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by

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Close ties: how trade dynamics and environmental regulations shape international dependence on oil

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Abstract

The European Union's energy security is increasingly challenged by its heavy dependence on imported oil, which exposes the region to geopolitical risks and market vulnerabilities. This study explores the role of trade dynamics in exacerbating this dependency, leading to what we term *trade lock-in*. Additionally, we assess the effectiveness of environmental policies in reducing oil import dependence, investigating whether these policies foster a shift toward greener investments (divestment effect) or inadvertently drive increased oil extraction (green paradox effect). We use network analysis to represent the international oil trade network and use this information in an econometric framework covering the period from 1999 to 2019, accounting for the presence of cross-sectional dependence. We identify two main factors that lock energy systems into an oil-based path: technological (represented by the level of energy intensity) and trade (represented by the existence of privileged trade relations with major oil-exporting countries) lock-ins. Furthermore, we find evidence of the divestment effect for some specific environmental policy instruments, but the effect is not uniform across instruments characterised as either demand-pull or technology-push. Finally, we find that an efficient eco-innovation system can effectively reduce oil import dependence only in countries with a comparative advantage in exporting clean technologies.

Keywords: oil dependence; network analysis; environmental policy; technological change; European Union

JEL Classification: F18; O32; Q32; Q37; Q48

1. Introduction

The recent energy crisis triggered by the war in Ukraine has highlighted the European Union's (EU) vulnerability due to its heavy reliance on imported fossil fuels, particularly oil, to satisfy its energy needs. This dependence has significant geopolitical implications, as it ties the EU's energy security to the stability of oil-exporting countries (Cappelli et al., 2023), many of which are in politically volatile regions. Such reliance on external oil supplies exposes the EU to risks, including supply disruptions, price volatility, and the influence of foreign political agendas on its energy policy (Chevalier, 2006).

The vulnerability of the EU's energy supply due to its dependence on oil imports necessitates a strategic approach to energy security. Diversification of energy sources and suppliers is essential to mitigate the risks associated with over-reliance on a few exporting countries (IEA, 2014). However, this is challenging, as the infrastructure and economic systems within many European countries are characterised by technological, infrastructural, institutional, and behavioural lock-ins, which substantially increase the costs associated with transitioning from existing capital stock designed for a fossil fuel-oriented economy (Unruh, 2000; 2002). This creates a mutually reinforcing relationship between energy resources, infrastructure, and industrial growth, which can lock an economy into specific consumption patterns.

The EU's ongoing struggle to transition away from fossil fuels is further complicated by financial commitments and subsidies that continue to support oil and other fossil fuels. Despite ambitious climate goals, substantial subsidies for fossil fuel consumption persist (Fouquet, 2016; EEA, 2023). This financial imbalance hinders the pace of decarbonization and perpetuates the EU's dependence on imported oil.

Moreover, the energy transition within the EU is not uniform across member states, with significant disparities in both the speed of transition and levels of oil dependency (Pérez et al., 2019; Cappelli and Carnazza, 2023). This heterogeneity has become more pronounced in the wake of the recent energy crisis, leading to varied policy responses among EU countries (Mišík and Nosko, 2023; Anghel and Jones, 2023). These differences not only reflect the diverse energy needs and economic conditions within the EU but also underscore the challenges of forming a cohesive and effective energy policy that addresses the collective vulnerabilities of the Union.

In this regard, the aim of this paper is twofold: first, we use complex network analysis to capture specific trade dynamics (e.g., the degree of concentration of oil imports and the presence of privileged relationships with key oil exporting countries) that, in addition to the well-established technological lock-in, can drive international dependence on oil (or, oil import dependence) and foster what we refer to as *trade lock-in*. Second, we aim to investigate the effectiveness of the stringency of environmental policy in mitigating international dependence on oil in EU countries. In particular, we evaluate, for each environmental policy instrument (categorized as either demand-pull or technology-push) whether the divestment effect (e.g., a shift toward greener investment as a result of environmental policy) or the green paradox effect (e.g., the increase in oil extraction as a response to the environmental policy) prevails.

From a methodological point of view, we rely on a Generalised Least Squares (GLS) estimator controlling for panel-specific autocorrelation structure ($AR1$) and heteroskedastic and correlated errors in European countries over the period 1999-2019. Our results warn against the existence of trade lock-in as a factor inducing international oil dependency, especially in relation to the existence of privileged trade relations with influential oil-exporting countries. On the environmental policy side, we find evidence of the divestment effect for some specific policy instruments, suggesting that an increase in the stringency of environmental policies can spur the ecological transition.

The rest of the paper is structured as follows. Section 2 illustrates the importance of fossil fuels in the European energy mix with some highlights of complex network theory applied to the EU crude oil market, the role of demand-pull and technology-push policy instruments and our main research questions. Section 3 describes in detail the EU crude oil trade network from a theoretical and empirical point of view, the dataset as well as the econometric framework. Section 4 presents the main results. Section 5 discusses the implications of our findings and concludes.

2. Background and research questions

2.1 Crude oil and the European Union

According to Eurostat data, despite the rise of renewable energies in the energy mix of European countries, oil still constitutes more than one third of total available energy in the EU. The progressive decrease in the share of fossil fuels in total available energy is the result of a decline in the use of solid fossil fuels rather than oil and natural gas. This highlights how heavily dependent the EU still is on fossil fuels, especially on oil. Energy dependence on oil consumption – and, more generally, on fossil fuels – is a feature shared by all countries in the world: taking 2019 as the reference year, at a global level, fossil fuels account for 84.3% of total energy consumption, while oil accounts for about 39% of fossil fuels and 33% of total energy (Table A1 in the Appendix).

Europe’s dependency problem is not only due to its dependence on external sources, but also to the concentration of responsibility for at least 25% of these supplies on a single supplier, namely Russia (according to *OEC* data, crude oil imports from Russia accounted for about 15% of total imports in 1999, while in 2019 this share rose to over 25%). In the pursuit of attaining the utmost level of energy security, the EU endeavours to implement various legal measures aimed at averting crisis scenarios within the energy sector; among these, the most pivotal measures that directly address crude oil issues are the Oil Stocks Directive (2009), the European Energy Security Strategy (2014) and the Energy Union Strategy (2015) (Kamyk et al., 2021). As seen, despite these legislative efforts, the EU continues to be highly dependent on crude oil both in terms of energy dependence (i.e., how much of the total available energy directly depends on the use of crude oil) and international dependence (i.e., the share of total energy needs of a country met by imports from other countries) (Cappelli and Carnazza 2023). In this regard, one of the problems that characterise the international crude oil trade network is its uneven distribution between production and consumption (Hao, 2023): in 2019, the production of oil is concentrated in Middle East (31.6%), North America (25.7%) and CIS (15.5%), while its consumption is concentrated in Asia Pacific (37%), North America (24.2%) and Europe (15.2%) (Figure A1 in the Appendix).

Following the most recent literature, we decide to conceptualise the international crude oil trade network using complex network theory (Hübler, 2016). Lately, many works consider this methodology for analysing the international crude oil market. An et al. (2014) present a trading-based network model of international crude oil to examine the connections between countries sharing common trade partners. Considering importing-based networks and exporting-based networks from 1993 to 2012, their evolution in size, stability, hierarchical structure and partition over time is examined. Considering a period from 2002 to 2013, Du et al. (2017) construct a directed and weighted world crude oil trade network to discuss its interrelation and evolution features. Selecting data from 2000 to 2013 and aggregating coal, crude oil and natural gas, Zhong et al. (2017) construct the integrated complex network model of fossil fuel. In this way, the resulting analysis of the roles of countries involves examining the primary relationships, central positions, intermediary abilities of the countries, and their roles within trade groups. More recently, Cappelli et al. (2023) employ network analysis to understand which countries are most connected and central in the global crude oil trade. This information is then used to estimate the effects of oil dependency on political stability on a panel of 155 countries over the period 1995-2019. Finally, Hao (2023) analyses the pressure of trade competition on crude oil imports from 2000 to 2020. The basic idea is to assist countries in identifying competitive pressure and offering recommendations for enhancing competitive advantages in the context of crude oil trade.[1]

From an empirical point of view, Figure 1 shows the chord diagram of the European crude oil network on the import side, considering the 27 EU member countries and the rest of the world as a whole (i.e., W). In the chord diagram, individual countries are represented by circular segments arranged along the circumference of a circle and the chords that connect two or more circular

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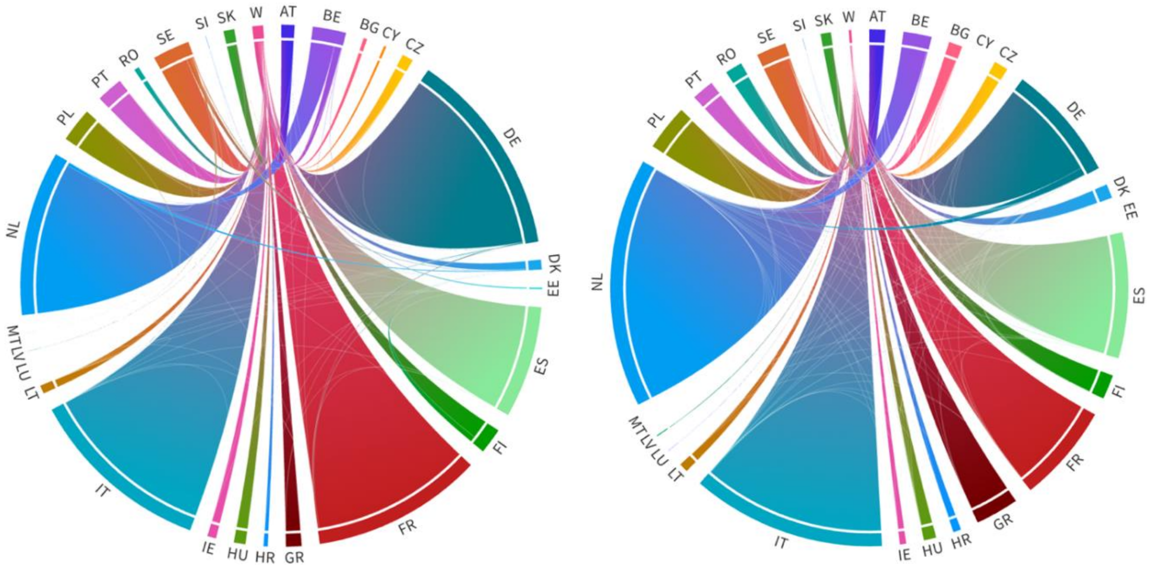
[1] Paragraph 3.1 will describe network analysis in detail from a theoretical and empirical perspective.

segments indicate the interactions between the corresponding countries. In our case, the width of the circular segments represents the country's share of total imports for that year.

Figure 1 – Chord diagram on the import side



(a) 1999 **(b) 2019**

Note: the international crude oil network is represented taking into consideration the connections within the EU, and between the European countries and the rest of the world (i.e., W).
Source: own elaborations on *OEC* (Observatory of Economic Complexity) data.

As expected, Europe is not a significant hub from the point of view of re-exporting crude oil, and its impact on world exports has decreased considerably over time. Almost all of the 27 European countries satisfy their imports by purchasing crude oil on the non-European market. Taken individually, in 2019 the five countries that import the most from the rest of the world are (in descending order) the Netherlands, Italy, Spain, Germany and France. Considering the period 1999-2019, it should be noted, on the one hand, the growth of Dutch imports and, on the other hand, the contraction of German and French imports on overall import.

2.2 The link between environmental policies and oil dependence

Policy instruments enacted by governments are crucial to overcome institutional lock-in dynamics hindering transition and transformation processes, by making investments capable of mitigating transition expenses and steering the system towards a trajectory that prioritises carbon neutrality (Seto et al., 2016). In recent years, there has been a growing interest in the interaction between climate policy and the supply of oil and fossil fuels in general (Lazarus and van Asselt, 2018). For instance, Bauer et al. (2015) perform scenario analysis using a suite of integrated assessment models and find that climate policies have a pronounced effect on diminishing coal consumption globally both in the short- and the long-term, while the decline in oil and gas usage is comparatively modest, particularly up to the year 2030. At the same time, the decline in revenues is substantially greater for oil and gas due to their higher prices relative to coal. However, Pasqualini and Bassi (2014) focus on the oil shale industry and find that for those companies achieving energy efficiency gains profits would be mounting even after the enactment of climate policies.

From a theoretical perspective, environmental policy can have two opposite effects on oil (and fossil fuel) consumption and imports: a divestment effect (e.g., Schellnhuber et al. 2016; Baldwin et al., 2020) and the green paradox effect (e.g., Sinn, 2008; 2012; Pittel et al., 2014; Jensen et al., 2015). In the first case, the expected decline in oil demand triggered by the introduction (or the announcement) of the environmental policy devalues the existing capital stock, inducing firms to redirect their investment towards greener assets, in turn triggering a price increase and a contraction of demand. In the case of demand-pull policy instruments (such as an environmental or carbon tax or a higher implicit tax rate on energy), this effect also directly affects oil imports. In the second case, the green paradox effect arises from the Hotelling model when, in reaction to the introduction (or the announcement) of the environmental policy, oil companies increase oil extraction to minimise future losses: in this way, in the near-term oil price declines and oil demand increases. In this context, there is currently no consensus on whether one effect outweighs the other. Bauer et al. (2018) perform a multi-regional energy-economic model to study the effect of the anticipation of climate policies on CO_2 emissions and find that, for most climate policies, the divestment effect prevails over the green paradox. Similar conclusions are reached by Bogmans et al. (2024), who estimate the effect of the climate policy on firms' oil and gas investment in a difference-in-difference econometric framework. Looking at the technological arena, several scholars find that environmental policy induces a redirection of technological change from non-green to green technological fields (e.g., Hascic et al., 2009; Aghion et al., 2016; Barbieri, 2016). On the other hand, the green paradox may manifest when subsidies are directed towards either fossil fuels or renewables, rather than imposing a carbon tax (Grafton et al., 2014). Such policies, though well-intentioned, inadvertently incentivise fossil fuel owners to expedite extraction and increase the rate of fossil fuel consumption, consequently exacerbating global warming. Additionally, government failure can occur if national governments struggle to coordinate in implementing a global carbon tax, leading to carbon leakage. In this vein, carbon leakage can be understood as a "spatial" green paradox, since a unilateral carbon tax raises fossil fuel prices only in the countries where the carbon tax is applied (Van der Ploeg and Withagen, 2015). Consequently, the reduced demand for fossil fuels in these countries due to the carbon tax is partially offset by increased demand in the countries without a carbon tax.

However, to our knowledge, the effects on international dependence on oil have remained underexplored. A recent paper (Usman et al., 2024) analyses the relationship between environmental policy and trade in coal, oil and gas in nine major polluting economies between 1991 and 2021 and finds that a higher stringency of the policy reduces trade in fossil fuels in both the long- and the short-run.

Government efforts to mitigate environmental impact and speed up the ecological transition are characterized as either between demand-pull or technology-push policy instruments. Technology-push instrument (e.g., environmental R&D spending) aim to foster technological development by reducing the costs associated with it through a direct subsidy scheme to R&D (Nemet, 2009). On the other hand, demand-pull policies (e.g., environmental and carbon taxes) aim to stimulate demand of new technologies (Peters et al., 2012). Albeit most studies agree on the inducement effect of technology-push and demand-pull policy instruments, or a combination of them, in fostering renewable energy consumption (e.g., Albrecht et al., 2015; Li et al., 2020; Khan et al., 2020; Xin-Gang et al., 2022; Herman and Xiang, 2022) and trade (e.g., Costantini and Crespi, 2008; Sung and Song, 2013), it is crucial to understand whether such instruments can, at the same time, weaken dependence on oil and fossil fuels. It may be the case, indeed, that an increased installed capacity of renewable energy technologies is accompanied by an increase in oil consumption, if final energy consumption grows (York and Bell, 2019) or if the composition of the different energy sources within the national energy mix changes. For instance, analysing a global sample of countries between 1960 and 2009, York (2012) estimates that reducing fossil fuel consumption by one unit requires between 4 and 13 additional units of renewable energy. Similar results are found by Chien and Hu (2008), who find that the expansion of renewable energy production does not necessarily imply the substitution of imported energy with domestically generated renewable sources but can increase overall energy imports. In addition, given the inherent resistance to change posed by lock-in dynamics, the most effective policies to counter oil dependence may vary depending on the specific phase of transition (Jacobsson and Lauber, 2006). As a result, the effectiveness of innovation efforts in the renewable technology sector in reducing oil dependence may vary across countries depending on the level of maturity reached by such technologies.

2.3 Research questions

In the first step of our analysis, we aim to understand the main sources of lock-in that drive international oil dependence, fostering EU's energy vulnerability. In particular, in addition to the well-established technological lock-in, we focus on proximity factors as potential sources of what we refer to as *trade lock-in*. Accordingly, we formulate the following research question:

RQ1*: How do global trade dynamics influence the extent of international dependence on oil?*

Then, we investigate whether our selected technology-push and demand-pull policy instruments can be effective to counteract the main sources of technological and trade lock-in in the transition from fossil fuels. In particular, we aim at evaluating, for each specific policy instrument, whether the divestment effect or the green paradox effect prevails. Accordingly, our second research question is as follows:

RQ2*: What is the prevailing effect of different environmental policy instruments on oil dependence?*

Finally, for an innovation to unlock the technological lock-in of the energy system and thus reduce dependence on oil, the country's production apparatus must be prepared for the industrial production of that innovation. For this purpose, we specifically focus on the innovative system, to understand whether the success of a country's (eco-)innovation system in curbing international dependence on oil is contingent upon its ability to leverage its strengths in the global market for clean technologies. In this sense, if a country has a comparative advantage in the export of low-carbon technologies, it means that its production system should be ready for industrial-scale production of such patented technologies. This critical aspect underscores the interdependence between a country's innovation strategy, its skilful exploitation of comparative advantages, and the ultimate success of these efforts in the global arena of exporting clean technologies. Consistently, we formulate our last research question as follows:

RQ3*: Does the success of innovation in renewable energy technologies in reducing international dependence on oil depend on countries' comparative advantage in exporting these technologies?*

3. Data and methodology

3.1 The European crude oil trade network: theoretical and empirical perspectives

A socio-economic network is typically characterised by a directed graph, which consists of a collection of $N = \{1, \dots, n\}$ nodes that are interconnected by a set of directed links (or connections). This graph can be represented by an adjacency matrix G, whose elements define the presence or absence of a link between nodes. Formally,

$$G = \left[g_{ij}\right]_{i,j \in N} \tag{1}$$

where $g_{ij} = 1$ indicates a link that goes from i to j, while $g_{ij} = 0$ indicates no such link. Note that, even if $g_{ij} = 1$, the reverse (i.e., $g_{ji} = 1$) is not necessarily true. In other words, if there exists a directed link that goes from i to j, it is not automatically the case that node j also exports to node i. This implies that the adjacency matrix G is a $n \ x \ n$ square matrix and is not bound to be symmetrical. Since we are interested not only in the number of connections but, more importantly, in their intensity (i.e., the value of trade flow), we consider the adjacency matrix of the resulting weighted directed graph W, which can be defined as follows:

$$W = \left[w_{ij}\right]_{i,j \in N} \tag{2}$$

where $w_{ij} = 0$ when countries i and j do not trade with each other, while w_{ij} assumes a certain monetary value when a link between the two countries that goes from i to j exists. In a nutshell, the importance of a node can be assessed considering, on the one hand, the number of connections this node has to other nodes and, on the other hand, the related flow of money. In this regard, the weighted link represents the trade intensity of a country with other countries, taking into consideration not only the number of connections but also the related amount of value.

In this theoretical context, the international crude oil trade network is conceptualised using complex network theory, where countries all over the world represent the nodes and trade flows between countries the corresponding links. Complex network theory allows using specific indicators for analysing the structural characteristics of our network. In traditional analysis of complex networks, one of the most important problems is related to the identification of the importance of nodes. Network centrality can be assessed through several methods aiming to capture different network structures. In this study, we concentrate on three prevalent centrality measures frequently employed in economic literature: degree centrality, eigenvector centrality and the Herfindahl-Hirschman concentration index (HHI) (Newman et al., 2006; Park and Yang, 2021). Degree centrality identifies the nodes with the highest number of incoming links, while eigenvector centrality evaluates the importance of a node based on the importance of its neighbours. Both measures assist in identifying the pivotal nodes in the network architecture. The two centrality measures provide different information in relation to the network structure: on the one hand, a node with high degree centrality but low eigenvector centrality may have many connections, but they might not lead to influential nodes in the network; on the other hand, a node with high eigenvector centrality but low degree centrality might not have many connections, but it links influential nodes in the network. Finally, the HHI is a commonly used measure in economics and finance to gauge the level of competition or market concentration within a market.

In recent research on the global trade network, weighted network indicators have been found to offer better perspectives than binary indicators (Minoiu and Reyes, 2013). Numerous scholars have contended that the assessment of the intensity of interactions between two nodes is central to understanding social and economic relationships. Adopting a binary undirected network approach to study such relationships would likely lead to the omission of significant information (Fagiolo et al., 2010). For these reasons, we consider both a network approach, instead of a binary one, and a weighted perspective that takes into account the intensity of trade flows in addition to the number of connections.

First, degree centrality measures the direct connections between nodes in a network. Being mainly interested in identifying the determinants of crude oil import dependence in the EU, we focus our attention on the import side of the network. In this regard, in-degree centrality denotes the total number of inflow links. In-degree centrality can also assign weights based on the importance of a node, as determined by the corresponding monetary value of the trade flow. This element defines the size of the network link. In these cases, we are dealing with weighted degree centralities, where the term 'weighted' refers precisely to the fact that we consider the monetary amount of trade flows. In-degree centralities generally serve as fundamental indicators that are commonly employed as an initial stage in network analysis (Wasserman and Faust, 1994). Formally, being n the overall number of countries, the weighted in-degree centrality (wID) of country/node i can be defined as follows:

$$wID_i = \sum_{\mathrm{j}=1}^{n} w_{ji} = \sum_{j \neq i} w_{ji} \tag{3}$$

where w_{ji} is the weight of the link (i, j).[2] In particular, i represents the focal importing country, while j defines the $n-1$ exporting neighbours. In other words, the weighted in-degree centrality measures the number of links, weighted for their corresponding monetary amounts, others have initiated with country i. In this way, it is possible to capture the community's engagement with it: those countries with high weighted in-degree centrality scores can be considered as market hubs since many countries have exported a lot to them in terms of value.

The eigenvector centrality is the second measure of centrality we consider. Whereas the degree centrality of a node simply depicts its influence in the network, eigenvector centrality takes into account the extent to which it is connected to crucial neighbours (Bonacich and Lloyd, 2001; Bonacich, 2007). Through a recursive algorithm, each node is assigned a centrality score proportional to the sum of its neighbours' scores. Nodes with higher eigenvector scores are connected to numerous significant neighbours that, in turn, significantly impact the entire network. The centrality of each node corresponds to its component in the eigenvector. Considering the focal node i, the weighted eigenvector centrality ($wEV = c$), which is proportional to the sum of the weighted degree centrality of node i's neighbours, can be defined as follows:

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[2] The connection between country i and itself (w_{ii}) does not exist. As a consequence, Equation 3 can be written in both ways.

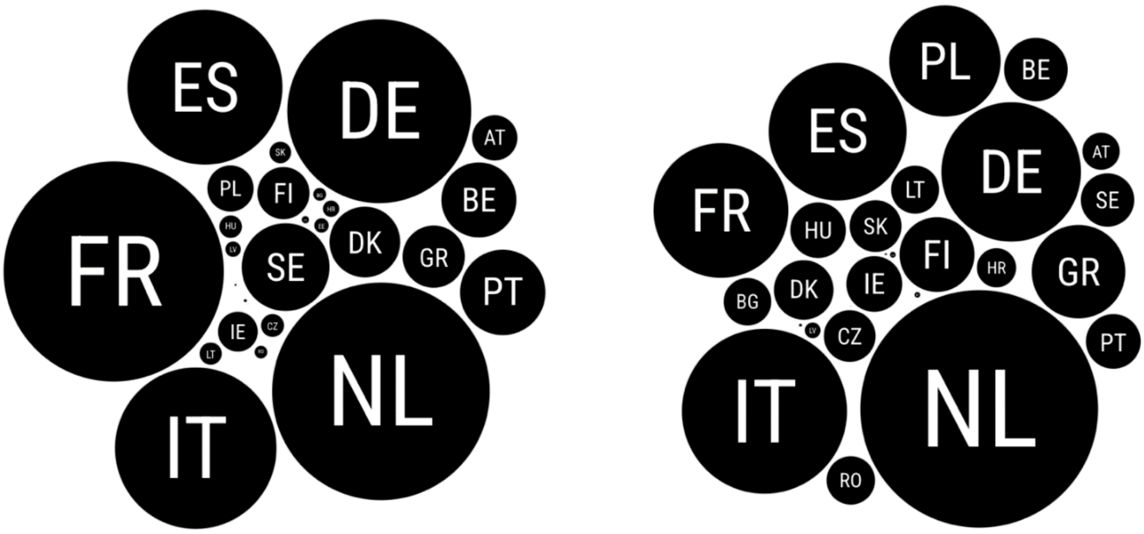
$$wEV_i = c_i = \frac{1}{\lambda}\sum_{j\neq i} w_{ji}c_j \tag{4}$$

where λ represents a non-negative scalar. Mathematically, eigenvector centrality calculates the centrality score of a node by summing the centralities of its neighbouring nodes, with the weight of each neighbour's centrality being proportional to its own centrality. This calculation is performed iteratively until the centrality scores converge. This definition implies that the centrality of each node i is proportional to the sum of the centrality of its neighbours. More specifically, it depends on the centrality of the $n-1$ nodes that point to it. This aspect clarifies the reason why eigenvalue centrality matters only within a directed network. More importantly, this kind of centrality is always well-defined for strongly connected networks (a directed network is strongly connected if there exists a directed path between any two nodes). Wasserman and Faust (1994) define the (weighted) eigenvector centrality as a prestige measure of centrality: being chosen by a popular country j would significantly enhance country i's own popularity. In economic terms, we could say that this type of centrality measures a country's privileged trade relations with the main oil-exporting countries.

Graphically, Figure 2 shows the magnitude of the eigenvector centralities for the 27 European countries (the size of the bubble indicates the value of the corresponding centrality), confirming the first result highlighted by the weighted in-degree centrality: in 2019, the Netherlands, Italy, Germany, Spain, and France represent, in descending order, the most connected to the most influential nodes. The importance of nodes such as Poland and Greece and, to a lesser extent, Finland and Belgium also emerges. Compared to 1999, all the European countries increase their connection to more important nodes.

From a theoretical point of view, following Park and Yang (2021), Figure 3 graphically illustrates the concepts of degree and eigenvector centrality. For the sake of simplicity, we assume that the connections are not weighted (see Equation 1) and are always bi-directional (i.e., $g_{ij} = g_{ji} = 1$). This implies the equality between in-degree and out-degree centralities. Node B has the largest number of (incoming and outcoming) links (i.e., 5), making it the node with the highest degree centrality. As mentioned above, high degree centrality does not necessarily imply high eigenvector centrality: node A is characterised by the highest eigenvector centrality, being interconnected with the three most important nodes in terms of degree centrality (i.e., nodes 2, 4 and A).

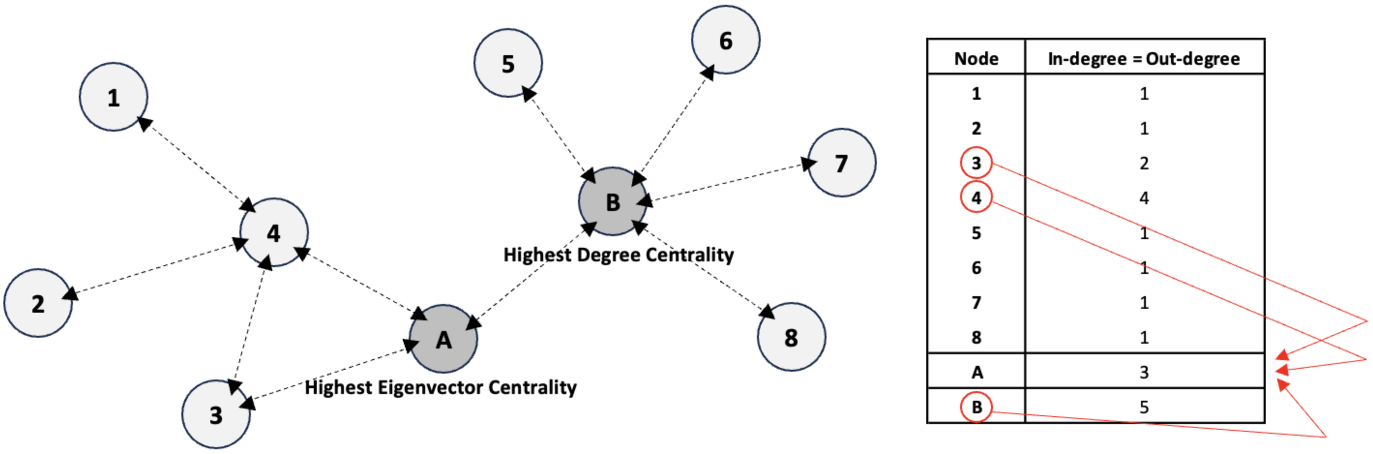
Figure 2 – Eigenvector centrality in the EU



(a) 1999 **(b) 2019**

Note: the size of the bubble indicates the value of the eigenvector centrality.
Source: own elaborations on *OEC* (Observatory of Economic Complexity) data

Figure 3 – Degree centrality and eigenvector centrality in a generic unweighted network



Node	In-degree = Out-degree
1	1
2	1
3	2
4	4
5	1
6	1
7	1
8	1
A	3
B	5

Note: since we are not representing a weighted network, in-degree and out-degree centralities coincide ($g_{ij} = g_{ji} = 1$ - see equation 1). Node B has the highest number of connections, while node A is connected to the three most important nodes (excluding A itself) in terms of network centrality: nodes 3, 4 and B. As is evident, degree centrality and eigenvector centrality provide different information about network structure and are both important in defining it.
Source: Park and Yang (2021) (own adaptation)

Finally, we quantify the diversification level of imports through the HHI, which represents our last centrality measure. The identification of specialisation in international trade is comparable to a similar issue in industrial organisation, that is the need for a theoretical and empirical measure of market power. In this regard, the Herfindahl-Hirschman Index (HHI) represents a typical example.[3]

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[3] The index has been developed independently by the economists Hirschman and Herfindahl. Hirschman presented the index in his book (1945), while Herfindahl presented it in his unpublished doctoral dissertation (1950). More details about the background of the index can be found in Hirschman (1964).

In a trade framework, the HHI can be applied both to the export and to the import side (Magee and Magee, 2008). As before, we focus our attention only on the import side. In our network, link weights now represent the market shares (MS). By definition, this implies that the sum of the incoming links to country i is equal to 100%. More precisely, let n be the number of all worldwide partner countries, the HHI of crude oil imports of a certain EU country i (HHI_import) is calculated by squaring and summing the market shares of oil volume in terms of value imported by partner countries j as follows:

$$HHI\_import_i = \sum_{j \neq i} MS_j^2 \tag{5}$$

where MS_j represents the market share of exporting country j to importing country i (i.e., $5\% = 5$). The HHI gives much heavier weight to countries with large market shares than to countries with small shares as a result of squaring the market shares. This feature of the HHI corresponds to the theoretical notion in economics that the greater the import concentration in a small number of countries (a high HHI), the greater the likelihood that, other things equal, competition in a market will be weak. In contrast, if concentration is low, reflecting a large number of countries with small market shares (a low HHI), competition will tend to be significant. The HHI ranges from a maximum value of 10,000 in which one country has 100 per cent of the market (monopolistic situation) to the minimum value of 0 which occurs when a purely competitive market exists with infinite countries with small market shares. The U.S. Merger Guidelines classifies market concentration as follows: (i) an HHI_i below 1,000 indicates absence of concentration; (ii) an HHI_i between 1,000 and 1,800 indicates moderate concentration; (iii) an HHI_i above 1,800 indicates high concentration.

Table 1 shows the HHI values for the 27 EU countries between 1999 and 2019. Oil imports of most European countries are highly concentrated: in 2019, the only countries showing moderate or no concentration are (in ascending order of concentration) Spain, France, Portugal, Italy and Germany. In dynamic terms, it is possible to note, with a few exceptions (i.e., Cyprus, Finland, Belgium, Slovenia and Austria), a general trend towards greater diversification.

Table 1 – HHI on the import side in the EU

	1999	2019	Δ
Austria	1,619	2,642	1,022
Belgium	5,726	8,895	3,169
Bulgaria	6,991	3,695	-3,296
Croatia	5,950	2,650	-3,300
Cyprus	3,636	7,859	4,224
Czechia	7,471	3,624	-3,847
Denmark	6,949	2,310	-4,639
Estonia	9,954	4,149	-5,805

Finland	3,051	6,915	3,864
France	1,247	1,087	-161
Germany	1,464	1,682	218
Greece	2,706	2,825	119
Hungary	9,966	5,100	-4,866
Ireland	5,200	4,959	-241
Italy	1,227	1,312	86
Latvia	9,064	9,824	760
Lithuania	9,400	5,028	-4,372
Luxembourg	9,191	9,927	736
Malta	9,925	9,987	62
Netherlands	1,710	1,967	257
Poland	7,362	4,254	-3,108
Portugal	1,164	1,144	-20
Romania	4,445	3,619	-826
Slovakia	9,746	9,341	-405
Slovenia	3,049	5,484	2,435
Spain	965	960	-5
Sweden	3,291	2,552	-740

Note: the greater the intensity of the three grey scales, the greater the level of market concentration according to the U.S. Merger Guidelines. The last column estimates the change in the HHI between 1999 and 2019: orange identifies those countries characterised by an increase in the concentration index, while green those characterised by an increase in import diversification.
Source: own elaborations on *OEC* (Observatory of Economic Complexity) data

In international trade, import diversification represents an important aspect, making a country less vulnerable to foreign supply shocks. From this point of view, an indicator that measures market concentration may help to understand the state of import security of a country. In any case, market concentration represents only one side of the coin. It is also important to take into consideration the level of political instability of the exporting countries. This geopolitical approach applied to the international trade network implies the creation of a geopolitical dependency index (Cappelli and Carnazza, 2023). For this purpose, the previous equation is modified in the following way:

$$HHI\_import\_PI_i = \sum_{j \neq i} MS_j^2 \cdot PI_j \tag{6}$$

where PI_j represents the level of political instability of the exporting country j. Our measure of political instability is based on the index “political stability and absence of violence and terrorism” estimated by the World Bank (Worldwide Governance Indicators).[4] It assumes both negative and positive values, with higher values corresponding to better outcomes, and has the advantage to cover a long-time span and be comparable across different countries. It ranges from -2.5 (weak political stability) to +2.5 (strong political stability). For our purposes, we decide to invert the sign and to

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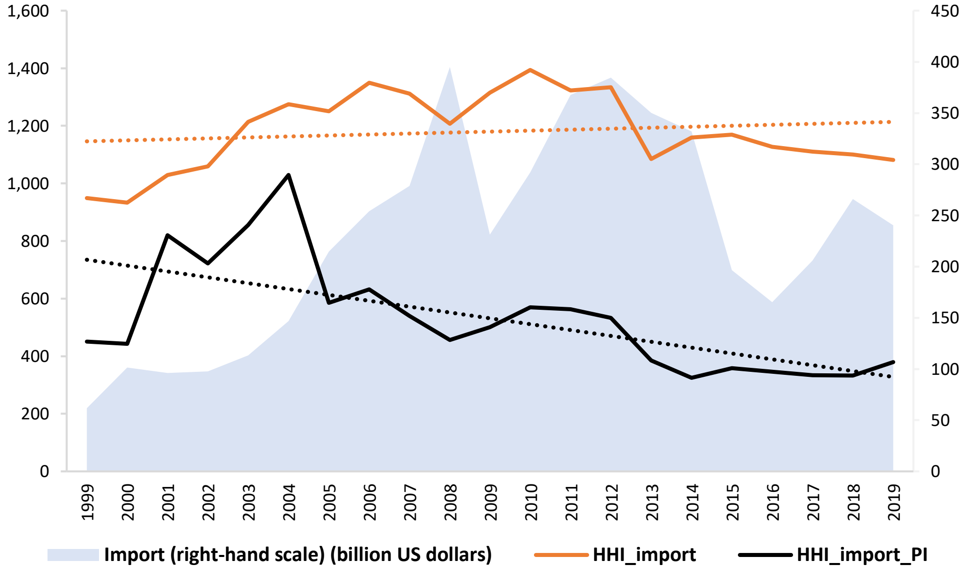
[4] For more technical information about the Worldwide Governance Indicators, see Kaufmann et al. (2010).

normalise the index from 0 (strong political stability or weak political instability) to 1 (weak political stability or strong political instability). For this reason, we rename the new indicator *political instability* (PI).[5] Equation 7 clarifies the reason to reverse the original definition of political stability, expressing it as *political instability*. In particular, the reversing relationship stems from the requisite of obtaining a measure that penalises unstable exporting countries. Accordingly, if such variable rises, a decrease in diversification and/or an increase in political instability of exporting countries occurs. In this way, HHI_import_PI maintains the same economic and statistical meaning of HHI_import.[6] Figure 4 shows the development of the HHI_import and HHI_import_PI indices over time at the aggregate EU level: on the one hand, the first index is characterised by a slight positive trend, highlighting a process of oil import concentration from a small number of countries; on the other hand, when adjusting for political instability in exporting countries, this process has taken place in favour of politically more stable countries.

Figure 4 – Import diversification in the EU



Note: the dotted lines represent the linear trend of the two indices.
Source: own elaborations on *OEC* (Observatory of Economic Complexity) data

3.2 Demand-pull factors

Among demand-pull policy instruments, environmental taxation is well-known for its capacity to influence price dynamics and consumer demand for new technologies, fostering technological change

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[5] The few missing values have been interpolated, limiting the minimum and maximum values between 0 and 1.

[6] The direct comparison between the two indices should be taken with caution since the two indicators assume the same value if and only if all the j countries from which country i is importing are characterised by maximum political instability. This extreme case is practically impossible, which always places HHI_imp_PI below HHI_imp.

(Peters et al., 2012). Environmental taxes are categorised into four main types: (i) energy taxes, (ii) transport taxes, (iii) pollution, and (iv) resource taxes. Given that energy taxes contribute to over three-quarters of EU environmental tax revenue, our focus centers on this category (Figure A2 in the Appendix). Energy taxes represent the amount of taxes on energy products used for both mobile and immobile purposes.[7] In this regard, we proxy them with the implicit tax rate on energy ($ITRE$), which is estimated as the ratio of energy tax revenue to final energy consumption.[8] This indicator is not influenced by carbon emissions or any erosion in the tax base, providing an effective measure of the average level of energy taxation. $ITRE$ allows quantifying the role of national fiscal policies in modelling energy demand, measuring the development of the burden of taxes on energy consumption and enabling international comparison. Although taxation of energy goods and services can primarily serve as a means of raising revenue for goods with relatively inelastic demand, a higher implicit tax rate has the effect of reducing energy consumption and serves as a proxy for the stringency of environmental policies in fossil-fuel dependent countries, leading to reduced energy consumption and associated emissions (Galeotti et al., 2020).

Despite these positive features, there is one important limitation: $ITRE$ treats all types of energy consumption equally, regardless of their environmental impact. In other words, if internal tax rates are differentiated according to the environmental impact of a given energy source, then an environmentally friendly structure of energy consumption would determine a modest $ITRE$; on the other hand, its low value could also indicate the presence of low energy tax rates on all energy products. The international comparison should then take into account the energy structure of the countries under consideration in order to incorporate this information. For this reason, we introduce renewable energy as a control variable, considering the share of renewable sources in final energy consumption ($renewables\ consumption$).[9]

In addition to the $ITRE$, we evaluate the effect of an alternative demand-pull factor, represented by the share of GDP covered by environmental taxes (env_tax).

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[7] While CO_2 taxes share characteristics of both energy and pollution taxes, they are classified as energy taxes in EU statistics.

[8] The overall linear increasing trend is depicted in Figure A3 in the Appendix, revealing distinct phases. Notably, from 1999 to 2008, a modest reduction is observed, primarily attributable to the increase in energy consumption and the constancy in energy tax revenues. Subsequently, energy taxes start to increase over time, while final energy consumption, despite fluctuations, shows a slight decrease. This implies a significant increase in $ITRE$.

[9] On average, renewable energy sources increased their share in the total, moving from 5.2% in 1999 to 11.1% in 2019 (Figure A4 in the Appendix). European countries are characterised by high variability, with minimum values ranging from 0% in 1999 to 4.3% in 2019 and maximum values ranging from 26.1% in 1999 to 27.2% in 2019.

3.3 Technology-push factors

To account for the possible role of government efforts in supporting innovative activity, we include two main variables. The first variable ($Energy\ KR\&D$) represents government budget allocation (GBARD) aimed at reducing the costs of developing new technologies in the energy and environmental sectors. We collect data on GBARD by socioeconomic objectives, namely Environment (NABS02) and Energy (NABS05) expressed as million purchasing power standards (PPS) at 2005 prices. To avoid the volatility associated with R&D flows and to account for the accumulated public R&D effort in the energy sector, we calculate the stock of R&D in the energy sector by applying the Perpetual Inventory Method (Hall et al., 2005; Peri, 2005) with a continuous discount approach and an assumed decay rate *d* of 15%, as suggested by OECD (2009). As a results, we calculate the stock of gross domestic budget allocation for R&D as follows:

$$Energy\ KRD_{i,t_0} = \frac{Energy\ RD_{i,t_0}}{g_i + d} \tag{7}$$

$$Energy\ KRD_{i,t} = Energy\ KRD_{i,t-1}(1-d) + Energy\ RD_{i,t} \tag{8}$$

The second variable ($patent\ intensity$) is a policy indicator of the efficiency of the eco-innovation system that captures the patent intensity in renewable energy technologies of public investment efforts in the energy sector. In this way, we account for the ability of the national innovative system to convert public investment in clean energy technologies into innovation output (Bointner, 2014; Consoli et al., 2023). To compute this measure, we first calculate the stock of renewable energy patents[10] (*KRE Patents*) by applying, even in this case, the Perpetual Inventory Method with a decay rate *d* of 15%:

$$KRE\ Patents_{i,t} = \sum_{s=0}^{t} \left(KRE\ Patents_{is} \cdot e^{[-d(t-s)]} \right) \tag{9}$$

Our final $patent\ intensity$ indicator is given by the ratio between the stock of patents in renewable energy technologies and the stock of public R&D in the energy sector:

$$Patent\ intensity_{i,t} = \frac{KRE\ Patents_{i,t}}{Energy\ KRD_{i,t}} \tag{10}$$

Additionally, to answer RQ3, we also distinguish the effect of patent intensity between countries that have a comparative advantage and those that have a comparative disadvantage in exporting clean

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[10] Data on Renewable Energy Patents are made available from IRENA, based on EPO PATSTAT 2021 Autumn edition and refer to the Climate Change Mitigation Technologies (Y02) classification by EPO.

technologies. For this purpose, we collect data on the relative advantage or disadvantage each country has in low carbon technology products from the IMF. A value greater than one indicates a relative advantage in low carbon technology products, while a value of less than one indicates a relative disadvantage. Then, we create two distinct dummy variables that reflect countries' export potential in low carbon technologies. As a final step, we create the two final variables *Patent intensity adv*. and *Patent intensity dis*. by multiplying the previous dummies with *Patent intensity*.

3.4 Econometric framework

Our empirical analysis is based on the 27 countries belonging to the EU over the period 1999-2019. To investigate the effects of demand-pull, technology-push and proximity factors on oil import dependence, we first perform two different tests to inspect the possible presence of cross-sectional dependence. Cameron and Trivedi (2005) advise that observations with NT correlation carry less information than independent ones, posing a risk of biased statistical inferences. As our dataset is characterized by $N > T$, Pesaran's CD test (Pesaran, 2004) proves most suitable and confirms the presence of cross-sectional dependence. As a further check, we also apply the Lagrange Multiplier test developed by Breusch and Pagan (1980), designed for data where $N < T$, and results confirm those of Pesaran's CD test. To address this issue, we implement a panel data model that relies on a Generalised Least Square (GLS) estimator controlling for panel specific autocorrelation structure ($AR1$) and heteroskedastic and correlated error structure. A standard assumption in panel data models is that the error terms are independent across cross-sections. In the worst case, cross-sectional dependence can lead to endogeneity and therefore to inconsistent estimates. In this context, the previous estimator allows us to deal with cross-sectional dependence in the error term.

The estimated model can be expressed as follows:

$$\begin{aligned} wID_{i,t} = \beta_0 + \beta_1 demand\_pull_{i,t-1} + \beta_2 technology\_push_{i,t-1} + \beta_3 wEV_{i,t-1} + \\ + \beta_4 HHI\_import_{i,t-1} + \beta_5 \boldsymbol{X}_{i,t-1} + \mu_i + \eta_t + \varepsilon_{i,t} \end{aligned} \tag{11}$$

where $wID_{i,t}$ is our dependent variable measuring oil import dependence as the weighted in-degree centrality in the crude oil trade network in country i and time t; $demand\_pull$ represents the two demand-pull factors we test (namely, $ITRE$ and $environmental\ taxes$); $technology\_push$ includes the stock of public R&D in the energy and environmental sectors (*Energy KR&D*) and the patent intensity of public R&D in the energy sector (*Patent intensity*) as technology-push factors; wEV is our proxy for the presence of privileged commercial relationships with influential oil exporters; HHI_import is a measure of oil import concentration (we also include its alternative version adjusted for the political instability of oil exporting countries, i.e. HHI_import_PI); **X** is a vector of control variables (i.e., $energy\,intensity$, $renewables\,consumption$, $urban\,population$, $real\ GDP\ growth$, $temperature\ change$ and $oil\,price$).[11] All variables are included with a first-order lag to account for possible endogeneity relationships. Finally, we include country specific fixed-effects μ_i (to control for unobserved time-invariant country characteristics), time fixed-effects η_t (to deal with possible exogenous shocks common to all countries in a specific year) to control for common global shocks, and the error component $\varepsilon_{i,t}$.

4. Results

4.1 The role of proximity factors and environmental policy instruments

Table 2 presents the main results of our empirical analysis. In Models 1-7 we test the effect of each key factor individually. In particular, in models 1 and 2 we include demand-pull factors (the ITRE and the share of GDP captured by environmental taxes, respectively); in models 3 and 4 we capture the effect of technology-push factors (the stock of R&D in the energy sector and the patent intensity indicator, respectively); in models 5-7 we test the effect of proximity (as measured by the HHI, the HHI weighted by political stability and the eigenvector centrality, respectively). Finally, model 8 shows results for the complete model accounting for the main demand-pull, technology-push and network factors.

The main sources of international dependence on oil can be classified into two categories: i) path dependence in the energy infrastructure system (i.e., technological lock-in), as captured by the positive coefficient of the energy intensity of GDP, and ii) privileged trade relations with influential oil exporting countries (i.e., trade lock-in), represented by the eigenvector centrality. On the other hand, demand-pull and technology-push policy instruments, as well as the degree of imports diversification, are all factors that contribute to reducing oil dependency. In particular, an increase in the ITRE has the largest mitigating effect on oil import dependency, suggesting that policy-induced changes in consumers' demand can promote the shift towards cleaner energy sources. The same result is confirmed when we evaluate the effect of the share of GDP covered by environmental taxes in model 2. Further, an increase in the public support on innovation in energy technologies (*Energy KR&D*) is also negative and significant, even though the magnitude is very small. The magnitude of the effect is however larger if we consider the patent intensity in energy technologies (*patent intensity*), to account for the responsiveness of a country's ability to translate public support on innovation in the energy sector into innovation output. The negative and statistically significant coefficients of the HHI and the HHI corrected for the level of political stability of exporting countries

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[11] Table A2 in the Appendix shows all descriptive statistics.

(*HHI_PI*) indicate that reliance on a small number of oil-exporting countries (indicated by a high *HHI*) can serve as a disincentive, particularly when those countries are politically unstable (reflected in a high *HHI_P*), prompting these countries to reduce their dependence on oil imports. As for control variables, their signs are always in line with our expectations: a higher share of renewable energies within the national energy mix reduces international dependence on oil. On the other hand, an increase in the urban share of the population, as well as a higher growth rate of real GDP increase overall energy demand, thereby intensifying dependence on oil imports. Finally, an increase in temperatures over the previous year and an increase in oil prices both have a positive, but not robust, coefficient. Higher temperatures may mean more prolonged use of air conditioning and are in line with the longer summers that have occurred across Europe in recent years. As for the oil price, its positive coefficient is straightforward: as our dependent variable is expressed in terms of value, in this way we correct for price fluctuations to isolate the quantity component.

Table 2 – Baseline results

	M1	M2	M3	M4	M5	M6	M7	M8
ITRE		-1.4349***						
		(0.0993)						
Environmental taxes			-0.1496***					
			(0.0373)					
Green R&D stock				-0.0001***				
				(0.0000)				
Patent intensity					-0.0016***			
					(0.0002)			
HHI						-0.0002***		
						(0.0000)		
HHI_PI							-0.0003***	
							(0.0000)	
Eigenvector								5.0051***
								(0.8669)
Energy intensity	9.3754***	11.7843***	9.6378***	10.7306***	4.8719***	11.1301***	11.3097***	10.0944***
	(1.7122)	(1.8631)	(1.6382)	(2.4051)	(0.9941)	(2.5224)	(1.3568)	(1.7866)
Renewables consumption	-0.1566***	-0.1861***	-0.1629***	-0.1651***	-0.1039***	-0.1539***	-0.1536***	-0.1630***
	(0.0082)	(0.0078)	(0.0084)	(0.0085)	(0.0049)	(0.0077)	(0.0080)	(0.0077)
Urban population	0.3256***	0.2435***	0.3184***	0.3115***	0.1481***	0.3398***	0.3760***	0.3300***
	(0.0222)	(0.0156)	(0.0224)	(0.0236)	(0.0159)	(0.0193)	(0.0262)	(0.0203)
Real GDP growth	0.0523***	0.0552***	0.0528***	0.054***	0.0655***	0.0607***	0.0560***	0.0524***
	(0.004)	(0.0033)	(0.0039)	(0.0040)	(0.0029)	(0.0035)	(0.0030)	(0.0037)
Temperature change	0.0829***	0.0696***	0.0341	0.0824**	0.0322	0.1068***	0.0804	0.0708**
	(0.0283)	(0.0249)	(0.0283)	(0.0326)	(0.0197)	(0.0288)	(0.0504)	(0.0324)
Oil price	0.1684**	0.8501***	0.1729***	0.2704***	0.5092***	0.0611	-0.0168	0.2085***
	(0.0713)	(0.0816)	(0.0654)	(0.0902)	(0.0600)	(0.0887)	(0.0676)	(0.0760)
Constant	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Country FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	540	540	540	540	540	540	540	540

Note: ***, **, * denote significance at 1%, 5% and 10% level, respectively. Standard errors are reported in parentheses. All independent variables are expressed at *t-1*.GLS (Generalised Least Squares) estimator controls for panel-specific AR1 autocorrelation structure and heteroskedastic and correlated error structure).

4.2 The potential of environmental policy stringency to break lock-in

To answer RQ2, in Table 3 we extend the baseline results to uncover possible mechanisms that can help reduce dependency. In particular, we test whether demand-pull and technology push factors are effective policy responses to break trade and technological lock-ins or, on the other hand, an increase in their stringency leads to the emergence of the green paradox.

As a first step, we estimate the combined effect of an increase in demand-pull policy instruments and eigenvector centrality, by means of an interaction term. We find that in countries with a stricter environmental policy as defined by both the ITRE and environmental taxes oil dependency resulting from trade lock-in is effectively mitigated. Similar results are found when we evaluate the combined effect of an increase in ITRE and the energy intensity of GDP. Even in this case, changes in consumers' demand induced by an increase in ITRE can reduce technological path dependence, paving the way for decoupling economic systems from energy use. On the other hand, higher environmental taxes are not able to mitigate oil dependence through their effect on energy intensity (model 4).

Turning to technology-push factors, we study whether an increase in public support to R&D in the energy sector, as well as an increase in the patent intensity in the energy sector can help mitigate oil import dependence by weakening technological lock-in (*l.Energy KR&D* * *l.Energy intensity* and *l.Patent intensity* * *l.Energy intensity*, respectively). Overall, we find that countries with a high energy intensity manage to reduce their oil import dependence as a consequence of an increase in both the stock of R&D devoted to the energy sector and the patent intensity in the energy sector. However, the magnitude of the effect is mild, especially in the case of the stock of energy R&D.

Finally, to answer RQ3, we further test for the possible presence of a non-linearity in the impact of patent intensity. In particular, we investigate whether the extent to which patent intensity in energy technologies succeeds in reducing a country's oil import dependence through a mitigation of technological lock-in may depend on whether or not it has a comparative advantage in exporting these technologies. Our results highlight the presence of such non-linearities: countries' ability to translate public support to R&D into effective innovation output in the energy sector is not sufficient *per se* in counteracting technological lock-in and then reducing oil dependency, but countries also need to have a comparative advantage in the export of clean technologies. On the other hand, in countries with a relative disadvantage no significant effect is found.

Table 3 – The effect of environmental policy

	M1	M2	M3	M4	M5	M6	M7	M8
ITRE	-1.5648***		-0.6992***					
	(0.0813)		-0.0989					
Eigenvector	4.9365***	4.4910***						
	(1.3622)	(0.5762)						
ITRE * Eigenvector	-6.3324*							
	(3.8104)							
ITRE * Energy Intensity			-12.587***					
			(2.1037)					
Environmental Taxes		-0.0615		-0.0948**				
		(0.0382)		(0.0392)				
Environmental Taxes * Eigenvector		-3.3766***						
		(0.8080)						
Environmental Taxes * Energy Intensity				0.5268				
				(1.0609)				
Energy KR&D					-0.0002***			
					(0.000)			
Energy KR&D * Energy Intensity					-0.0063***			
					(0.0006)			
Patent Intensity						-0.0003	-0.0018***	-0.001***
						(0.0002)	(0.0002)	(0.0002)
Patent Intensity * Energy Intensity						-0.0453***		
						(0.0055)		
Patent Intensity Adv. * Energy Intensity							-0.1072***	
							(0.0071)	
Patent Intensity Dis. * Energy Intensity								-0.0172
								(0.0127)
Renewables	-0.1716***	-0.1419***	-0.1908***	-0.1706***	-0.1835***	-0.1025***	-0.0953***	-0.0977***
	(0.0073)	(0.0088)	(0.0085)	(0.0081)	(0.0082)	(0.0063)	(0.0041)	(0.0059)
Urban Pop.	0.2671***	0.3406***	0.1655***	0.3237***	0.3098***	0.1291***	0.1439***	0.1455***
	(0.0159)	(0.0223)	(0.0162)	(0.0204)	(0.0205)	(0.0136)	(0.0104)	(0.0162)
Real GDP Growth	0.0522***	0.0493***	0.0531***	0.0604***	0.054***	0.0673***	0.0716***	0.0667***
	(0.0029)	(0.0041)	(0.0033)	(0.0028)	(0.0038)	(0.0025)	(0.0028)	(0.0031)
Temp. change	0.0672***	0.0507	0.0432	0.1086***	0.0537**	0.0049	0.0416*	0.0322*
	(0.025)	(0.0342)	(0.0291)	(0.0244)	(0.0272)	(0.0401)	(0.0236)	(0.0191)
Oil Price	0.4828***	-0.1550***	0.8804***	0.1325**	0.1342*	0.532***	0.4885***	0.4606***
	(0.073)	(0.0611)	(0.0601)	(0.0615)	(0.0759)	(0.0757)	(0.063)	(0.0754)
Energy Intensity			7.9173***	9.0258***	-0.1834	2.6305**	5.5511**	3.9881***
			(2.0124)	(1.7322)	(2.3249)	(1.197)	(2.2921)	(1.3662)
Constant	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Country FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	540	540	540	540	540	540	540	540

Note: ***, **, * denote significance at 1%, 5% and 10% level, respectively. Standard errors are reported in parentheses. All independent variables are expressed at *t-1*. GLS (Generalised Least Squares) estimator controls for panel-specific AR1 autocorrelation structure and heteroskedastic and correlated error structure).

4.3 Robustness checks

To validate our results, we subject them on some robustness checks. As a first robustness, we estimate the same models as in Table 3 by means of a 2SLS estimator with Driscoll-Kraay standard errors in order to control for cross-sectional dependence and ensure comparability of our results. In this way, we control for the potential endogeneity of some regressors (namely, all our environmental policy instruments, as well as *Eigenvector*, *Energy Intensity*, *Renewables*). As instruments, we simply use the two-year lags of endogenous regressors. Results are reported in Table A3 in the Appendix, while Figure 5 below provides a comparison of key coefficients estimated with a GLS estimator (as in Table 3) and a 2SLS estimator (as in Table A3).

As the figure shows, accounting for the endogeneity of some regressors causes the coefficients associated with *ITRE*Eigenvector*, *Env Tax*Eigenvector*, *ITRE*Energy Intensity* and *Patent Intensity*Energy Intensity* to no longer be significant. In contrast, the robustness of the result associated with the role of the stock of public expenditure in R&D in the energy and environmental sectors in reducing oil import dependence through the counterbalance of high energy intensity is confirmed. Results are robust also when we distinguish the effect of patent intensity between countries that have a comparative advantage or disadvantage in exporting clean technologies, while the combined effect of environmental taxes and energy intensity is not significant with either estimator. As an additional robustness, we estimate the effect of alternative policy instruments to break technological lock-in and reduce oil import dependence. In particular, we use the synthetic indicator on Environmental Policy Stringency (*EPS*), as well as the EPS excluding taxes (*EPS No Tax*) and the EPS excluding market-based instruments (*EPS No Mkt*) provided by the OECD. We do not use these variables in our main model because data are not available for our full sample[12]. Results are reported in Table A4 in the Appendix and show that all synthetic indicators are effective in reducing oil import dependence through a mitigation of technological lock-in, as expressed by energy intensity.

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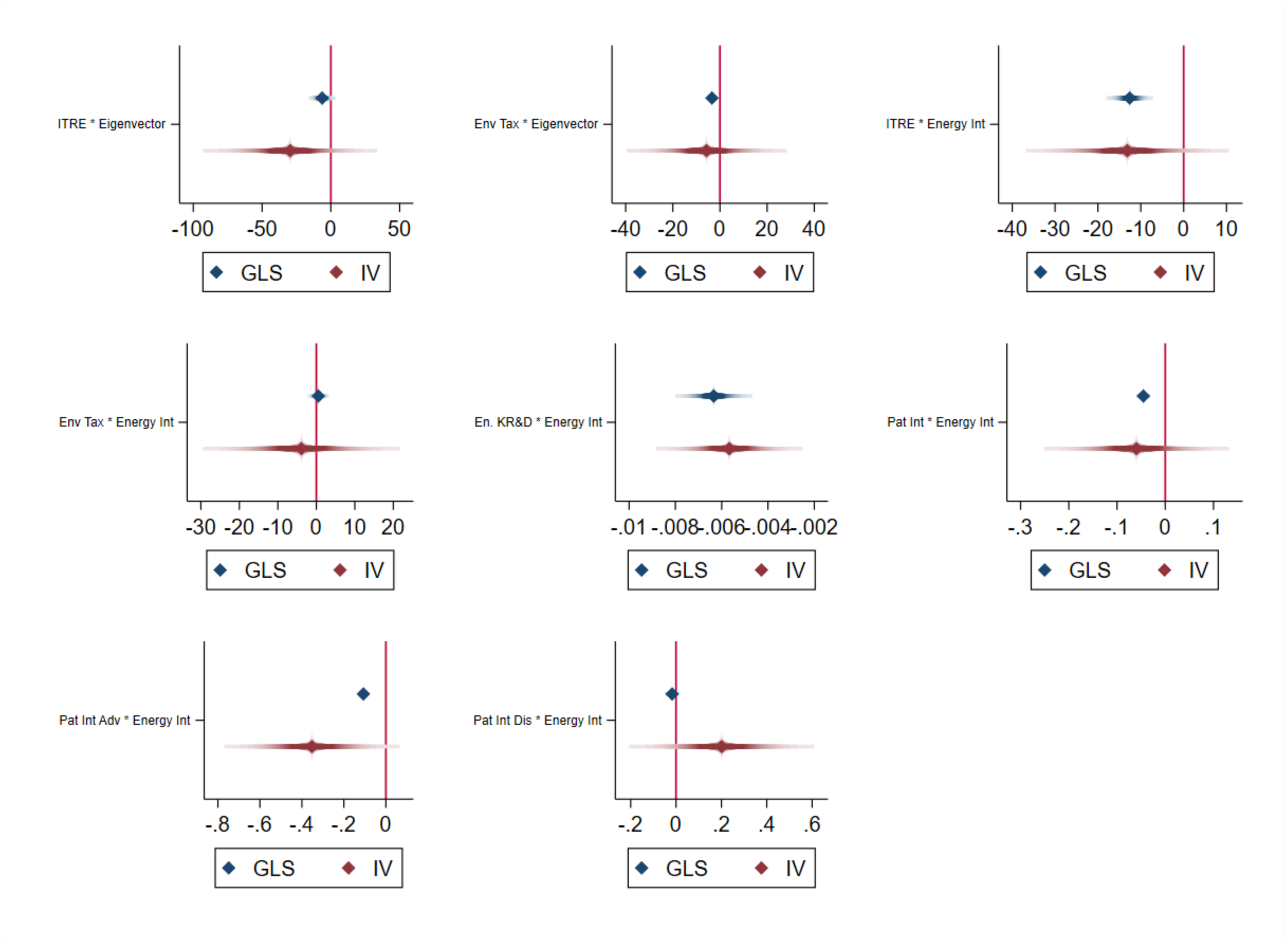
[12] Data for Bulgaria, Croatia, Cyprus, Latvia, Lithuania, Malta, and Romania are missing.

Figure 5: Comparison of key coefficients estimated with GLS and 2SLS estimators



5. Conclusions and policy implications

Despite the European Union's leading role in the ecological transition, its heavy dependence on oil imports significantly heightens the vulnerability of its energy supply, exposing it to geopolitical risks and market volatility. However, many EU countries are struggling to move away from fossil fuels, with significant internal differences. The dynamics of global trade further entrench this dependency, making it crucial for the EU to reconsider its energy strategies and diversify its sources to enhance resilience and ensure long-term energy security. In this context, the EU is actively working on creating a regulatory framework that effectively turns environmental constraints into development opportunities.

In this paper, we pursue a twofold objective: first, we explore how specific trade dynamics, such as concentrated oil imports and strong ties with key oil-exporting countries, contribute to international oil dependency, by fostering *trade lock-in*; second, we assess the effectiveness of environmental policies in reducing oil dependence in EU countries, examining whether these policies lead to the divestment effect or the green paradox effect. Our results show that countries with high energy intensity of GDP, whose economies are thus trapped in a technological lock-in, are the most oil dependent. In addition, we find evidence of trade lock-in, suffered by those countries that have established strong and privileged trade relations with key oil-exporting countries. This interdependence not only heightens vulnerability to supply disruptions and price volatility but also complicates the geopolitical landscape, as countries must balance the dual imperatives of maintaining energy security and pursuing broader strategic objectives.

Framing our results within the alternative theoretical explanations, we find evidence of the divestment effect for some specific environmental policy instruments. An important finding from our analysis is that we cannot assume all demand-pull or technology-push policy instruments have a uniform effect. Instead, as highlighted, each policy instrument needs to be evaluated individually, as each has its own distinct impact on oil import dependence. This highlights the necessity for policymakers to carefully consider the specific design and implementation of each policy tool in order to gain a nuanced understanding of how each instrument functions in practice and its unique influence on reducing oil import dependence. More in detail, our study reveals that increasing the implicit tax rate on energy has the strongest effect on reducing oil import dependence, suggesting that fiscal tools can play a pivotal role in energy transition if designed and implemented carefully. However, this result is not robust when we account for endogeneity. This aligns with Borozan (2019), who finds that the effect of energy taxes on energy consumption is heterogeneous across EU countries. In this respect, it is crucial for policymakers to conduct comprehensive evaluations of country-specific effects of each policy instrument.

We also find that public R&D in the energy and environmental sectors has the potential to mitigate international dependence on oil, and this result is very robust. This implies that policies should aim to promote technological innovation and diversification through incentives for R&D, subsidies for clean technology adoption, and support for industrial transformation, especially in countries characterised by high technological lock-in. This is in line with previous literature finding that environmental innovation and R&D expenditure help to reduce overall fossil energy consumption and promote renewable energy consumption (e.g., Usman et al., 2023; Paramati et al., 2022). Nonetheless, potential sources of heterogeneity and policy fragmentation in this context may stem from the constraints imposed by European fiscal rules. As Guarascio et al. (2024) point out, countries with stronger fiscal capacities, such as Germany, can invest more heavily in green technologies, while those with higher debt levels, such as Italy and Greece, are constrained in their ability to make similar investments. This creates an uneven playing field, where some countries are able to advance their green transition efforts more rapidly than others. To address this issue, a centralized and coordinated EU-wide investment plan focused on key sectors for the energy transition is needed.

Another important result is that countries' export potential in low-carbon technologies enhances their ability to translate public support for R&D in the energy and environmental sectors into effective innovation output capable of mitigating oil import dependence. This result may be especially useful for countries with strong trade ties to oil-exporting nations that need strategies to diversify their energy sources and trade partnerships. This could involve fostering relationships with countries that export renewable energy technologies and that are aligned with the EU’s climate goals, encouraging domestic production and enhancing the export potential of low-carbon technologies. In this perspective, developing alternative supply chains for renewable energy technologies can be crucial to reduce reliance on fossil fuels and reduce energy and economic vulnerability.

On the other hand, we do not find any evidence supporting the green paradox effect, which suggests that, on average, environmental policies do not inadvertently increase oil consumption in the short term by accelerating extraction rates as a consequence of an increase in the stringency of the environmental policy. The robust evidence supporting public R&D as a catalyst for reducing oil dependency highlights the need for increased investment in green innovation. Policymakers should prioritise funding for research and development in clean technologies and renewable energy sources, as these investments have demonstrated potential to transform energy systems. This can be achieved through targeted subsidies, grants for startups, and collaboration with academic institutions to spur technological advancements. Furthermore, enhancing the export potential of low-carbon technologies will not only contribute to reducing domestic oil dependence but also position EU countries as leaders in the emerging global green economy.

In conclusion, while COP28's outcome signals a step forward in acknowledging the critical role of fossil fuels in climate change, the compromise reached indicates that significant challenges remain. The EU's efforts to harness environmental policies as development opportunities highlight the complexities and disparities within the Union. Our findings underscore the need for nuanced and targeted policy measures that address specific lock-ins and leverage each country's unique strengths. By focusing on individualised assessment and supporting the export potential of low-carbon technologies, there is a pathway to more effectively reduce oil dependence and meet international climate commitments. A one-size-fits-all approach is inadequate; instead, policies must account for varying levels of technological development, economic structures, and existing trade relationships. For instance, countries with high energy intensity of GDP may require targeted support for industrial transformation and incentives for energy efficiency to break free from technological lock-ins. In this perspective, Guarascio et al. (2024) highlight that sectoral specialization may drive significant heterogeneities in terms of countries' capacity of and vulnerability to the energy transition. In particular, countries with a high reliance on energy-intensive industries like steel, cement, chemical, and sectors such as automotive manufacturing face distinct challenges during the green transition, particularly due to the high costs associated with restructuring these sectors.

This may also influence the relative effectiveness of different policy instruments: for instance, the sectoral specialization of a country may affect its overall capacity to innovate and integrate new green technologies, as economies that are highly specialized in energy-intensive industries may find it harder to diversify into low-carbon industries without sustained policy intervention and investment in research and development. This stands in contrast to countries that have diversified industrial bases, or those that are already leaders in renewable energy and green technologies, such as Denmark or Sweden, which face fewer barriers in adapting to the demands of the green transition. In this perspective, future research may benefit from a sectoral approach to better address these complex dynamics, recognizing that different industries will require tailored strategies to facilitate the transition. A sectoral analysis could provide detailed insights into the specific challenges faced by industries that are integral to the economies of certain countries and help design more effective policy interventions.

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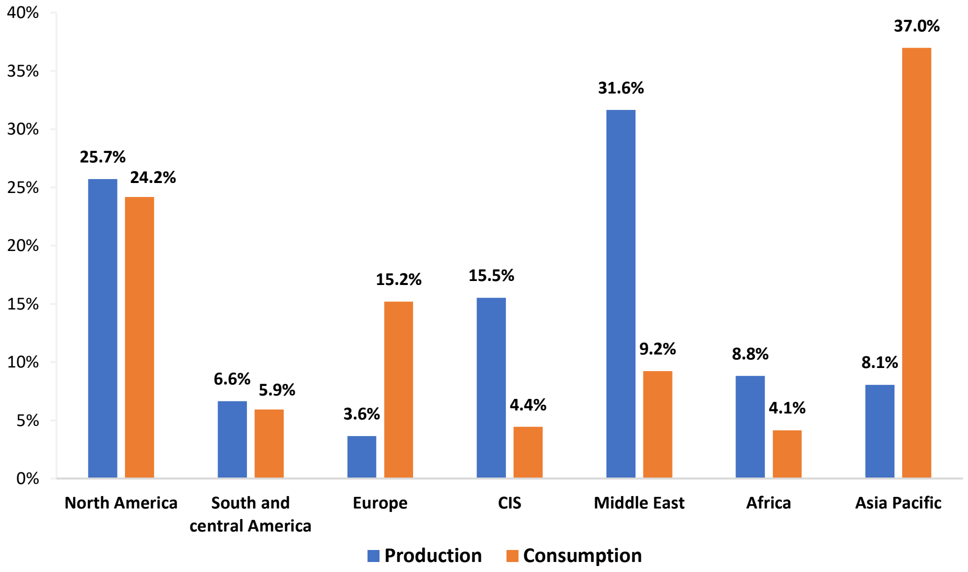
Appendix

Table A1 – Primary energy: consumption by fuel in 2019

	Fossil fuels on total	Oil on fossil fuels	Oil on total
Middle East	98.7%	46.0%	45.4%
Africa	91.5%	45.5%	41.7%
CIS	89.4%	24.9%	22.2%
Asia-Pacific	87.3%	31.6%	27.5%
North America	81.8%	47.2%	38.6%
Europe	73.5%	49.4%	36.3%
Central and South America	67.7%	61.8%	41.8%
Total	84.3%	39.2%	33.0%

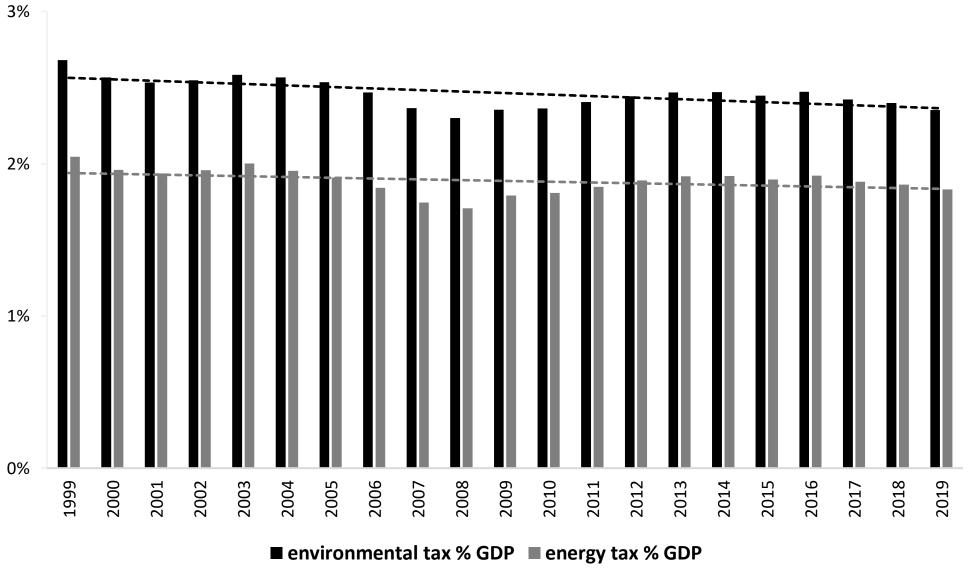
Source: own elaborations on *BP* (*Statistical Review of World Energy*) data

Figure A1 – Oil production and consumption in 2019 (% of total)



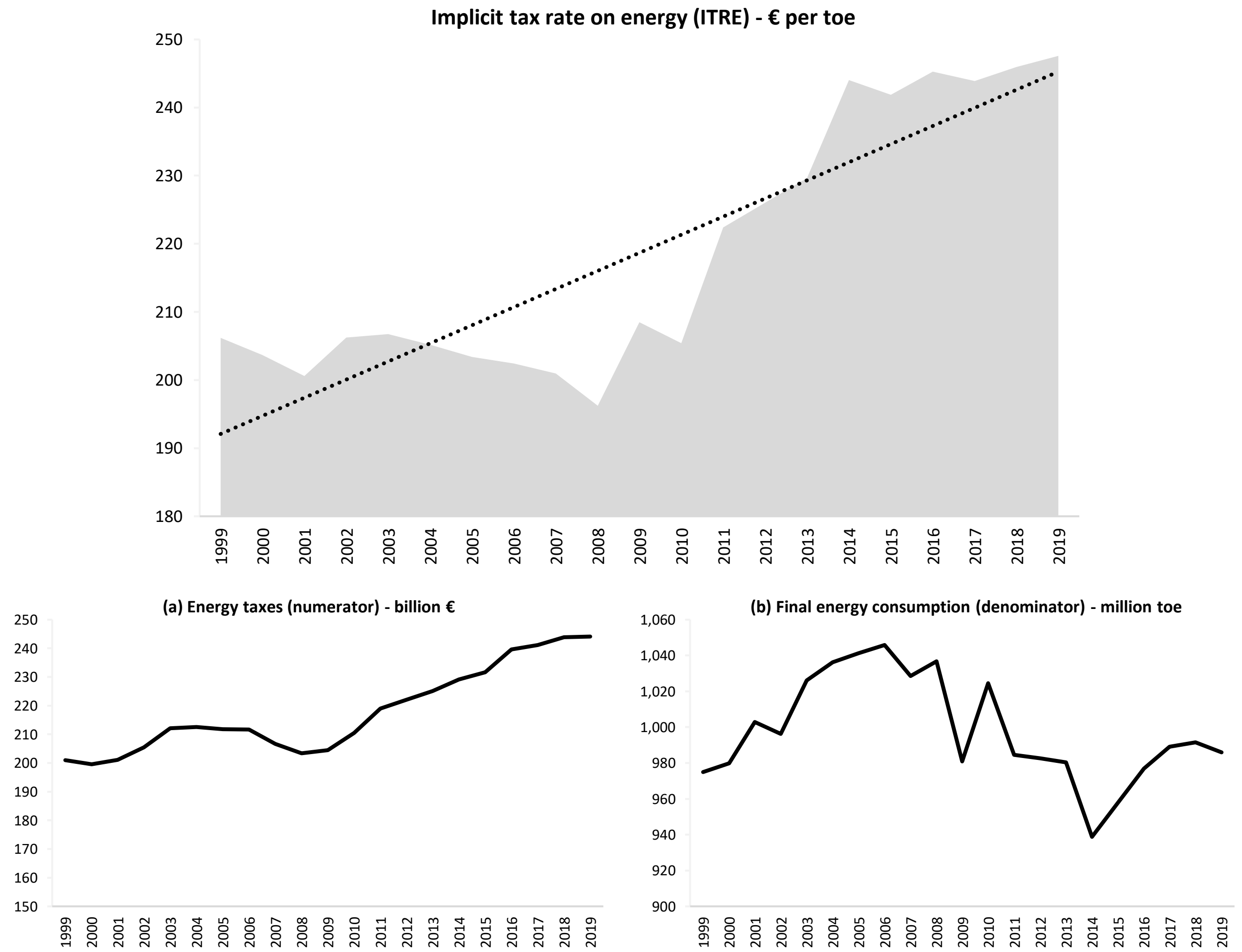
Note: oil includes crude oil, shale oil, oil sands, condensates and natural gas liquids.
Source: own elaborations on *BP* (*Statistical Review of World Energy*) data

Figure A2 – Environmental and energy taxes in the EU



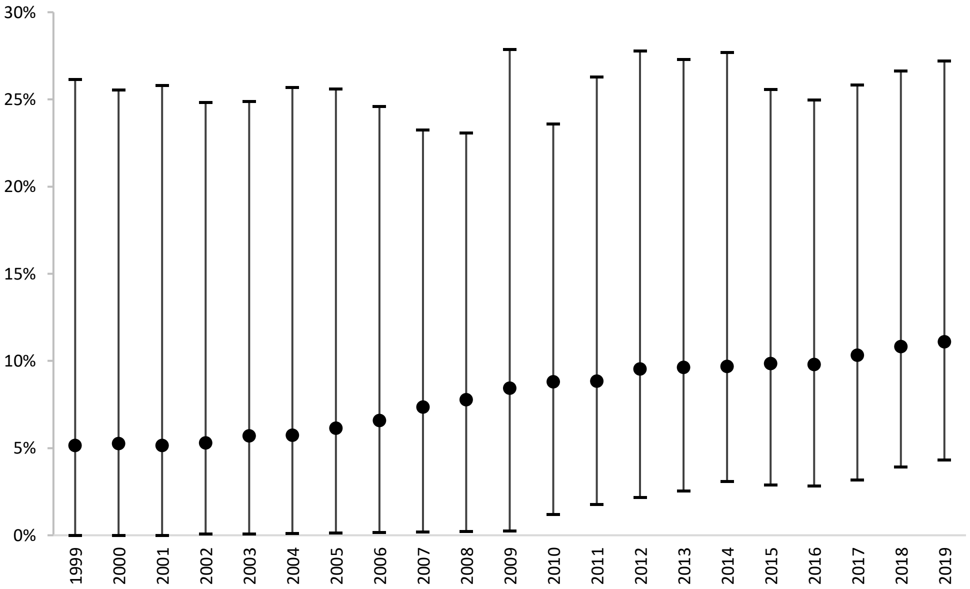
Source: own elaborations on *Eurostat* data

Figure A3 – Implicit tax rate on energy in the EU



Note: the dotted line represents the linear trend. (a) Energy tax revenues are measured at constant price euros (deflated with the implicit GDP deflator, prices of year 2015). ITRE is expressed in terms of euros per tonne of oil equivalent (toe).
Source: own elaborations on *Eurostat* data

Figure A4 – Share of renewable sources in final energy consumption in the EU



Note: the round marker shows the average value of renewables on final energy consumption. The two extremes define the minimum and maximum value recorded by European countries over time. The term renewable includes renewable energies and biofuels. For the definition of final energy consumption, see note (b) in Figure A3 in the Appendix.
Source: own elaborations on *Eurostat* data

Table A2 – Descriptive Statistics

Variable	Obs.	Mean	Std. dev.	Min	Max	Source
Weighted In-Degree (ln)	567	20.67794	3.805935	0	25.18917	Authors' elaboration on OEC
Energy Intensity (kg of oil-eq/GDP)	567	0.051887	0.068533	0.001225	0.335086	Authors' elaboration on World Bank and Eurostat
Renewables Consumption (%)	567	10.11407	6.63549	0	27.85892	Eurostat
Urban Pop. (%)	567	71.81759	12.54926	50.728	98.041	World Bank
Real GDP growth (constant 2015€)	567	2.544925	3.481213	-14.8385	24.37042	Eurostat
Temperature change (ln)	567	0.011753	0.143017	-0.91306	1.306252	World Bank
Oil price (ln)	567	3.990837	0.529819	2.892661	4.675315	BP
HHI	567	5096.483	3156.085	745.8972	10000	Authors' elaboration on OEC
HHI_PI	567	2365.659	1877.645	217.8189	7234.776	Authors' elaboration on OEC and World Bank
Eigenvector	567	0.019787	0.032333	1.34E-13	0.204422	Authors' elaboration on OEC
ITRE (ln)	567	5.165648	0.408617	3.771343	6.14292	Eurostat
Environmental Taxes (% GDP)	567	2.657385	0.616652	1.408149	5.303193	Eurostat
Energy KR&D (million PPS at 2005 prices)	567	1250.708	2362.298	0	10904.48	Authors' elaboration on Eurostat
Patent Intensity	567	53.89864	389.8585	0	5013.503	Authors' elaboration on Eurostat and IRENA
Patent Intensity Adv.	567	9.291663	51.37323	0	797.645	Authors' elaboration on Eurostat, IRENA and IMF
Patent Intensity Dis.	567	44.60698	387.5317	0	5013.503	Authors' elaboration on Eurostat, IRENA and IMF

Table A3 – Robustness checks: 2SLS estimator

	M1	M2	M3	M4	M5	M6	M7	M8
ITRE	-1.7541**		-0.8546*					
	(0.7988)		(0.4691)					
Eigenvector	24.2661***	16.77**						
	(4.8401)	(7.4629)						
ITRE * Eigenvector	-29.593							
	(22.0216)							
ITRE * Energy Intensity			-13.145					
			(8.2334)					
Environmental Taxes		0.1784		0.2553				
		(0.2189)		(0.3095)				
Environmental Taxes * Eigenvector		-5.6956						
		(11.7887)						
Environmental Taxes * Energy Intensity				-3.8807				
				(8.8701)				
Energy KR&D					-0.0002**			
					(0.0001)			
Energy KR&D * Energy Intensity					-0.0057***			
					(0.0011)			
Patent Intensity						0.0000	-0.0026***	-0.0088*
						(0.0021)	(0.0006	(0.0047)
Patent Intensity * Energy Intensity						-0.0597		
						(0.0666)		
Patent Intensity Adv. * Energy Intensity							-0.3520**	
							(0.1450)	
Patent Intensity Dis. * Energy Intensity								0.2012
								(0.1418)
Renewables	-0.0475	-0.0007	-0.0521	-0.0046	-0.0422	0.0465	0.0737	0.0178
	(0.0674)	(0.0647)	(0.0785)	(0.0633)	(0.0579)	(0.0627)	(0.0603)	(0.0631)
Urban Pop.	0.2566***	0.2464***	0.1426**	0.2149***	0.2132***	0.1111**	0.0201	0.2152***
	(0.0630)	(0.0341)	(0.0609)	(0.0590)	(0.0410)	(0.0520)	(0.0575)	(0.0625)
Real GDP Growth	0.0726**	0.0933***	0.0703**	0.0903**	0.0928***	0.090***	0.1034***	0.1028***
	(0.0305)	(0.0322)	(0.0277)	(0.0335)	(0.0318)	(0.0264)	(0.0285)	(0.0289)
Temp. change	-0.0958	-0.0821	-0.0263	-0.0456	-0.0653	-0.0799	-0.0075	0.0699
	(0.4092)	(0.4120)	(0.3662)	(0.3757)	(0.3994)	(0.3757)	(0.4255)	(0.4161)
Oil Price	0.8905	0.0973	1.093	0.3124	0.3317	0.6023	1.2592*	0.2493
	(0.5527)	(0.3872)	(0.9205)	(0.8363)	(0.6191)	(0.4917)	(0.6554)	(0.6001)
Energy Intensity			-2.8909	1.5537	-5.4271	-7.9827	-7.7644	3.2854
			(10.0530)	(17.4687)	(13.0353)	(13.7320)	(12.7675)	(13.4897)
Constant	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Country FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	513	513	513	513	513	513	513	513
R-squared	0.7942	0.7947	0.7947	0.7912	0.7933	0.8098	0.8035	0.7958
Adjusted R-squared	0.7714	0.7720	0.7720	0.7681	0.7704	0.7888	0.7817	0.7733

Note: ***, **, * denote significance at 1%, 5% and 10% level, respectively. Standard errors are reported in parentheses. All independent variables are expressed at *t-1*. 2SLS estimator with Driscoll-Kraay standard errors to correct for cross-sectional dependence.

Table A4 – Robustness checks: alternative environmental policy instruments

	M1	**M2**	**M3**	**M4**	**M5**	**M6**
EPS	-0.4191***	0.1793***				
	(0.0060)	(0.0240)				
EPS * Energy Intensity		-8.7388***				
		(0.4170)				
EPS No Tax			-0.26***	0.1369***		
			(0.0100)	(0.0185)		
EPS No Tax * Energy Intensity				-7.7748***		
				(0.3702)		
EPS No Mkt					-0.375***	0.0604***
					(0.0039)	(0.0234)
EPS No Mkt * Energy Intensity						-7.1379***
						(0.4617)
Renewables	-0.119***	-0.111***	-0.1156***	-0.105***	-0.1164***	-0.0969***
	(0.0010)	(0.0025)	(0.0017)	(0.0030)	(0.0007)	(0.0042)
Urban Pop.	0.0413***	0.0007	0.0426***	0.0074*	0.0463***	0.0051
	(0.0034	(0.0033)	(0.0030)	(0.0042)	(0.0024)	(0.0038)
Real GDP Growth	0.0035***	0.0107***	0.0042***	0.0102***	0.0037***	0.0112***
	(0.0004)	(0.0008)	(0.0006)	(0.0008)	(0.0002)	(0.0010)
Temp. change	-0.3375***	-0.4316***	-0.3304***	-0.4061***	-0.3358***	-0.4213***
	(0.0053)	(0.0181)	(0.0095)	(0.0178)	(0.0045)	(0.0229)
Oil Price	1.6082***	1.0635***	1.5308***	0.9779***	1.6082***	1.0802***
	(0.0241)	(0.0331)	(0.0306)	(0.0377)	(0.0206)	(0.0415)
Energy Intensity	11.5944***	3.5496***	13.0693***	3.2325**	12.7124***	3.9611**
	(0.6071)	(0.9371)	(0.5585)	(1.2917)	(0.5100)	(1.7310)
Constant	Yes	Yes	Yes	Yes	Yes	Yes
Country FE	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Observations	400	400	400	400	400	400