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Interdependencies between countries in the provision of energy☆

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ABSTRACT

Many economies are concerned with the future security of electricity supply. This is rooted in the necessity to decarbonise energy systems and in the nuclear phase-out. Hence, some economies, instead of investing in own domestic energy capacity, rely on energy production by their neighbours. At the same time, countries claim to drastically cut back their fossil fuel energy production. Yet, they increasingly depend on fossil fuel energy imports from abroad. To analyse these interdependencies we employ data for 17 European countries from 1978 to 2017. We first examine how countries respond to changes in energy capacity investment by countries in the vicinity. Using spatial econometric models we find a negative relationship between countries' investment in energy capacities. Second, we use fixed effects and instrumental variable estimators as well as an event study framework to analyse the link between domestic fossil energy production and imports. Our results reveal that a decline in domestic fossil energy production is associated with increasing fossil energy imports, suggesting that countries partially substitute one for the other.

1. Introduction

Energy market reforms and concerted efforts to fight climate change call for a complete overhaul of the way countries address future energy production. The decarbonisation of energy systems accompanied by a simultaneous phase-out of nuclear energy raise concerns about the security of electricity provision. Even in the past, economies have constantly covered part of the domestic electricity demand through imports. The following map shows the geographical distribution of electricity production capacity. The map conveys quite a heterogeneous picture, with neighbouring countries displaying very different amounts of electricity production capacities (see Fig. 1).

This heterogeneity is rooted in different country-characteristics, e.g., different import- or export risks,[2] different import- and export capacities, different priorities in policies dealing with climate change or different values attached to the security of supply from own production. As such, the heterogeneity can also be traced back to country-specific and different ways of dealing with the so-called "magical triangle" of energy policy. As explained by Zweifel et al. (2017), energy policy has a triple mission: It should secure the supply of energy, contribute to economic competitiveness, and render the use of energy compatible with the environment. It is clear that non-complementarities or non-neutralities in the achievement of those goals are likely to arise, and that country-specific priorities are finally determining the setup of the concrete goals. Since 1996, the European Commission emphasises and promotes the creation of a single electricity market that enhances the economic competitiveness and the strengthening of liberal market conditions (for an excellent overview on the European electricity market reform we refer to Jamasb and Pollitt (2005), Pollitt (2019)). In this evolving environment, investments into energy capacities are (increasingly) driven by market signals. However, they can – and since the beginning of the 2000s they significantly do – benefit from various forms of public support (provided these are in line with EU state aid rules, European Commission (2015)). The start of the new millennium thus marked the increasing importance of renewables for the electricity industry. As Pollitt (2019) documents, the 2001 renewable electricity directive (2001/77/EC) and the 2009 renewable energy directive (2009/28/EC) have both massively increased the requirement for electricity to be generated by renewable sources. Significant government subsidies have since then been deployed. These subsidies have reduced the amount of generation that is competitively added on the basis of

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1 All views contained in this paper are solely those of the author and cannot be attributed to the COMCO or its Secretariat.

2 Switzerland, for instance, may experience disadvantages regarding access to energy markets products in Europe if an electricity agreement with the EU cannot be reached.

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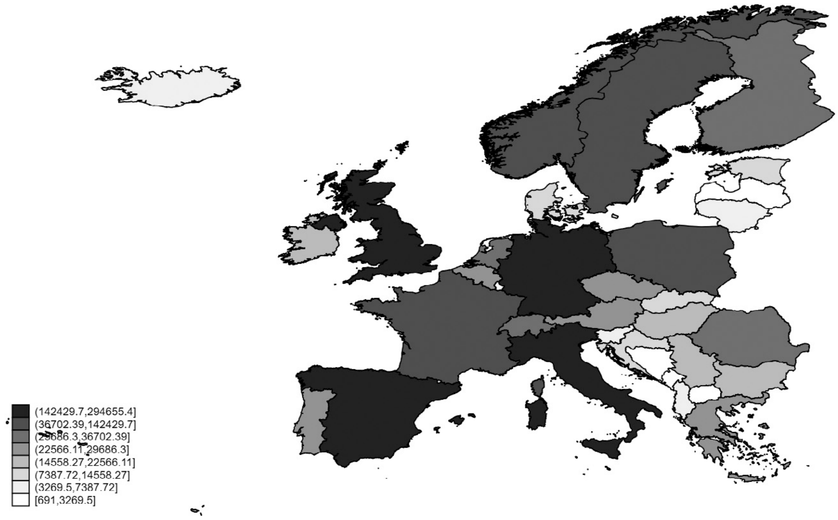

Fig. 1. Electricity production capacities in European countries. Note: Own illustration using data from Standard&Poor's Power Platts database. The map depicts the overall invested capacity in these European countries in MW.

predicted future wholesale market prices. Meanwhile, the introduction of the European Union's (EU) Emissions Trading Scheme (ETS) in 2005, including electricity within a traded carbon allowance system, has incentivised the use of gas-fired power generation over coal fired power generation (and sometimes vice versa).

However, as the above illustrated country-specific heterogeneity in capacity-investments shows, countries differ in how they implement these directives, and to what extent they incentivise and subsidise the generation of electricity from renewable energy sources. This, in turn, gives rise to a potential strategic regulatory behaviour among countries, both before and after the start-off of the liberalisation process at the beginning of the 2000s.

The adjustment of energy production towards more renewable energy resources also accounts for the differences in the investments into domestic energy capacities we observe in the data. In Germany, for instance, large renewable energy investments financed by generous government support schemes have been deployed during the last decade.[3] Despite the heterogenous picture on a country-specific level, on an aggregate level we can see a clear energy transition in Europe, where the nuclear and coal energy phase-out between 1970 and the mid nineties was followed by an expansion of wind, solar and gas cogeneration plant capacities, as depicted in Fig. 2.

This surge in supply of cheap renewable energy during sunny hours of the day has pushed down electricity prices. Hence, for energy utilities in different countries, investments in own energy capacities are potentially not economically feasible if future revenues are not high enough to cover incurred costs. This problem is aggravated by the relative high capital intensity and relative low operating costs of renewable energy capacities, such as solar and wind installations, in conjunction with an uncertain production pattern due to the intermittency of these energy sources. Thus, with increasing diffusion of renewable energies, wholesale energy price levels decrease during some hours of the day, and become more volatile, resulting in a non-favourable investment environment.[4] At the same time, energy and in particular electricity demand, is projected to steadily increase at a rate of around 1% per year in the upcoming decades (IEA, 2019). As an illustration for the growing relevance of energy, Fig. 3 depicts the added capacities per year for 36 European countries since 1900. We can see that these investments start to take off in the 1960s until the 1980s. After a drop in the beginning of the 1990s, they drastically increase with a peak in 2010.

In this paper we tackle the above mentioned issues by means of different econometric methods. First, we investigate whether there is a spatial interdependency that is associated with countries' investments in energy capacities (Section 3.1). More precisely, we hypothesise that countries' investments in energy capacities are spatially *negatively* correlated which would be consistent with a reliance on neighbouring countries' energy investments, and with a free riding-argument. We account for the spatial relationship between European countries by considering their distances, contiguities and availability of electricity transmission lines in appropriate spatial weighting matrices, and control for other observable and unobservable exogenous variables that are drivers of energy capacity investments (e.g., GDP per capita, electricity prices and demand).

Second, we relate energy imports and production as further evidence of strategic interdependencies (Section 3.2). That is, we investigate whether countries substitute fossil energy production for fossil energy imports.

Third, in order to further assess the validity of our findings, we employ an event study strategy (Section 3.3). More specifically, we use the implementation of the European Union's (EU) Emission Trading Scheme (ETS) programme in the year 2003, and analyse the evolution of fossil energy imports around this year.

Our results support the existence of strategic interdependencies between countries that are suggested by a negative spatial correlation in countries' investments in energy capacities. Furthermore, we find that countries react to a reduction in domestic fossil energy production with increasing fossil energy imports. The substitution is however only partial and most pronounced for coal and natural gas. Our results let us reason that strategic interactions between governments are an important degree of freedom in a country's repertoire with respect to the provision of secure and greener energy supply.

[3] In 2018, German renewable electricity production was for the first time as high as electricity production from coal (http://web.archive.org/web/20190926180915/https://www.agora-energiewende.de/presse/neuigkeiten-archiv/2018-war-ein-ausnahmejahr-der-energiewende-aber-eines-mit-gemischter-bilanz/, 9/26/19).

[4] Though it is also reported that the installed cost of wind and solar photovoltaic facilities have drastically fallen over the last several years, making wind and solar competitive with new fossil generating capacity with similar load factors and output profiles, these comparisons typically ignore the backstop costs required to respond to intermittency in order to meet demand reliably (Joskow (2019), and the references therein).

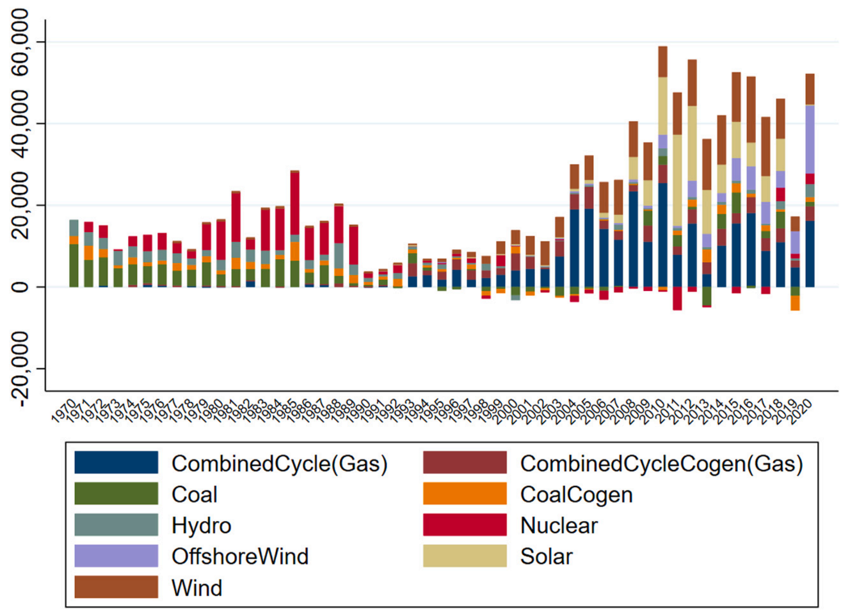

Fig. 2. New capacities by fuel type between 1990 and 2020. Note: Own illustration using data from Standard&Poor's Power Platts database. The figure shows the new capacities by fuel type between 1990 and 2020 in Europe in MW.

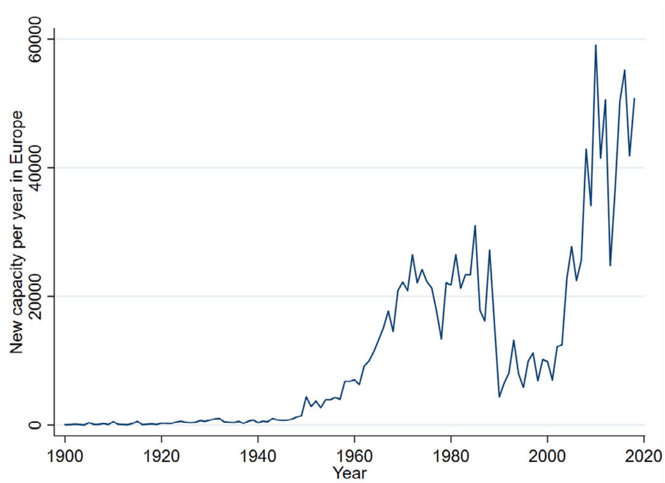

Fig. 3. Additional energy capacities by year in Europe. Note: Own illustration using data from Standard&Poor's Power Platts database. The figure graphs the additional energy capacities by year in MW.

2. Literature

The present research is related to the strand of literature that focuses on investment decisions in both renewable and conventional energy capacities, wherein investment decisions are often evaluated against the goal of securing the supply of energy. In the recent literature, factors that influence the deployment of capacities based on renewable energy resources are at the forefront (Tietjen et al. (2016), or Masini and Menichetti (2013)). However, economic literature also emphasises more basic principles about the relationship between investment and macroeconomic variables as well es energy-specific variables (European Commission (2015)). Factors such as economic growth, the size of population, the change in energy demand, the interest rate, and electricity price volatility are considered to be important drivers of investment decisions into energy capacities. Other important factors are the level of competition in energy markets, the institutional environment and the legal certainty, the specific design of energy markets, and the penetration of renewable technologies (European Commission, 2015; Joskow, 2019). Specifically, the literature on different market designs is vast. While it is beyond the scope of this paper to discuss broadly the relevant aspects in this regard,[5] we refer to Joskow (2019) or Joskow and Tirole (2007) for this strand of literature. Joskow (2006) emphasises that organised wholesale electricity markets do not provide adequate incentives to stimulate sufficient investments in generating capacities. He analyses the currently employed mechanisms that address this inefficiency such as capacity payments or demand response mechanisms. Battle and Rodilla (2010) review the different approaches such as price mechanisms (i.e., capacity payments) or quantity mechanisms (i.e., long term forward contracts) regulators worldwide adopt to guarantee the security of electricity supply in a market environment. Other scholars focus on informal, and social determinants of energy investments. Ellenbeck et al. (2015) analyse the investment decisions of electricity market participants in the EU. The authors consider several factors beyond formal market design to be of relevance in this context. They also highlight that, if the market is understood as a social institution, formal as well as informal systems of rules impact the social interactions between actors. In markets that are highly complex and less transparent, economic actors have incentives to act strategically. Masini and Menichetti (2013) highlight the relevance of non-financial factors in the decision to invest in renewables. Their analysis shows that a priori beliefs on the technical adequacy of investment opportunities are key drivers of investments.

Still, these studies, do not scrutinise the spatial interactions between economies, as we do in the present paper. More specifically, we add to this literature by accounting for interdependencies that might also be strategic to some extent from a regulatory perspective. The above illustrated features of a currently transiting energy system towards more renewable sources seem to enforce strategic incentives in governments' energy policies and the regulations flowing from it. In particular, an environment of low electricity prices, also driven by the above mentioned subsidisation of renewable energies, makes energy imports more attractive. At the same time, energy utilities do not face the "right" incentives to invest in domestic capacities. Since

[5] That is, aspects such as energy-only-markets, or markets with, price caps, capacity obligations, capacity pricing, and scarcity pricing mechanisms.

investments in energy capacities tend to be lumpy, capital intensive, and long-lived,[6] many of those investments bear a certain elevated risk or uncertainty compared to other investment opportunities, especially in liberalised market environments. Hence, an economy may "free ride" on neighbouring economies by shifting the investment risk, thus indirectly benefitting from subsidies which are financed by the neighbouring country's taxpayers or reducing its own CO_2 emissions by producing less domestic electricity at the expense of foreign economies' electricity production and emissions. In this sense, the current pressure to decarbonise economies by expanding renewable energy capacities, emphasises interdependencies even more since not only overall energy capacities matter, but also the type of resource these capacities are built on. Hence, it may be in a country's interest to self-praise itself as a clean domestic energy producer while importing "dirty" energy produced abroad. However, an increased preference for imported energy at the expense of own production increases the dependence on foreign trading partners and may endanger the security of domestic electricity supply.[7] These features imply that the stakes involved in those interdependencies are high and may even gain importance, because the functioning of societies and economies increasingly depends on energy and in particular electricity (Bhattacharya, 2019; IEA, 2019; Zweifel et al., 2017). Hence, we argue that before and after the liberalisation process in European energy markets took off in the beginning of the 2000s, strategic regulatory interdependencies play a role when it comes to investments into energy capacities. While the influence of government policies was straightforward before liberalisation, it is a more indirect country-specific regulation of markets – which is largely driven by the decarbonisation agenda – that influences those interdependencies in the aftermath of liberalisation.

The concept of strategic (regulatory) interdependencies in the context of spending on energy capacities can be related to the literature of strategic interactions among governments, more precisely to the class of *spillover models* (Brueckner, 2003). The free riding phenomenon has already been addressed in the context of national defence spending, where the evidence suggests that spending by one government affects spending by others (Murdoch and Sandler, 1984). Later, such effects have also been found in the context of environmental regulation (Murdoch and Sandler, 1997), medical research funding for infectious and parasitic diseases (see Kyle et al. (2017), and the references therein), and governmental spending (Solé-Ollé, 2006). To the best of our knowledge, the consideration of the presence of spatial effects in energy/electricity *production* is a novel feature in the energy economics literature. In the context of energy *consumption*, Gomez et al. (2013) employ a spatial autoregressive model with autoregressive disturbances to analyse residential electricity demand considering the existence of spatial effects. The authors find spatial effects in Spanish residential electricity consumption. Akarsu (2017) analyses spatial interdependencies among different Turkish regions resulting from socio-economic relations, such as relocation of economic activity or migration, and spillover effects of policy measures by using a spatial panel data model. Her findings show that energy policy related to only one province can affect electricity consumption in other provinces.

Our paper is also closely related to the literature on the so-called "waterbed" as well as the carbon leakage effect. The former focuses on internal leakage within countries that adhere to the EU ETS, and stipulates that government intervention that reduces emissions in one particular sector covered by the ETS will have no impact on total ETS emissions as they may rise elsewhere. Carbon leakage focuses on countries outside the policy jurisdiction. With respect to the manufacturing sector, carbon leakage leads to a higher share of imports in total consumption and to lower exports, since domestic firms can either relocate to regions with less stringent environmental regulation or they lose market shares to unregulated foreign competitors. Research results on carbon leakage are mixed. On the one hand, papers using computable general equilibrium models find strong carbon leakage where rates vary between 10 and 30 per cent (Carbone and Rivers, 2017). Some empirical papers also find support for adverse effects of environmental regulations on trade, employment, plant location or productivity, albeit of small magnitude (Dechezleprêtre and Sato, 2017) or a carbon leakage effect of the Kyoto protocol (Aichele and Felbermayr, 2015). On the other hand, some empirical papers using sector level or firm level data find no effect of the EU ETS on firm relocation through an increase in outbound FDI (Koch and Basse Mame, 2016) or that it increased carbon leakage through relocation or decreased competitiveness of firms in sectors and countries subject to the EU ETS (Naegele and Zaklan, 2019). For the United States, Levinson (2010) employs data on U.S. imports and input–output tables, and shows that from 1972 to 2001 the composition of U.S. imports shifted towards relatively clean goods, rather than polluting goods and hence the United States does not appear to have been offshoring pollution by importing polluting goods.

Whereas these papers focus on firms or sectors and their output, competitiveness or trade patterns of output goods, we focus on the inputs/resources used for production of goods and electricity, namely domestic versus imported fossil energy.

3. Empirical analysis

3.1. Analysis of spatial interdependencies in capacity investments

For the empirical analysis we resort to the Power Platts database provided by Standard&Poor's for data on new energy capacities. Power Platts provides this data on power plant level and by fuel type but for the main analysis we collapse the data on country-year level. We use information on electricity exports, imports, final consumption, population and GDP in USD ppp from the World Energy Balances and Statistics Database provided by the International Energy Agency (IEA). Data on interest rates is retrieved from the IMF International Financial Statistics database and data for electricity prices for industrial users from Eurostat and OECD. Spot price volatility data is also computed using information on daily electricity spot prices from the Power Platts database. However this information is available for few countries (Austria, Denmark, Finland, France, Germany, The Netherlands, Norway, Spain, and Sweden) and only from around 2004 onwards. The following Table 1 displays the summary statistics for the dependent variables and the covariates. The original Power Platts database has information on 36 countries going back to the beginning of the 20th century (with more reliable data from the 1960s onwards), but we only use information on 17 economies and the years 1978–2017 as the IEA database provides information on electricity demand, exports and imports for some countries only as far as the 1970s and electricity price and interest rate data are complete only from 1978 onwards and only for a low number of economies. The 17 countries considered are Austria, Belgium, Denmark, Finland, France, Germany, Greece, Ireland, Italy, Luxembourg, Netherlands, Norway, Portugal, Spain, Sweden, Switzerland and the United Kingdom.

The spatial models stipulate that jurisdiction i's investment in energy capacity decision in year t depends on i's neighbours' investment decisions and on different characteristics of country i. There are different reasons why spatial models are appropriate, such as time-dependence, omitted variables, spatial heterogeneity, externalities or uncertainties.

The specification of the model we estimate reads

$$y_{it} = \alpha + \rho \sum_{j=1}^{n} w_{ij} y_{jt} + \sum_{k=1}^{K} x_{itk} \beta_k + \sum_{k=1}^{K} \sum_{j=1}^{n} w_{ij} x_{jtk} \theta_k + \mu_i + \gamma_t + v_{it}, \qquad (1)$$

[6] Bhattacharya (2019).

[7] For Switzerland, for instance, the transition towards higher reliance on renewable energy sources and imports, increases the risk of not being able to secure the supply at every point during the year (ElCom, 2020).

Table 1
Summary statistics - 1.

	N obs	Mean	Std dev	5th perc	Median	95th perc
New capacity (in MW)	680	822.81	1,641.7	−322.6	300.5	4,261.05
GDP (in USD ppp) per capita	680	35,109.5	12,953.5	19,085.3	33,143	58,715.4
Electricity imports (in TJ)	680	44,456.8	43,209.9	1,087	29,401	145,860
Electricity exports (in TJ)	680	−41,773.5	60,955.4	−209,387	−17,251	−63
Delta electricity final cons. (in TJ)	680	6,395.01	17,279.3	−12,096	3,918.5	37,190
Electricity price (in USD p. MWh)	680	79.72	40.16	34.84	75.47	138.41
Interest rate	680	7	4.47	.94	5.71	15.7

where y_{it} denotes new capacity in country i in year t, $\mathbf{x}$ the vector of K control variables x_k, w_{ij} an element of the spatial-weighting matrix that gives the value of the weights for each pair of countries $(i, j) : i \in \{1, n\}$ and $j \in \{1, n\}$, μ_i country fixed effects, γ_t time fixed effects, $v_{it} = \lambda \sum_{j=1}^{n} m_{ij} v_{it} + \epsilon_{it}$ the spatially correlated error component, and ρ our coefficient of interest, showing if there is spatial dependence between the dependent variable of neighbouring entities. As rules that define the spatial relations among the countries, and as such, the elements w_{ij}, we employ four alternative specifications of the spatial weighting matrix. First, the inverse-distance matrix, second the contiguity-matrix, third a matrix that contains information on the number of bilateral electricity transmission lines between countries and fourth a matrix that accounts for the total bilateral electricity transmission capacities between countries. The two latter approaches are introduced since electricity imports and exports are constrained by available transmission capacity between the neighbouring countries. Information on transmission lines and capacity is retrieved from CESI (2005). The contiguity matrix is a matrix of ones and zeros, where $w_{ij} = 1$ indicates a geographic adjacency between country i, say Germany, and country j, say France. Those bilateral weights are filled in accordingly for the matrices accounting for the number of transmission lines, i.e., with the number of those lines, and for the total transmission capacity, i.e., the total capacity measured in MW.[8] For the inverse-distance matrix $\mathbf{W}$, we let $w_{ij} = 1/[D(i, j)]$, where $D(i, j)$ represents the distance between countries. We use the haversine distance (or great circle distance) between two points since we employ geographical coordinates of the countries located on the earth surface (Drukker, 2013). All matrices are normalised using a minmax-normalisation, that is, each element of the matrix is divided by the minimum of the largest row sum and column sum of the matrix.[9] By employing these four matrices, we implicitly assume that the contiguity, the number and capacity of bilateral electricity transmission lines, and the geographic proximity are important factors with respect to the spatial dependency between countries' investment in capacities.

The other control variables included are a country's GDP ($in\ USD\ ppp$) $per\ capita$, $DeltaElectrFinalCons$, $InterestRate$, $ElectricityPrice$, $ElectricityExports$, $ElectricityImports$ and $Price\ volatility$. We hypothesise that richer economies in terms of GDP per capita should invest more in power capacities to meet a larger demand. Hence, the coefficient of this covariate should be positive. Interest rates reflect the cost of capital for these investments whereas electricity prices reflect the revenue per sold unit of output such that the first should exert a negative and the second a positive influence on investments in energy capacities. The change in electricity consumption between two consecutive periods $DeltaElectrFinalCons$ mirrors the effect of demand on new capacity investments and should hence feature a positive coefficient. The standard deviation of daily spot electricity prices captures uncertainties related to potential revenues and hence higher values should imply lower investments in power plants.

We employ a Spatial Durbin Model (SDM) and estimate the model by quasi maximum likelihood. The SDM model is an appropriate approach as it includes both the spatially lagged dependent as well as independent variables. Indeed, investments in energy capacities in a country may be affected by investments in such capacities in other countries justifying the inclusion of a spatially lagged dependent variable, where the spatial lag of the variable can be defined as a vector of a weighted average of the neighbouring values. Formally, the SDM implies that $\rho \neq 0$, $\theta \neq 0$ and $\lambda = 0$ in Eq. (1) above.[10] We argue that the SDM is more appropriate in our context, since, in contrast to the spatial autoregressive model (SAR), it also accounts for spatially lagged explanatory variables. For instance, the division of the EU wholesale market into different bidding zones with their own characteristics and containing different countries may also affect the results.[11] The following table summarises the regression results using the contiguity matrix in columns (1) and (2), the inverse distance matrix in columns (3) and (4), the matrix with the number of bilateral transmission lines as entries (column (5)), and the matrix that accounts for the total bilateral transmission capacity in column (6). In columns (2) and (4) we use as an additional explanatory variable the electricity price volatility which however considerably reduces our sample, since information on this variable is only available for 9 countries and 13 years. Furthermore, as a robustness check, we only keep the years prior to 2007 or 2003 and present the results in columns (7) and (8), respectively. The weighting matrix for these last regressions employs information on total bilateral electricity transmission capacity and the dependent variable refers to new electricity capacity investments. This robustness check is motivated by the EU market liberalisation, enacted by Directive (03/54/EC) in 2003 and providing a regulated third-party-access in all Member States by 2007. We perform these alternative specifications using only information prior to the liberalisation of electricity markets since one may argue that in the EU's liberalised markets, investment decisions are taken by energy companies that even operate in multiple economies and are not decided by national strategic actors. This is why in the last regressions we only use data on investments undertaken prior to these developments where it is safe to assume that investment decisions are taken at the national level.

All regressions include time and country fixed effects and are clustered at the country level. As the results in Table 2 show, the coefficient on our main variable of interest ρ, is negative and highly significant, indicating a negative spatial correlation between neighbouring countries' investments in new power capacities. This suggests a negative spatial correlation in capacity investments between countries.

[8] For the UK and Ireland we use information from the ENTSO-E-grid map, https://www.entsoe.eu/data/map/, and from https://www.elexon.co.uk/about/interconnectors, 02/04/21.

[9] Since we cannot determine theoretical issues that suggest a row-normalised weights matrix, and in order to avoid the risk of a misspecified model, we choose this single normalisation factor (see, e.g., Kelejian and Prucha (2010), for a more detailed discussion).

[10] In contrast, the Spatial Error Model (SEM) posits that the dependent variable depends on a set of local observable characteristics and does not include any spatially lagged variable. It incorporates instead a spatially correlated error component such that $\lambda \neq 0$, $\rho = 0; \theta = 0$. By construction this model eliminates spillovers but includes unobserved shocks that follow a spatial pattern.

[11] The SAR model implies $\lambda = 0$, $\rho \neq 0$, and $\theta = 0$. We also performed the regressions using the SAR specification. The results are qualitatively similar and available from the authors upon request.

Table 2
Spatial autoregressive model regression results.

Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
GDP (in USD ppp) per capita	0.005	0.255	−0.012	0.135	0.010	0.013	−0.006	0.002
	(0.01)	(0.17)	(0.01)	(0.19)	(0.01)	(0.02)	(0.01)	(0.01)
Electricity imports	0.003	−0.015[a]	0.005	−0.021[c]	−0.004	−0.003	0.001	−0.006[b]
	(0.00)	(0.01)	(0.00)	(0.01)	(0.01)	(0.01)	(0.00)	(0.00)
Electricity exports	0.001	0.014[a]	0.003	0.006	0.015[a]	0.013	0.020[c]	0.019[c]
	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.00)
Delta electricity final cons.	0.011[a]	0.007	0.010	0.008	0.011[a]	0.012[b]	0.009	0.005
	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)
Electricity price	−0.090	−22.887[c]	−0.064	−0.453	0.653	0.380	0.201	−6.008
	(2.53)	(5.97)	(2.44)	(13.97)	(2.24)	(2.31)	(1.14)	(6.19)
Interest rate	0.157	−643.012[c]	−19.712	−693.693[c]	−38.777	−33.545	−7.490	3.131
	(30.77)	(183.29)	(30.09)	(157.65)	(42.32)	(41.47)	(17.98)	(15.05)
Price volatility		−98.399[c]		−96.210[c]				
		(30.11)		(29.12)				
GDP (in USD ppp) per capita	−0.058	−0.608	−0.120[b]	−1.255[b]	0.150	0.206	0.014	−0.062
	(0.04)	(0.43)	(0.05)	(0.61)	(0.13)	(0.15)	(0.06)	(0.05)
Electricity imports	0.004	−0.050	0.046	−0.067	0.014	0.001	0.012	−0.006
	(0.02)	(0.03)	(0.04)	(0.05)	(0.03)	(0.04)	(0.04)	(0.01)
Electricity exports	0.009	0.011	0.043	−0.051	0.014	0.019	0.022	−0.013
	(0.01)	(0.04)	(0.04)	(0.04)	(0.01)	(0.02)	(0.02)	(0.01)
Delta electricity final cons.	−0.012	0.006	−0.016	−0.002	−0.005	−0.003	−0.009	0.000
	(0.01)	(0.02)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)
Electricity price	5.389	−13.580	−2.742	−4.924	−5.145	−0.466	5.737	−5.331
	(6.81)	(31.38)	(5.12)	(43.32)	(9.12)	(3.57)	(4.54)	(9.85)
Interest rate	−180.874	−1145.565[c]	−441.497[b]	−1318.425	−377.248	−271.278	−136.883	−71.791
	(154.00)	(424.67)	(224.63)	(887.32)	(249.19)	(262.55)	(146.81)	(114.78)
Price volatility		−27.843		−194.459[a]				
		(73.26)		(109.46)				
Rho	−0.483[c]	−0.201	−1.039[c]	−0.723[b]	−0.260[b]	−0.363[b]	−0.615[c]	−0.572[c]
	(0.14)	(0.23)	(0.27)	(0.36)	(0.11)	(0.14)	(0.15)	(0.14)
Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Country FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Number of countries	17	9	17	9	17	17	17	17
Number of years	40	13	40	13	40	40	29	25
N Obs	680	117	680	117	680	680	493	425
R^2	0.086	0.418	0.007	0.070	0.013	0.134	0.015	0.071

Note: Columns (1) and (2) report the results using the contiguity matrix and columns (3) and (4) using the inverse distance matrix. Column (5) reports the results using the matrix with information on the number of bilateral transmission lines, in column (6) the weighting matrix accounts for information on the total bilateral electricity transmission capacity. Columns (7) and (8) report results for the years before 2007 and 2003, respectively, using the matrix with information on the total bilateral transmission capacity. The dependent variable is the new electricity capacity invested in country i in year t in MW. Clustered standard errors in parentheses.

[a] $p < 0.1$.

[b] $p < 0.05$.

[c] $p < 0.01$.

3.2. Energy production and import patterns

In the following we scrutinise a different type of interdependency. During the last years, a number of countries stated that they now virtually stamp out coal power and produce energy fossil free. Still at the same time, European countries continue to rely on imports of oil, coal, and gas, as well as on electricity produced from these resources. For instance, according to the Financial Times (2019), Britain stated that it has quit coal power generation, however, it continues to import considerable amounts of coal to produce steel and cement. Fig. 4 depicts the evolution of the share of domestic fossil energy production in total energy consumption (left panel) and the share of fossil energy imports in total energy consumption (right panel) for 25 European economies since 1960. Besides the 17 European economies considered in the spatial analysis we now also include Albania, Bulgaria, Czech Republic, Hungary, Iceland, Malta, Poland and Romania. We define fossil energy imports as the sum of (a) crude oil, natural gas liquids (NGL) and feedstock, (b) oil and oil products, (c) coal and coal products and (d) natural gas imports. The same applies to the definition of fossil energy production.

Whereas the share of domestic fossil energy production in total energy consumption decreased from around 80% to around 30% between 1960 and 2019, the share of fossil energy imports in total energy consumption recorded a considerable increase from around 30% to around 70% during the same time frame. We depict in Fig. 5 the evolution of fossil energy imports as a share of total energy consumption by fuel type, to scrutinise which type of fossil fuel drives the import share upward. The graph shows that natural gas, oil products and coal imports recorded an increase during the considered time frame, whereas crude oil imports registered a drastic decrease.

Table 3 depicts the moments of the distribution of our main variables of interest for the subsequent empirical analysis.

To study the relationship between fossil energy imports and domestic fossil energy production we employ fixed effects panel data and IV methods. The model we estimate reads

$$y_{it} = \alpha + \boldsymbol{\beta}_k \mathbf{x}_{it} + \mu_i + \gamma_t + v_{it}, \tag{2}$$

where y_{it} denotes the share of fossil fuel imports in domestic total final consumption for country i in year $t = 1975, \ldots, 2017$. Additionally, we introduce the row vector of country-and-time-specific covariates $\mathbf{x}_{it}$ along with year fixed effects γ_t, and country fixed effects μ_i. $\mathbf{x}_{it}$ includes the variables *Population, GDP, Number of Heating Degree Days, Number of Cooling Degree Days*, as well as our main variable of interest, the share of domestic fossil fuel energy production in total consumption. As further controls we include the share of domestic renewable and nuclear energy production in total consumption as well as the share of industrial and residential sector in total energy consumption. Data on the number of cooling and heating degree days is retrieved from Eurostat, data on energy production and imports by source is derived from the World Energy Balances database (IEA).

Fig. 4. Fossil energy production and imports as a share of total energy consumption between 1960 and 2019.
Source: Own illustration using data from the IEA World Energy Balances database.

Fig. 5. Energy imports as a share of total energy consumption by fuel type between 1960 and 2019.
Source: Own illustration using data from the IEA World Energy Balances database.

Table 3
Summary statistics - 2.

	N obs	Mean	Std dev	5th perc	Median	95th perc
Fossil imports/Total ener. cons.	903	1.11	.78	.31	.97	2.26
(Fossil imp-exp)/Total ener. cons.	903	.57	1.74	−.27	.79	1.32
Domestic fossil ener. prod./Total ener. cons.	903	.65	1.56	0	.18	1.65
Renewable ener. prod./Total ener. cons.	903	.2	.28	0	.1	.63
Nuclear ener. prod./Total ener. cons.	903	.13	.18	0	.02	.53
Fossil ener. cons./Total ener. cons.	903	.67	.14	.39	.69	.85
Nb. cooling days	903	87.88247	147.904	0	14.33	447.83
Nb. heating days	903	3,109.21	1,356.49	768.88	3,022.16	5,671.74
Industry ener.cons./Total ener. cons.	903	.2849126	.1080933	.1385905	.271814	.5031729
Residential ener.cons./Total ener. cons.	903	.2413329	.0638016	.1419569	.2391527	.3383448

The results of this fixed effects specification are presented in column (1) in Table 4 below. Since just using fossil imports as a share of energy consumption may bias the estimates as imports may occur for the purpose of export but not to substitute production, we employ an

Table 4
Fossil energy domestic production and imports.

Variables	(1)	(2)	(3)	(4)
Share of domestic fossil energy production in total final cons.	−0.080[b]	−0.983[c]	−0.075[c]	−0.992[c]
	(0.03)	(0.01)	(0.01)	(0.01)
Share of domestic renewable energy production in total final cons.	−1.036	−0.908	−0.980[c]	−0.988[c]
	(0.63)	(0.64)	(0.15)	(0.15)
Share of domestic nuclear energy production in total final cons.	−0.711[a]	−0.622[a]	−0.891[c]	−0.733[c]
	(0.37)	(0.34)	(0.16)	(0.15)
Number of heating degree days	−0.000	−0.000	0.000	0.000
	(0.00)	(0.00)	(0.00)	(0.00)
Number of cooling degree days	0.001	0.001	0.001[c]	0.001[b]
	(0.00)	(0.00)	(0.00)	(0.00)
GDP in USD ppp	−0.000	−0.000	0.000	−0.000[c]
	(0.00)	(0.00)	(0.00)	(0.00)
Population	−0.013	−0.005	−0.018[c]	−0.008[a]
	(0.01)	(0.01)	(0.01)	(0.00)
Ratio of industrial energy consumption to total energy cons.	1.545[a]	1.321	1.487[c]	1.437[c]
	(0.90)	(0.92)	(0.24)	(0.24)
Ratio of residential energy consumption to total energy cons.	0.632	0.291	0.661[b]	0.129
	(0.52)	(0.42)	(0.30)	(0.27)
Share of fossil energy in overall energy cons.	−0.632	−1.143	−0.942[b]	−1.479[c]
	(1.05)	(0.97)	(0.41)	(0.41)
Constant	1.538	2.289[b]		
	(0.95)	(0.88)		
Year FE	Yes	Yes	Yes	Yes
Country FE	Yes	Yes	Yes	Yes
Number of countries	25	25	25	25
Number of years	43	43	43	43
N Obs	1,029	1,029	903	903
R^2	0.304	0.891	0.302	0.835
Cragg Donald Wald F stat.			630.8	630.8
Hansen J stat. overid.			40	18.15
Chisq P-val endog.test			0.53	0.51

Note: Columns (1) and (2) report the results of fixed effects estimations and columns (3) and (4) the second stage results of the IV estimations. The dependent variable is the share of fossil energy imports in total energy consumption in columns (1) and (3) and the share of net imports (imports-exports) in total energy consumption in columns (2) and (4). The number of observations in specifications (3) and (4) is smaller since we do not have information on coal, gas or oil reserves for all countries in the data set. Clustered standard errors for columns (1) and (2) and robust standard errors for regressions (3) and (4).

[a] $p < 0.1$.

[b] $p < 0.05$.

[c] $p < 0.01$.

alternative dependent variable to account for this effect. The dependent variable in column (2) is the share of *net* fossil imports in total energy consumption where net imports are defined as imports less exports. We also cluster standard errors at the country level to account for possible spatial autocorrelation.

In addition to energy production determining imports, a reverse causality may also apply. One can imagine that, for instance, lower foreign fossil energy prices due to the expansion of fossil energy capacities abroad or due to lax environmental regulations or even the increase in possible trading partners, increases fossil energy imports and hence decreases domestic production for a given level of consumption. Thus imports and domestic energy production may be jointly determined, and estimating the model by OLS would render the coefficients biased and inconsistent. We address the simultaneity issue by estimating a two-stage least squares equation model with instrumental variables. For the IV approach to be a reasonable identification strategy, the instrumental variable should be correlated with energy production while it should not be correlated with the error terms. As possible instruments we use the domestic coal, oil and gas reserves of each country in the data set. Data on oil, coal and gas reserves come from the BP Statistical Review of World Energy.[12] These variables unquestionably determine energy production. Higher (lower) available fossil energy reserves should be positively (negatively) correlated with domestic fossil energy production. It seems plausible that the only way domestic fossil reserves influence imports is indirectly through domestic fossil energy production, in which case, the exclusion restriction would hold. Columns (3) and (4) in Table 4 report the second stage results of the two-stage least square estimations based on Eq. (2) above. In column (3) we use the share of imports in total energy consumption and in column (4) we employ the share of net imports in total energy consumption as a dependent variable. Since we do not have data on reserves for all countries and years, the number of countries is lower than in the previous two specifications. Hence, we employ robust standard errors since we do not have enough countries to accurately use clustered standard errors. We also report the Cragg Donald F statistics for strong instruments, the Hansen J test for overidentification and the Chi square p value of the endogeneity test in this table. The F-statistic for the three instruments is highly significant indicating that the instruments are relevant. We also run a test on overidentification and the test on endogeneity of domestic energy production in a standard OLS specification. We can reject the null hypothesis that the error term is uncorrelated with the instruments which provides us with confidence on the validity of our instruments. We can also not reject the null hypothesis of energy production being exogenous.

The coefficients of our main variables of interest are negative and significant, suggesting that countries substitute domestic fossil energy production with increasing fossil energy imports. Yet, the coefficients are in absolute terms below one such that the substitution pattern between domestic production and imports cannot be interpreted as a zero-sum game and implies only a partial substitution. This is in line with the aggregate energy transition trends in the EU towards a low carbon economy, where, on the country level, we observe different transition trends of conventional and renewable energy production

12 Since, for coal reserves data in between 1980 and 2007 are collected only every third year, we linearly interpolated the missing years' values.

Table 5
Coal, natural gas, crude oil energy domestic production and imports.

Variables	(1)	(2)	(3)
Share of domestic coal energy production in total final consumption	−0.214[b]		
	(0.10)		
Share of domestic natural gas energy production in total final consumption		−0.060[c]	
		(0.02)	
Share of domestic crude oil energy production in total final consumption			−0.033[c]
			(0.01)
Share of domestic renewable energy production in total final consumption	0.062	−0.146[b]	0.059
	(0.08)	(0.06)	(0.05)
Share of domestic nuclear energy production in total final consumption	−0.027	−0.147[a]	−0.022
	(0.11)	(0.08)	(0.16)
Number of heating degree days	0.000	0.000	−0.000
	(0.00)	(0.00)	(0.00)
Number of cooling degree days	−0.000	−0.000	−0.000
	(0.00)	(0.00)	(0.00)
GDP in USD ppp	0.000[b]	0.000	0.000
	(0.00)	(0.00)	(0.00)
Population	−0.005	0.014[a]	−0.020[c]
	(0.01)	(0.01)	(0.01)
Ratio of industrial energy consumption to total energy consumption	0.357	−0.036	0.077
	(0.41)	(0.11)	(0.13)
Ratio of residential energy consumption to total energy consumption	0.245	0.063	−0.013
	(0.30)	(0.13)	(0.21)
Share of fossil energy in overall energy consumption	−0.056	−0.088	0.193
	(0.16)	(0.21)	(0.32)
Constant	0.029	−0.061	0.660[b]
	(0.19)	(0.21)	(0.32)
Year FE	Yes	Yes	Yes
Country FE	Yes	Yes	Yes
Number of countries	25	25	25
Number of years	43	43	43
N Obs	1,029	1,051	1,051
R^2	0.262	0.616	0.288

Note: Columns (1)-(3) reports the results of alternative specifications of column (1) in Table 4. The dependent variable is the share of coal imports (column (1)), natural gas imports (column (2)) or crude oil imports (column (3)) in total energy consumption. Clustered standard errors in parentheses.
[a] $p < 0.1$.
[b] $p < 0.05$.
[c] $p < 0.01$.

and investments in generation capacity.[13] Accordingly, some countries still rely on conventional fossil fuel energy consumption while pushing their own energy production towards renewable-based resources. Fossil based energy is then partially imported from countries with less ambitious renewable energy production targets.

Since our main dependent variable is an aggregation of different types of fossil fuels, we perform the main specification presented in column (1) in the above table for different fossil fuel types separately. Hence, in Table 5, we report the coefficients using coal imports and production (column (1)), natural gas imports and production (column (2)) or crude oil imports and production (column (3)). The coefficients of the main variable of interest are negative and highly significant with the largest magnitude for coal and coal products, followed by natural gas.

3.3. Event study design

One further possibility to assess these interdependencies between countries is to investigate how countries' imports change when domestic fossil energy production becomes less attractive due to more stringent environmental regulations. One such policy is the introduction of the Emission Trading Scheme (ETS) programme in the EU in the year 2003. One could argue that this event increased the costs of fossil energy within countries subject to the EU ETS rendering energy imports from countries with less stringent regulations and thus possibly lower fossil energy costs more attractive. To this purpose we employ an event study design. Event studies have been initially implemented in the field

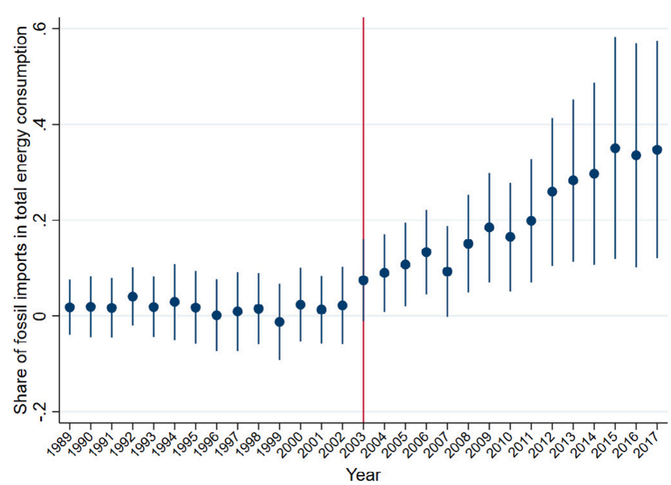

Fig. 6. Event study regression coefficients.

of finance but have increasingly been employed in economics in recent years as well.[14] We take 2003 as the event year because this was the year the EU Parliament adopted the corresponding legislation. Since the cap and trade system covering EU energy utilities introduced more

[13] See European Commission (2015).

[14] See Funk and Litschig (2020) of an application of event study to the effects of policy choices in Assembly versus representative democracies or Simon (2016) on the effect of smoking on childhood welfare.

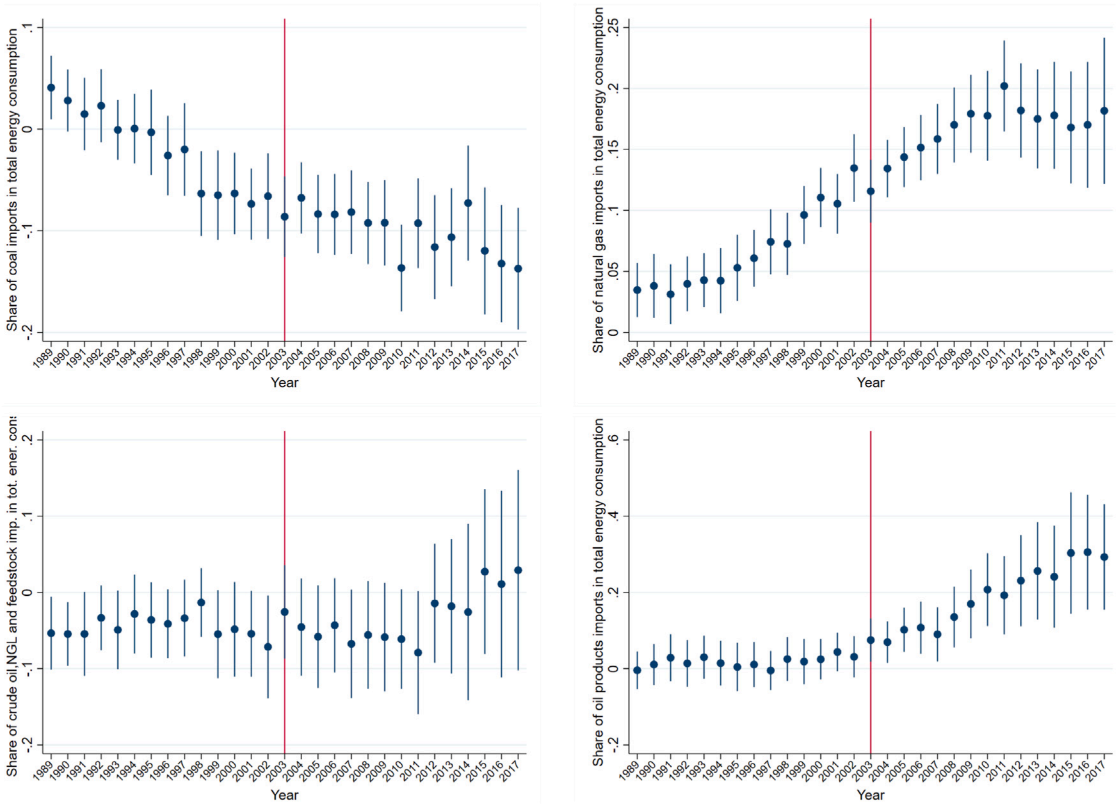

Fig. 7. Event study regression coefficients by fuel type.
Source: Own illustration using data from the IEA World Energy Balances database.

stringent rules for domestic fossil power production it is possible, that it increased the incentives to decrease domestic fossil energy production. As a consequence, we could observe an increase in fossil energy imports after the event. The use of an event study also allows us to consider the dynamics over time and to see if we notice an immediate or a more gradual reaction. Plotting the coefficients on the event dummies makes explicit how the policy (introduction of the EU ETS) affected the variable of interest over time prior and after the event. We define $1\left[\text{Time to EU ETS-adoption} = t\right]_{it}$ as an indicator for "event time", such that $t = 0$ is the year 2003 when countries implemented the EU ETS scheme, $-T = -14$ is 14 time periods prior to EU ETS adoption, and $T = 14$ is 14 time periods after EU ETS adoption occurs. The group of countries included are Austria, Belgium, Denmark, Finland, France, Germany, Greece, Italy, Ireland, Luxembourg, Netherlands, Portugal, Spain, Sweden and the United Kingdom. Once again, imports and total energy consumption are measured in TJ and accordingly the share of imports in total energy consumption refers to the quantity and not the monetary value of imports and consumption. Unfortunately, the IEA World Energy Balances database does not allow us to distinguish between imports from different groups of countries. Hence, fossil energy imports include an aggregate measure of overall imports for each country, without the possibility to distinguish by trading partner. This is a caveat, insofar as if we look at imports from countries within the EU ETS the emission cost is embedded in the price, and trade between countries occurs due to the comparative advantage in energy production and is not related to strategic decision making by governments. If we consider trade with countries outside the EU ETS that lack comparable climate policies and instruments, the increase in import may be explained by the lower fossil prices abroad and could be interpreted as carbon leakage. We are aware of this shortcoming but believe it is still interesting to look how fossil energy imports evolved after the introduction of these more stringent policies.

The event study equation reads:

$$y_{it} = \sum_{-T}^{T} \beta_t 1\left[\text{Time to EU ETS-adoption} = t\right]_{it} + \lambda_k \mathbf{x}_{it} + \mu_i + \epsilon_{it},$$

where y_{it} represents the share of fossil fuel imports in total energy consumption in EU member state i in year t, μ_i country fixed effects and the row vector $\mathbf{x}_{it}$ includes the same country-and-time-specific covariates as above. The figure below plots the event study impact estimates for fossil fuel imports as a share of total energy consumption and 95 percent confidence interval bars from 14 years prior to the adoption of the EU ETS until 14 years after the EU ETS-adoption. The figure shows that the effects prior to 2003 were low, close to 0 and not always significant followed by a sharp and persistent larger and highly significant effect after EU ETS implementation.

Since fossil fuels include four different categories, namely coal, crude oil, natural gas and oil products, it is interesting to consider to which fuel type this upward trend can be ascribed to. The decomposition by fuel type is presented in Fig. 7. This graph shows that coal imports actually declined throughout the entire time window under consideration whereas natural gas imports increased even before the introduction of the EU ETS. It seems to be that only the share of import of oil products in total energy consumption markedly increased in countries subject to the EU ETS after its introduction. Since natural gas and oil products represent more than 50 per cent of overall fossil energy imports whereas coal only accounts for on average 13 per cent of these countries' fossil imports, the increase in the former two fuel types is also mirrored in the aggregate measure depicted in Fig. 6.

4. Conclusion

In recent years several countries have expressed concerns about the security of electricity supply. The nuclear phase-out accompanied by the gradual shut down of coal fired power plants raise questions as to how the future increased electrification of economies is to be secured.

The increasing pressure to decarbonise economies and the stringent CO_2 emission targets have triggered an expansion of renewable energies such as wind and solar power. This trend poses a number of challenges for the supply of electricity. First, the marginal cost of renewable energy is close to zero and this has put a considerable strain on electricity prices which during sunshine hours can be extremely low. Second, the intermittency of renewable energy provision has increased the volatility of electricity prices. These developments make investments in domestic energy capacities unattractive such that countries have an incentive to forego these strategically important investments and instead import electricity from abroad. In this paper we scrutinise the interdependencies between countries in the provision of energy. We find a negative relationship between countries' investments in new energy capacities. In addition, our results show that countries partially substitute domestic fossil energy production for imports. These findings question different countries' self-praise according to which electricity production is now virtually fossil free, since these do not account for the flip side of such policies and neglect the fact that many economies still depend on fossil energy imports to meet the needs of the domestic industrial production sector. This could be interpreted as non-cooperative behaviour and it could be associated with a negative externality when it comes to the compliance with EU's common goal of a transition towards an energy system based on renewable energies. A possible policy-implication could be the implementation of a tax on energy imports that have been produced with fossil energy resources.

In terms of the already existing policies and their effects, the EU announced that it achieved its three 2020 climate and energy targets and greenhouse gas emissions declined by 10 per cent between 2019 and 2020. This however can also be attributed to the pandemic and the reduction in emissions is quite heterogeneous between countries with Bulgaria, Cyprus, Finland, Germany, Ireland and Malta not meeting their predefined national targets.[15] The reasons for the discrepancies are manifold and hinge upon many different factors. For instance, countries such as France that still rely on nuclear power to a large extent can produce electricity with lower emissions compared to Germany where the nuclear phase-out is ongoing. With respect to emission reductions the European Union stipulates both regulations and targets that apply to the Union overall as well as country specific annual emission targets, especially for sectors not covered by the EU ETS. With respect to the future, the EU adopted a 55 per cent net emissions reduction target by 2030 paving the way of achieving climate neutrality in the EU by 2050. According to the latest national projections, implementing the current national climate and energy policies could lead to a net emissions reduction of 41 per cent by 2030. Hence, the adopted "Fit for 55" climate package envisages a number of additional instruments such as extending the ETS to the transport sector or a Carbon Border Adjustment Mechanism (CBAM) to achieve the projected reductions. Insofar as EU member countries substitute domestic fossil energy production with imports as implied by our results, or import carbon intensive manufactured goods from abroad, the CBAM is an appropriate tool to address these effects and goes in a similar direction as our suggested tax on fossil energy imports but has a broader scope. The CBAM is a carbon-pricing system for imports into the EU.[16] It is aimed at adjusting the price of certain imported products to the amount of CO_2 emissions incorporated in them, in order to equalise the cost of carbon between EU products and these imports. This measure thus aims to reduce the risks of carbon leakage that we also identify in our paper, though it not only relates to energy goods but to the energy content of the whole spectrum of imports. Such instruments are necessary if the EU aims to achieve its ambitious target of reaching climate neutrality by 2050.

[15] https://www.eea.europa.eu/highlights/eu-achieves-20-20-20, 12/16/2021.

[16] Regulation of the European Union and the Council establishing a carbon border adjustment mechanism COM(2021) 564 final, 14.7.2021.

CRediT authorship contribution statement

Doina Radulescu: Conceptualization, Methodology, Data provision, Empirical analysis of energy production and import patterns, Draft preparation, Writing – review & editing. **Philippe Sulger:** Data curation, Empirical Analysis of Spatial Interdependencies in Capacity Investments, Writing – original draft.

Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.eneco.2021.105799.

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