization of NTCs. With regard to international electricity trade and the expansion of NTCs, our analysis shows that the basic structure of imports and exports between GB and neighboring countries depends significantly on



the assumed development path. While Blue is characterized by a high average utilization of lines, the picture is different for Green. Hours with high and low utilization often alternate hourly. With a view to the future development of line capacities, the question arises as to whether an import–export structure as shown in Green creates sufficient investment incentives for the expansion of NTCs. On the other hand, however, it must be taken into account that due to the volatile generation structure of renewable plants in the Green scenario, the expansion of NTCs can be significantly more important for system stability than is the case in the Blue scenario variants.

In Fig. 5, the price deviations from the reference scenario (soft Brexit, no Pound depreciation) are shown. It

is clear that, in the Green scenario variants, the effects are more distributed and that the impact of depreciation is more important than the impact of reduced NTC expansion. This is intuitive given the role of GB as a net exporter in the Green scenarios, with the Pound depreciation leading to the greater attractiveness of British power on the continent. In contrast, in the Blue scenarios, the effects are concentrated in France, Norway, Sweden and Denmark and are driven by the reduction in NTC expansion rather than the Pound depreciation. This effect is caused by the fact that GB is a net importer under the Blue scenarios and a fall in NTC expansion capacities reduces its ability to import from its key partners. The distributional effects differ according to the



**Fig. 6** Monetized power flows between GB and neighboring states in €million

scenario. Generally, in the Green scenario variants, the changes caused by the Pound depreciation are good for EU consumers, who benefit from lower wholesale prices, and for GB producers, who are better able to export to the EU markets. In contrast, the changes are bad for GB consumers, who see price increases, and for EU producers who must compete against cheaper British imports. Under the Blue variants, the changes are good for EU consumers and for GB producers, but negative for EU producers, not able to sell as much electricity as they would like to GB and for GB consumers, who face higher prices through the reduced import potential.

### Costs of Brexit

The costs of Brexit in terms of GB leaving the IEM have been estimated at €300 million by Newbery, Gisse [45] and €700 million by Geske, Green [6], respectively. In this section, we conduct a monetary assessment of the different scenario variants. In doing so, we compare the monetary value of electricity flows between GB and the neighboring states on the one hand, and the total expenditure on electricity provision in GB on the other. All estimates are in 2019 euros.

Figure 6 shows the monetized power flows between GB and neighboring EU member states in reference to the soft\_def variants—i.e., the variants without reduced expansion of NTCs and without Pound devaluation. The values shown represent the differences in trade balances, according to Eq. 6, of the respective countries with GB. Positive values correspond to additional spending by neighboring countries, negative values to reduced spending. The variants of the Green scenario are plotted on the left, those of the Blue scenario on the right.

An examination of the Green scenario variants shows that here the exchange rate effect exceeds that of the NTC reduction: with full NTC development and a permanent devaluation of the Pound against the Euro, the expenditures of neighboring European countries on British electricity increase by a total of almost €700 million per annum. In contrast, hard\_def leads to a decrease in spending of around €135 million annually. The combination of both effects together leads to additional expenditures of around €454 million annually, with the reduced expansion of NTC capacity mitigating the exchange rate effect.

The Blue scenarios show a somewhat different picture. Here, the effect of a reduced NTC expansion clearly predominates, while the exchange rate effect plays only a minor role. In the event of a devaluation of the Pound (*soft\_infl*), spending by EU member states on GB electricity will fall by €169 million annually. The other two sub-scenarios result in an increase of €1,688 per annum (*hard\_def*), and €1,508 per annum (*hard\_infl*) million, respectively, resulting from selling less power to the GB grid.

In summary, in the Green Scenarios, from the perspective of the European neighboring countries, a reduction in electricity trade expenditures with GB can only be achieved if NTC capacity is reduced. In the analysis presented, a devaluation of the British Pound and an expansion of capacities as planned leads to GB being able to sell higher volumes of green electricity to the EU member states at more favorable prices overall. In contrast, the unilateral introduction of a carbon price in GB results in electricity producers in surrounding states having a competitive advantage over GB producers. The devaluation

**Table 5** GB's total expenditure for electricity supply compared to baseline scenarios in €million

Variant scenario	<i>soft_infl</i>	<i>hard_def</i>	<i>hard_infl</i>
Blue	1711.64	1341.39	3025.08
Green	1430.00	269.19	1619.38

of the Pound can only compensate for this to a very limited extent. Here, a reduction in planned NTC capacity means that neighboring countries can sell less electricity to GB, which negatively impacts trade balances.

Total GB spending on electricity supply, described by Eq. 7 in the methodology section, is €22.99 billion for Green and €25.77 billion for Blue.

The potential cost of Brexit can then be estimated using the difference in total spending in each scenario variant relative to the scenario without NTC capacity reduction and without permanent depreciation of the Pound, as shown in Table 5.

Again, we see that total costs in the Green scenario are only marginally responsive to the reduction in NTC capacity. The *hard\_def* variant responds with only a slight increase in expenditures. In contrast, the exchange rate effect leads to a more significant increase in *soft\_infl*, and the combined effect of the exchange rate and reduced NTC capacity in *hard\_infl* causes expenditures to increase the most. Although in this case, too, the exchange rate effect has a stronger impact than the reduction in NTC capacity, the difference in Blue's scenario variants is smaller. The isolated exchange rate effect results in an increase of 6.64%, the NTC effect in an increase of 5.20%. The combined effect results in an overall growth of 11.74%. Compared to the estimates of €300 million to €700 million annually [6, 45], our cost assessments show that they are significantly higher on average. At €269.19 million, Green\_ *hard\_def* is the scenario with the lowest additional costs due to Brexit. At €1,430 million and €1,619 million, the other variants are significantly more pessimistic than the estimates by Newbery, Gisse [45] and Geske, Green [6]. In the case of Blue, the range between €1,341 million and €3,025 million is even higher.

### Impacts of Brexit on emissions

The impacts of Brexit on emissions from power generation in GB and neighboring countries across the Blue and Green scenario variants are shown in Fig. 7. We are not concerned with the overall level of UK–EU CO<sub>2</sub> emissions, but, rather, changes in the distribution of these emissions. Our goal is to identify shifts in the

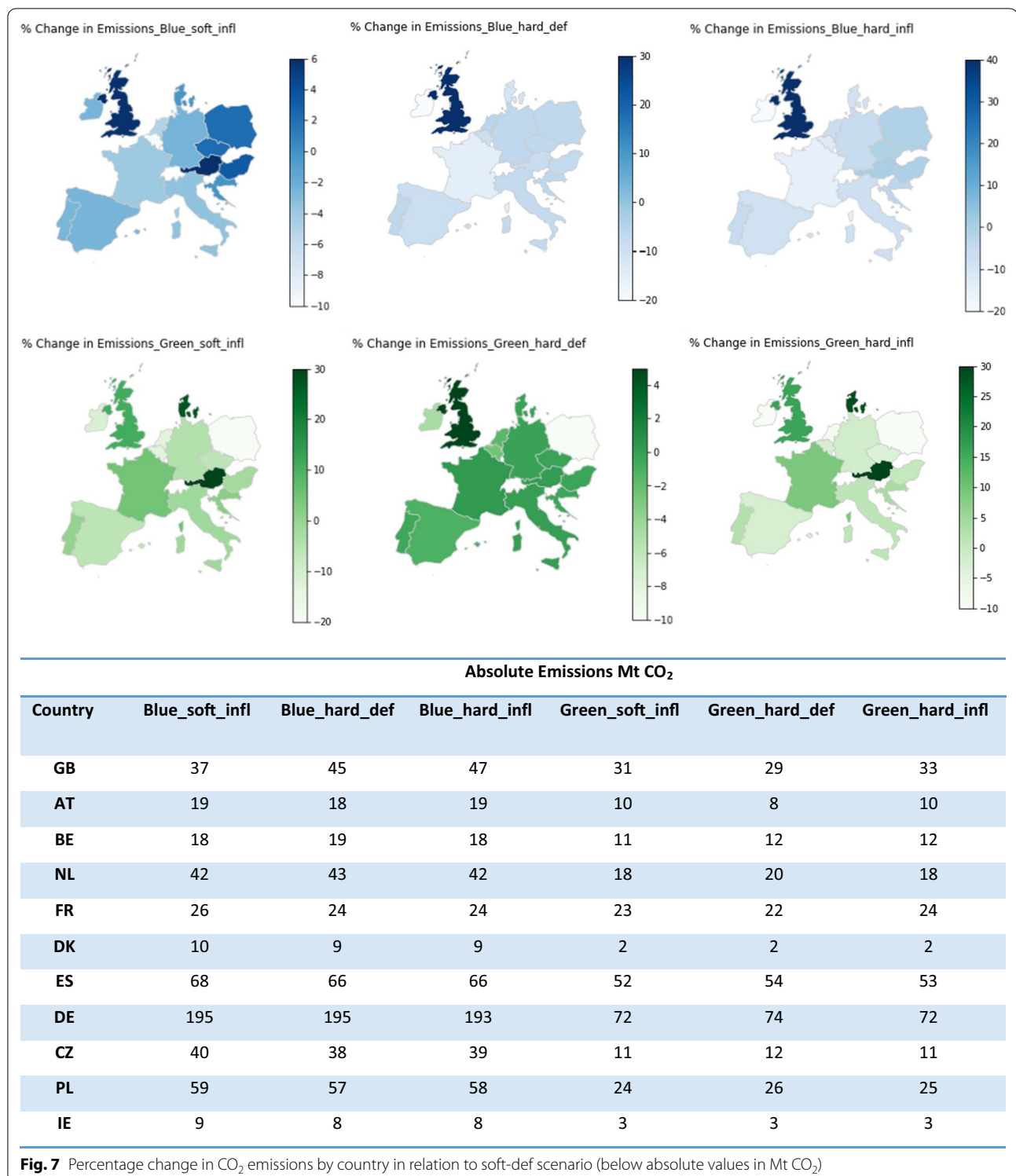
neighboring countries' power sector emissions across the different scenarios.

The reduced expansion of NTC capacities is the trigger for emissions changes in the Blue variants, with changes being much more pronounced than in the Green scenario variants. Under Blue\_ *soft\_infl*, there are limited rises in GB's and Austria's emissions contrasted with minimal falls in emissions in the Netherlands, Belgium and France. However, in Blue\_ *hard\_def*, emissions rise substantially in GB (more than 30%) and this is accompanied by significant falls in France (8%) and Denmark (5%). Belgium and Spain also both experience falls in emissions of 3% under a reduced expansion of NTC capacity, with Austria seeing a rise of 3%. In Blue\_ *hard\_infl*, the depreciation of the Pound, for the most part, amplifies the effect of the reduced NTC capacity expansion—of course, this is especially the case for GB, with power sector emissions increasing by 35% compared to the reference case (Blue\_ *soft\_def*).

While there is a certain degree of movement in emissions in Blue\_ *soft\_infl*, caused by the depreciation effect, this is relatively weak. GB, under the Blue scenario, is a net importer, so there are marginal reductions in emissions in the Netherlands, Belgium and France, as their exports of power are less attractive to the GB market. As a net importer, GB is far more reliant on imports from its neighbors and, under reduced expansion of NTC capacity, it must resort to less efficient natural gas plants to meet its needs. This drives up emissions considerably. For the exporters of power to GB, this leads to opportunities to reduce their power-related emissions, especially for France and Belgium.

Figure 7 shows that the depreciation effect is the dominant effect in the Green Scenario variants. This is due to GB's position as a net exporter of renewable power in the Green scenario; the depreciation of the Pound leads to cheaper imports of clean power for its EU neighbors. Emissions fall in Belgium and the Netherlands and there is a corridor to central and Eastern Europe, with emissions reductions in Germany, the Czech Republic and Poland in the Green\_ *soft\_infl* and Green\_ *hard\_infl* variants. It is proposed that the greater availability of British green electricity in France, the Netherlands and Belgium has a cascading impact on these central and Eastern European countries, namely they benefit indirectly through being able to purchase surplus French and German power. Poland, in particular, experiences a 16% drop in emissions and this can be partly attributed to the greater presence of fossil fuel generation in Poland in 2030 compared to other states. There is a southern corridor, with French emissions increasing and Spanish emissions decreasing. In fact, in Green\_ *soft\_infl*, French production increases slightly whereas Spanish production





decreases by a similar quantity, with the additional French power produced being passed through to Spain, shifting the emissions reduction to Spain. Denmark and Austria are outliers, seeing spikes in emissions of 25%

and 27%, respectively, however, it must be said that Danish emissions are very minimal in the Green scenario and this could be caused by a small reduction in imports from GB. In the case of GB, there is a significant rise of 10% in



Green\_soft\_infl and this is caused by increased production linked with exports which have become more competitive thanks to the Pound depreciation.

Under the reduced expansion of NTC, there is minimal impact on emissions—with only GB and Poland experiencing effects. In GB's case, more limited import capacity means that it has to resort to domestic fossil fuel production in times of power shortages, while the causes of the effect in Poland are not clear at this stage.

An analysis of this picture demonstrates that there are opportunities and risks arising out of Brexit for continental Europe. Under the Green Scenario variants, there are opportunities for modest reductions in emissions in certain EU nations, with some notable exceptions, including France and Austria. Across the Blue scenarios, there is, in general, potential for emission reductions across the continent. From GB's perspective, the risks are considerably higher and these are amplified in the Blue scenario variants with reduced expansion of interconnector capacity. In these variants, GB's power sector-related emissions rise considerably and this is a political concern for GB, especially given its recent commitments, including the introduction of its own emissions trading scheme and Net Zero pledge [60]. The British government must consider how it could respond to Brexit-related vulnerabilities related to currency and NTC capacities—e.g., whether it needs to invest in additional back-up capacity, in the form of greater amounts of hydrogen or batteries.

### Conclusions and limitations

The developments arising from GB's exit from the EU may not only have far-reaching consequences for the electricity market in GB itself, but also in the neighboring EU member states and, thus, in the EU as a whole. We show that there is a significant link between the expansion of NTCs and wholesale electricity prices in the affected countries. This effect, in turn, has a direct impact on the flow of electricity between countries.

A closer look at the electricity flows over the course of the year shows that even adverse effects can occur with regard to the climate protection targets. Due to the higher price spread, a power plant fleet as assumed in the Blue scenario would use the existing NTCs much more intensively than in the case of the Green scenario. Higher price spreads and higher NTC utilization in Blue suggest that investment incentives in additional transmission capacity could be significantly higher than in Green. However, due to the volatile generation profiles of renewable energy plants, such as wind power or PV plants, sufficient interconnectors to neighboring countries could make a significant contribution to the stability of national power systems. Consequently, delayed or even cancelled

**Table 6** Coefficients of the linear model applied in the analysis of structural changes

	Dependent variable y
$\log(x_{i-2})$	0.629*** (0.128)
$\log(x_{i-4})$	− 0.065 (0.106)
Constant	0.056*** (0.011)
Observations	61
$R^2$	0.465
Adjusted $R^2$	0.446
Residual std. error	0.022 (df = 58)
F statistic	25.189*** (df = 2; 58)

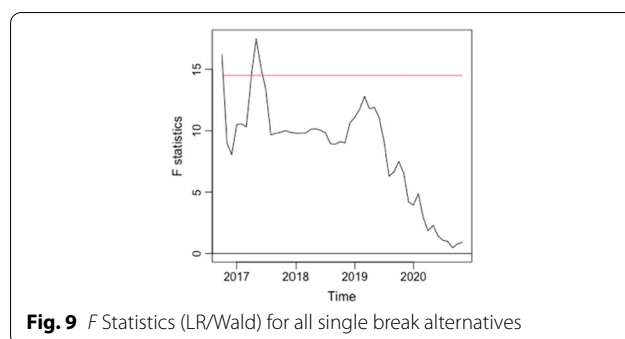
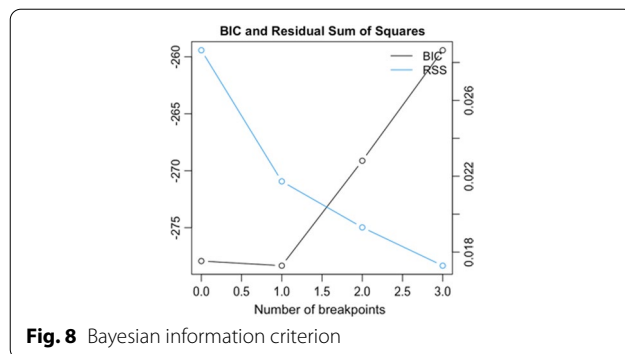
\*  $p < 0.1$ ; \*\*  $p < 0.05$ ; \*\*\*  $p < 0.01$

NTC expansion could have a negative long-term effect on the power sector's transition to a low-carbon system.

Despite Brexit, national CO<sub>2</sub> avoidance targets remain in place for both GB and European member states. Our results show that both the depreciation of the British Pound and a reduced expansion of NTCs can have a significant impact on shifts in electricity generation-related CO<sub>2</sub> emissions. Due to the high share of renewable energy sources in Green, emissions from electricity generation react minimally to the scenario variants. In Blue, on the other hand, it can be seen that the variants can lead to a local shift in emissions. In order to successfully decarbonize both the European and GB electricity systems, it is important to account for such regional shifts so that emissions abatements in one region cannot simply be offset in the other.

Lastly, we assessed the potential costs of Brexit in terms of electricity supply in monetary terms. Other studies, which also determined the electricity sector-related annual costs of Brexit, valued them at €500 million and €700 million, respectively. Although one scenario variant in our study results in additional costs for GB of only €269 million, all other scenarios show a significantly higher burden of up to €3025 million Euro. In addition, an examination of the monetarily valued electricity flows of neighboring countries shows that their expenditures for electricity trade also increase in most scenario variants.

By looking at different scenarios, we were able to show the range of potential effects on the power systems of GB and its EU neighbors. This range reflects the great uncertainty associated with Brexit. The authors conclude that many potentially negative effects can be mitigated or even averted by appropriate policy measures. In order to



ensure this, however, a suitable framework must be created for the stakeholders involved, which reduces or, at best, eliminates the existing uncertainties regarding the future partnership between GB and the EU. A future study could consider ways of doing this while preserving the integrity of the Single Market. For instance, ways and implications of linking the UK ETS with the EU ETS could be explored in more detail. Our study provides putative lessons from Brexit for the electricity systems of GB and its neighbors and could, therefore, stimulate debate about possible electricity system-related risks should other member states, such as Poland or Hungary, consider departing from the EU.

A limitation of this study is that it, unlike Pollitt and Chyong [42], does not consider the impact of reductions in GDP, arising from Brexit, on the British electricity demand and future studies would benefit from including GDP-impacts into their analysis. Furthermore, future studies could benefit from looking at the impact of progressive reductions in the expansion of interconnector capacity, i.e., from a modest 1GW to more substantial reductions in expansion. Future studies could also consider the impact on the energy markets in the context of wider economic effects from Brexit on supply chains,

labor markets and the long-term position of markets for capital, services and goods.

## Appendix

The structural breaks were defined with the methodology described in Zeileis, Shah [32]. The computations are carried out in the R system for statistical computing with packages *fxregime* 1.0–4 [61] and *strucchange* 1.5–2 [62].

The exchange rate model is a standard linear regression model (see Table 6 for the summary):

$$y_i = x_i^t \beta + u_i (i = 1, \dots, n),$$

in which the  $y_i$  are returns of the target currency and the  $x_i$  is the vector of the monthly currency exchange rates. To identify structural change, we compare the natural logarithm of the SMI time series with the natural logarithm of the lagged (two and four month lags) time series:

$$\log(x_i) - \log(x_{i-2}) - \log(x_{i-4}).$$

The fluctuation of GBP and Euro exchange rate (Fig. 1) a structural change that with some certainty can be identified within the period between October 2016 and July 2017. The Bayesian information criterion (BIC) criteria reach its minimum for the 1 breakpoint (see Fig. 8). The same is proved by the  $F$  statistics (LR/Wald) for all single break alternatives (see Fig. 9). They correspond to the breaks between October 2016 and July 2017. Visually, this approves changes in the mean, max and min values of the GBP and Euro exchange rate presented in Fig. 1.

## Abbreviations

GB: Great Britain; ENTSO-E: European Network of Transmission System Operators-Electricity; EMME: Electricity Market Model for Europe; NTC: Net Transfer Capacities; IEM: Internal Energy Market; EURATOM: European Atomic Energy Community; Def: Default exchange rate; Infl: Pound depreciation; FAB: France–Alderney–Britain interconnector; EU ETS: EU Emissions Trading Scheme.

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## Author contributions

CB, KG, PM and SV worked on the conceptualization, writing and visualization of the results. PM worked on the methodology. SV developed the model. DR and WK undertook reviewing and editing. All authors read and approved the final manuscript.

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## Availability of data and materials

The datasets used and analyzed in during the current study are available from the corresponding author on reasonable request.

## Declarations

### Ethics approval and consent to participate

No human participants, human data or human tissue have been involved.

### Consent for publication

Not applicable.

### Competing interests

The authors declare that they have no competing interests.

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