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Assessing the industrial effects of the deployment of renewable energy technologies: when product identity matters

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Abstract

Investment in renewable energy technologies (RET) produces impacts on economic activity and job creation that are fundamental to increase the social acceptability of those technologies. Previous research that attempted to measure the impacts of RET has mainly focused on its effects in energy production and climate mitigation, but surprisingly little is known about the potential of RET to transform the industrial structure of an economy. This paper proposes a methodology to understand and measure the industrial transformative impact of RET. The paper draws on contributions from the sustainability transitions literature and from the economic literature that analyses the socioeconomic impacts of RET, and combine them with the economic complexity literature in order to address two main gaps: the lack of measurement of industrial transformative effects in the first; and the assumption of product homogeneity in the second that precludes an assessment of more structural impacts. We develop a conceptual approach to the way technology deployment can lead to changes in the industrial structure, centered on the notion of product heterogeneity intrinsic to the economic complexity literature. We advance three main dimensions along which to measure the changes in the industrial structure driven by modifications in the basket of products being produced due to the development of the technology value chain: sophistication, connectivity, and competitiveness. We also propose a more precise delineation of the industrial value chain of the technology, by considering the actual weights of each sector to the technology and the technology to each sector. This approach is applied to the case of wind energy in Portugal (a successful fast follower), compared with three other main wind energy producers (Spain, Denmark, Germany). The results show a strong relationship between the deployment of the technology and the sophistication and the competitiveness of the Æcloud of productsÆ composing the industrial value chain. The paper proposes a novel analytical framework and

measurement tools that can support a timely assessment of the effects of sustainable energy technologies in the industrial structure, with relevance for policy.

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1. Introduction

Renewable energy technologies (RET) are a key element in mitigating the effects of climate change, by enabling the energy transition (IEA, 2021). On the other hand, there is evidence that renewable energies bring other socioeconomic co-benefits in terms of environment and health, as well as economic activity and employment (IRENA, 2019; Makešová & Valentová, 2021). The correct assessment of these benefits can facilitate the social acceptability of these technologies (Andersen et al., 2020). This is particularly important to increase the acceptability of RET in circumstances where the energy transition leads to the destruction of jobs in pollutant activities (Vona, 2019).

Previous research that attempted to measure the impacts of renewable energy technologies has mainly focused on their effects in terms of energy production and climate mitigation (Gouveia et al., 2014; IPCC, 2018; Valentine, 2011). Attempts to measure the socio-economic impacts of RET are more limited and have addressed almost exclusively employment effects (Mu et al., 2018; Oliveira et al., 2013; Wei et al., 2010). As a result, little is known about the industrial effects of RET, namely their potential to transform the industrial structure (Andersen et al., 2020; Fontes et al., 2021). This paper addresses this gap, proposing a methodology to understand and measure the effects induced by the deployment of the new technology in the industrial structure of a country.

For this purpose, the research draws on contributions from three literature streams. The sustainability transitions literature has conducted extensive research on the ways the development and diffusion of new sustainable technologies lead to major socio-economic transformations (Bergek et al., 2008; Geels, 2002; Markard, 2018). A recent stream of this literature focuses on the industrial transformation effects (Andersen et al., 2020; Köhler et al., 2019)). At this level, Fontes et al. (2021) offers a conceptual framework to address the transformative impact of new technologies on the sectors that contribute to their value chain and provides insights into the conditions in which such impact can occur. However, they still do not provide the tools to assess these structural effects. The (diverse) literature that assesses the socio-economic impacts of RET (Brown et al., 2012; Graziano et al., 2017; Jenniches, 2018) has conducted some attempts at measurement that go behind the employment effects. But in what concerns industrial effects, these authors measure impacts to value-added in terms of monetary units produced of products (Connolly, 2020; Lee et al., 2021). This approach has an implicit assumption of product homogeneity, being myopic to the specific features of the products. Thus, this research overlooks the fact that such features can influence the effects produced in the industrial structure by the development of the new technology value chain.

To address this limitation the paper mobilizes the economic complexity literature (Hidalgo et al., 2007; Hidalgo, 2021). This literature developed the concept of product heterogeneity and provided an analytical approach that permits to keep the identity of the products (Hausmann et al., 2014; Hidalgo & Hausmann, 2009). The assumption that products differ from each other supports our central proposal: that changes in the level of production of existing products or the introduction of new products, driven by the implementation of a new technology, can affect the industrial structure in different ways. Hence, changes in the industrial structure can be assessed by considering the specific features of the industrial products that compose the value chain of the technology.

This conceptual perspective supports the development of our methodology. Inspired by the theoretical and analytical instruments provided by the economic complexity literature, we propose a number of dimensions to assess the effects in the industrial structure of changes in the “basket of products” being produced due to the development of the new technology value chain: sophistication, connectivity and competitiveness.

Sophistication is a classical measure of the technological intensity of a product (Gala et al., 2018; Surana et al., 2020)and is proposed as a measure of the effect of RET deployment in the complexity of economy. Connectivity indicates the linkages of a product with the other products that a country produces. It denotes whether the capabilities required to producing one product are similar to those required by a few or many other products that are not produced yet (Hidalgo et al., 2018). Connectivity is proposed as a measure of the effect of RET deployment in the creation of new diversification pathways (Boschma et al., 2012; Pinheiro et al., 2018). Competitiveness refers to the capacity of a country to produce a product with competitive advantage (Pegels & Lütkenhorst, 2014). It is proposed as a measure of the effect of RET deployment in the relative position of the country in international trade.

In addition, the methodology also addresses the need for a more precise definition of the technology value chain, to prevent an overvaluation of the contributions of the technology. We develop a method to assess the weight of each sector to the technology and the weight of the technology to each sector. This permits to identify the “cloud” of products effectively involved in the deployment of the technology and to assess the effects of the dynamics of that “cloud” in the industrial structure.

The methodology is applied for the case of onshore wind energy in Portugal (a successful fast follower), compared with three main wind energy technology producers (Spain, Denmark, Germany). The results show a strong relationship between the dynamics of technology deployment and the sophistication and the competitiveness of the “cloud” of products composing the technology industrial value chain.

This research contributes to recent calls, in the sustainability transitions literature, to a better understanding of the potential of sustainable technologies to drive a transformation in the existing industrial structures (Andersen et al., 2020; Köhler et al., 2019). By combining, in a novel way, theoretical and methodological contributions from three sets of literature that are not usually brought together, the paper proposes an analytical framework and tools to measure these transformative effects. The availability of a methodology that can effectively assess structural impacts at the industrial level is also relevant from a policy standpoint as it can provide evidence towards the wider benefits of sustainable energy technologies.

The paper is organized as follows. Section two discusses the contributions and gaps of the three streams of the literature that are relevant to study the industrial effects of new energy technologies, and proposes a novel analytical framework. Section three operationalizes the methodology. Section four applies the methodology to the case of wind energy technology deployment, for which there is already an established industry. The final section discusses the main conclusions and derives implication for theory and policy.

2. Literature review

2.1 Starting point – transitions literature on the transformative impact of sustainable technologies

At a time of climate emergence and major economic recession, it is important to understand how the development and implementation of sustainable energy technologies can have a positive impact on the economy. Thus, research on sustainability transitions has become increasingly concerned with the need of aligning environmental and economic goals to increase the social legitimacy of transitions (Andersen et al, 2020).

The sustainable transitions literature have shown that the development and deployment of sustainable technologies do not take place in a void but involves extensive interactions between the technology and the context structures (sectors, institutions, technologies, geography) within which they are embedded (Bergek et al., 2015; Köhler et al., 2019; Markard & Hoffmann, 2016). The characteristics of the context influence both the development of the technology and the impact that it can have on its environment.

The interaction with the industrial context has been given particular attention by this literature. To address it, researchers have investigated the role played by existing industries that provide resources and competencies and contribute to the formation of the new technology value chain (Andersen & Gulbrandsen, 2020; Hanson, 2018); and looked at the effects of sectoral interactions in the creation of new innovation opportunities related to the new technology (Stephan et al., 2019). But while most research has been concerned with the role played by the industrial context in the development of the technology (Mäkitie et al., 2018; van der Loos et al., 2021), only recently have researchers focused on the reverse effect i.e. the way technology development can stimulate new activity in existing industrial sectors, driving changes in the industrial structure (Fontes et al, 2021).

Fontes et al., (2021) introduced the concept of the industrial transformative capacity of technologies, uncovered some of the mechanisms behind such capacity, and produced an indicator that permits to compare the transformative (potential) capacity of technologies, according to the number and diversity of sectors engaged by them. This research provided some important insights into the *conditions* under which the emergence and diffusion of sustainable energy technologies can drive changes in the industrial sectors that take part in their development and production, and conducted a first assessment of the extent of sectoral effects. But it did attempt to assess the type of transformative effects that the involvement of these sectors could have in the industrial structure

The possibility to measure these effects is particularly important as the acceptance of sustainable technologies and more generally of climate and energy policies that promote sustainable transitions increases with the growth of new economic opportunities they can generate (Andersen et al., 2020).

2.2. Contributions of other literature

There is extensive literature that attempts to measure the socio-economic impacts of renewable energy technologies. The focus of this literature tends to be on the effects on employment. Only a few studies also address the industrial impacts that go beyond employment effects. The approach adopted by these studies is to measure the growth of the gross value added induced by an increase in renewable energy deployment, using three main methods: input/output, computable general equilibrium, and supply chain analytical approach. Table 1 presents the studies reviewed, in which these types of impacts were addressed.

Table 1 - Works on socioeconomic effects of renewable energies deployment

Work	Type of industrial impact	Method				Techno-logy	How contributed
		I/O	Sup Cha	CGE	Other		
Brown et al., 2012	Value-added				X	Wind onshore	Multiple parameters could be explicative of the value-added increase.[1]
Kandrot et al., 2020	Value-added		X			Wind off-shore	The potential of a renewable energy technology to improve the industrial sectors in a country
Lund, 2009	industrial growth ($) and exports		X			All	Technology push policies must be associated with demand-pull policies
Cai et al., 2017	Value-added	X	X			All	The sector relevance vectors for the technology[2]
Surana et al., 2020;	new manufactu-rers emergence		X			Wind	The components are classified after the technological sophistication using the product complexity index
Dai et al., 2016;	Sectoral revenue, carbon emissions, pollution			x		All	The reflection about the stimulus effects that a technology has in a sequence of sectors
Connolly, 2020	Value-added	X		x		Wind offshore	The importance of renewable energy technologies for the reindustrialization of the country
Lee et al., 2021	Value-added	X				All	The bidirectional effects approach: a) response ratio: the relative impact of one additional unit of products of all units over the focal industry and b) effect ratio: the effects of the focal industry in the other industries.
Pegels & Lütkenhorst (2014)	Competitive ness, GHG emissions, innovation, policies costs				X	Solar and wind	The competitiveness parameter and the sector selection
Mamkhezri et al. (2021)	Environ-mental benefices	X			X		They evaluated the distribution of jobs territorially considering alternatives with distributed energy sources

While these studies can provide some important insights into ways of examining the industrial impacts of the deployment of new energy technologies, they have a main limitation that

[1] A similar approach was tested to the Portuguese municipalities in the North region. However, the results indicate a poorly explicative capacity in this context probably due to the concentration of the wind power plant in half a dozen of municipalities.

[2] The sector relevance vectors for the technology and international trade were required and kindly provided by the authors and they will be used in this methodology to assess the relative weight of the sectors at the technology

reduces their effectiveness in measuring whether they lead to changes in the industrial structure. This form of measurement has an implicit assumption of product homogeneity.

All products are considered just by the monetary units they represent. Even if a couple of studies differentiate the products according to their environmental features, this does not allow an assessment that goes beyond their monetary value, as all of them are grounded in the mainstream economic tradition of considering products as homogeneous.

We argue that to measure the effects of a new product or the increase in the product in an industrial sector structure, the products should be considered, as they are, heterogeneous. One euro of electric circuit produced has not had the same effect as one euro of cement produced because the two products need different capabilities to be produced and indicate the presence of different "abstract factors of production"(Hidalgo, 2021).

Despite the limitation identified, some of these studies were found to offer useful insights for an analysis of the industrial impacts of the technology, considering product heterogeneity. Pegels & Lütkenhorst, (2014) work provides a cost-benefit analyse of policies associated with the development of wind and solar energy deployment in Germany between 2000 and 2012. They suggest that it is possible to consider the competitiveness of one product as an indicator of the economic effects of energy technology deployment. They compare the Revealed Comparative Advantages (RCA) and the market share of one product by technology (those that are exclusively used in the value chain of the technology deployment). Besides the competitiveness, they assessed the innovation with patents share, avoided emissions, and employment creation of the two technologies with the respective system cost in terms of feed-in tariffs.

Surana et al., (2020) work uses the technological complexity of the products combined with a large dataset of the trade between the 13 main original equipment manufacturers and their suppliers. They aimed to identify where the manufacturers tend to emerge and in which part of the value chain they tend to occupy each place. The value chain has parts that are more complex than others, due to the technological content of the products that are in those parts. They suggest that the technological sophistication of products can be a useful dimension to assess the place that manufacturers emerge. By considering the product complexity index (PCI) as a suitable way to measure it, they provided also a tool to measure technological sophistication.

At a different level, Cai et al., (2017) combination of supply chain analytic approach and input-output matrix offers a straightforward way of combining information of the different sectors that make up the value chain of a technology. Their objective was to compare the employment and value-added effects from the renewable energy deployment in Italy between 2006 and 2014 with the expectations of the ex-ante analysis.

In addition, Lee et al., (2021) highlight the need of considering the bidirectional interaction between one sector and the rest of the economy. Their research called attention also to a problem that we have equally identified as an important limitation of these studies. These authors include in their analysis all sectors, agnostic to their relevance for the technology. This superficial approach to the delimitation of the sectors involved in the technology is likely to result in a lack of accuracy in the assessment of the industrial impacts of the technology.

Deciding which sector to focus on research to identify the industrial effects of renewable energies is not simple. To draw up a technology supply chain it is necessary to identify the products that make it up. There is a wide spectrum of possibilities, ranging from identifying just one sector for each energy source as done by (Pegels & Lütkenhorst, 2014) or including practically all sectors involved in the value chain as in (Lee et al., 2021; Surana et al., 2020). The advantage of using the first approach is the certainty that all the dynamics affecting that product were actually caused by the advance of the use of renewable energies. The disadvantage is that each installation involves dozens of industrial products that, if not considered in the analysis, can lead to an underestimation of the industrial effects of the implementation of renewable energies. On the other hand, considering all the sectors involved, without taking into account the production volume of each sector actually associated with renewable energies, could lead to an overestimation of industrial effects. According to Sandén & Hillman (2011), depending on the purpose of the investigation, technology can be defined by a larger or smaller set of value chains. Stephan et al. (2017)highlight how the sector perspective is relevant for the evaluation of a TIS. These last authors map the interaction between the configuration of the architecture of each of the parts of the technology in question concerning the productive sectors.

Our view is that an assessment of the industrial impact of the technology requires greater precision in the delimitation of sectors affected by a technology deployment. This means that it is necessary to specify both the weight of the technology in each sector - that it's the part of the sector that is effectively demanded by the technology; and the weight of the sector in the technology - that is how relevant is each sector to the technology. The latter can be described as how many monetary units of each product were necessary for each unit of energy capacity that is installed.

2.3. Contributions of economic complexity

As pointed out above, one major limitation of extant research that attempts to measure the industrial impacts of renewable energy technologies is to overlook the heterogeneous nature of products with implications for the ability to assess the effects of such heterogeneity. In this paper we mobilize the economic complexity literature to address this gap, proposing that, in the value chain of a technology, the features of the product can influence the effects of technology deployment.

The economic complexity literature draws on the initial works on economic theory, namely on Adam Smith, to propose a way to measure the differences in the specialization of labor (or complexity) that justify the differences in the wealth of nations (Hidalgo, 2021; Hidalgo & Hausmann, 2009). The central proposal of the economic complexity framework is that the industrial fabric of a country reflects part of the knowledge incorporated in that country. The production of a product requires many resources: human, physical and institutional (Hidalgo et al., 2007). These resources, also called capacities, are difficult to measure, but the fact that two countries produce the same product is a good indication that the capacities to produce such a product are present in both countries. The capabilities are the labor, capital, and institutional conditions of a production process.

By analysing international trade, it would be possible to have an approximation of the capacities of each country according to what they are capable of producing. For a complex product, the capabilities that the industrial structure of a region must have are different from those in less complex products Therefore, the notion of heterogeneity of products is intrinsic to the economic complexity approach (vs. homogeneity assumed by other approaches). Economic Complexity *understanding of the organization and evolution of the industrial structure* can provide a conceptual framework to more adequately address the question of how to assess the impact of the development and deployment of sustainable energy technologies

Based on that notion, we argue that the *specific features of each product* are a key explanatory factor for the differential effects of both changes in the production of a given product, and the introduction of a new product, induced by the implementation of new energy technology. That is, it permits to argue that changes in the level of production of products that are part of the value chain of the new technology have greater effects for some products than for others. Similarly, it permits to argue that the introduction of new products that were not produced before has more effects for some products than that for others. In methodological terms, what makes EC useful for that purpose is the mathematical approach known as dimensionality reduction that keeps the features of the data in opposition to the traditional aggregation methods

We propose that technology deployment can lead to changes in a country's industrial structure through three types of effects - increase in the technological sophistication, connectivity, and competitiveness of a *group of products that compose the value chain of the technology. T*hat results from the creation of a new value chain that encompasses an increase in the production of some existing products and the introduction of new products.

These effects are described in more detail below.

SOPHISTICATION: A feature of the products that can lead to different impacts on the economic structure is the degree of technological sophistication. The fact that product A is more technology-intensive than product B indicates that the impact of producing A or B is different, from both an ex-ante and ex-post point of view. To start producing a product with greater technological content, a country must be able to acquire the necessary physical infrastructure and also probably attract or train professionals who have the know-how and tacit knowledge to produce the product. According to Gala et al. (2018), economic development itself can be seen as a process of transformation of the productive structure of countries towards production sophistication. Ex-post, the atmosphere of attraction of new technological structures associated with the increase in product sophistication could lead to further innovation. Gao et al. (2021) assesses China's economic diversification between 1990 and 2015 at the provincial level and conclude that relatedness between products and geographic proximity affect the spread of productive capacities The sophistication of the product seems to be the more intrinsic feature because indicates the technical level of the product.

CONNECTIVITY: According to the economic complexity framework, the products that need similar capabilities are close or related. A more connected product has the potential to “open the doors” of diversification for the industrial sector. The fact that a country or region did not produce a certain product and started to produce it means that the country or region has acquired a series of capabilities that could be useful for the production of other related products that were also not produced before. Mealy & Teytelboym (2020) use similar logic in identifying the products with the greatest green potential for transitioning to sustainability. The connectivity of a product indicates how far that product is from the other products produced by a country. To assess these connections, the products are considered in the product_space (Hausmann et al., 2014). If a country does not produce a product in an “empty part” of the product_space and starts producing it, this indicates that the country acquired the capabilities necessary to produce it. As those capabilities tend to be similar to the “neighbour” ones, this increases the probability of diversification to other products. According to this interpretation, the new products can act as a “bridge” for other new products, thus the higher the distance between one product and the rest of the economy, the higher its potential to make “bridges”.

Competitiveness: Production capacities are not evenly distributed around the globe, so when a certain region starts producing a product that it did not produce before that means it has acquired a set of capacities. Competitiveness indicates the position of the products in the exports of a country and also the relevance of that product to the exports basket of all countries. The effects that a new product will bring for the economy in terms of international competitiveness vary because they depend on other products that the economy already produces and also on the position of the product in the international market. This is the feature with greater structural content and probably with greater inertia. It differs from the connectivity that indicates the position of the product only in the productive structure of one country. In terms of competitiveness, a product that is already produced by many countries will have a smaller impact than a product produced by fewer countries. To measure the competitiveness, the amount of exports is relevant, so this feature is more relevant for existing products, as the production of new products will probably be less relevant in the exports basket. More ubiquitous products i.e. products that are produced by a few countries, lead to a more complex economic structure. The competitiveness parameter is present in the work of Pegels & Lütkenhorst (2014), who seek to assess the cost-effectiveness of energy policies aimed at solar energy in the context of Energiwiede (EEG) in Germany. The competitiveness parameter is present in the work of Pegels & Lütkenhorst (2014), is proposed as a benefit in their assessment cost-effectiveness of energy policies aimed at solar energy in the context of Energiwiede (EEG) in Germany.

As pointed out before, when we consider the effects of the development of a technology value chain, it is important to consider both the production of new products and the increase in the production of existing products. The three parameters proposed above dialogue in different ways with these two possibilities, see Table 2.

The production of new products is more likely to produce effects in terms of connectivity – as they can lead to the creation of “bridges” and thus of opportunities for diversification; and sophistication – as they indicate the presence of new capabilities, contributing to the complexity of the economy. On the other hand, the increase in production of existing products is more likely to have an impact in terms of competitiveness, as it will affect the total production and consequently the weight of that product on the export basket, while the production of a new product is less likely to have an (immediate) effect in exports basket.

Table 2 - Parameters and products novelty relationship

Why it ↓matters to this→	*New products*	*Increase in existing production*
CONNECTIVITY	*Increases the probability of diversification processes*	-
SOPHISTICATION	*If the new product is complex, it contributes to the complexity of the economy*	-
Competitiveness	*If a country star to produce a product, it will affect the export basket but it tends to be **less relevant** than existing products*	*If a country produces more of a product, its role in the national industrial structure and international trade can change*

To summarize, Figure 1 illustrates the contributions and gaps of the three main literature streams that supported the development of our analytical framework. Sustainability transitions research is developing the notion of industrial transformative effects associated with the deployment of a new sustainable technology (contribution). But it is still not provided the tools to fully measure the technology impact on the industrial structure (gap). The literature on the socioeconomic effects of RET provides some measurement tools (contribution). But the assumption of homogeneity of products that underlie these tools overlooks the possibility that changes in the production of different products can have different effects, thus preventing an effective assessment of structural impacts (gap). The economic complexity literature brings the conceptual perspective of product heterogeneity and, operationally, a mathematical approach that permits to bring the identity of the products into the analysis. However, this approach has not yet been used to measure the effects of technology deployment. Therefore this research extends the economic complexity approach, by proposing the use of three parameters from the economic complexity analytical framework to measure the industrial structural effects of RET, based on the type of products. Figure 1 highlights the novelty of the present research, which is the use of known features of products in a new way, to assess the impact of the technology deployment on the industrial structure.

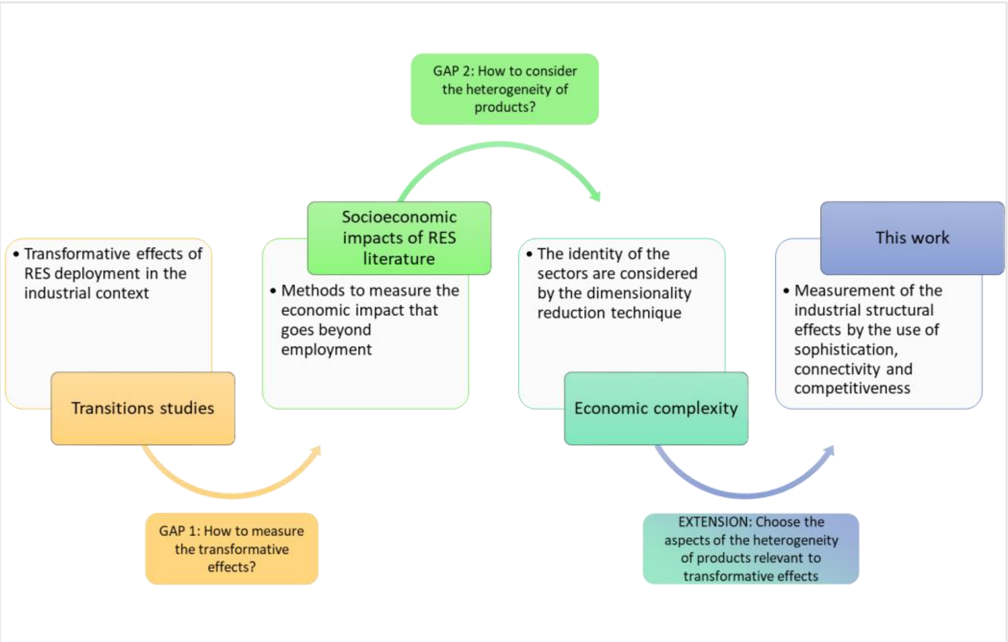


Figure 1 - Contributions and gaps in the literature review

3. Methodological approach

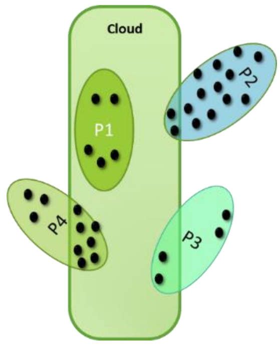
In this section, we proposed a methodological approach to measure the impact of the deployment of renewable energy technologies in the industrial structure. The approach addresses the two measurement issues above discussed. First, the more precise delimitation of the technology value chain, i.e. the industrial sectors involved that can be affected by the deployment of the technology. Second, the operationalisation of the three defined parameters as permitting to an assessment of the effect of the features of products - both production of new products and changes in the production of existing ones – upon the industrial structure of a country.

3.1 Delineation of the technology industrial value chain involved of RES

In order to empirically investigate the impact of the implementation of the new technology in the industrial structure, it is necessary to delineate the technology industrial value chain, namely which sectors are relevant and in which proportion. By technology, we mean modern renewable electricity generation technology (e.g. wind or solar). The technology lifecycle comprises five major stages; the first is initial planning, development and consents; the second is the manufacturing of the necessary equipment and materials; the third is construction and installation; the fourth is maintenance and operation; and the fifth is decommissioning. The stage that interests this analysis is manufacturing. The manufacturing value chain stage is the set of all products in the industrial products that make up the value of technology from an industrial point of view.

Let's call the representation of the set of products that are in some way part of the manufacturing stage in the life cycle of renewable energies, a "product cloud". For some products, the entire product value chain may be exclusively directed to the implementation of a certain renewable electricity generation technology; it means that the product is only used in that technology. A product can be more or less important for the technology deployment. On the other hand, the technology can be more or less relevant to the total sector production. As a result of that, the product can be of great relevance within the technology value chain, but because this product has several possible uses within the regional/national sectorial production, what is used for the implementation of the technology is not relevant for the sector as a whole.

To represent simply this idea of a cloud, we can hypothetically assume a simplified technology that uses a set of four manufactured products (P1, P2, P3, P4) for the installation of a technology unit (in MW), totalling a value of 16 monetary units in a specific year and country as in Figure 2. Of these, P1 is unique to the technology, that is, everything that is produced from that product/sector is used only for the implementation of the technology; it produces 5 monetary units of product. Sector P2 produces in its entire value chain 12 monetary units, of which 2 are used in the technology in question and the remaining are for other uses. Sector 3 produces 2 monetary units for technology and 2 for other uses. Sector 4 produces 7 monetary units for technology and 3 for other uses. To assess the impact that technology has on various sectors, these 4 sectors cannot be treated in the same way. They do not have an equal impact on the value of the technology. The impact that the technology has on sectors is also unequal. For this reason, it is necessary to outline the importance of each sector in the technology and also the importance of the technology in each sector that composes the technology value chain.



$$PR_{tech,P1,n,c} = \frac{5}{5} \qquad PR_{P1,tech} = \frac{5}{16}$$

$$PR_{tech,P2,n,c} = \frac{2}{14} \qquad PR_{P2,tech} = \frac{2}{16}$$

$$PR_{tech,P3,n,c} = \frac{2}{4} \qquad PR_{P3,tech} = \frac{2}{16}$$

$$PR_{tech,P4,n,c} = \frac{7}{10} \qquad PR_{P4,tech} = \frac{7}{16}$$

Figure 2 - Ilustrative example ofdelineation of the technology value chain

3.2 Metrics

In this section, we operationalise the three parameters proposed in the conceptual framework: technological sophistication, connectivity, and competitiveness.

The first parameter is the technological sophistication of each product and the objective is to measure whether and how the change in cloud dynamics contributed to change the technological sophistication of the industrial structure as a whole. The PCI (product complexity index) indicates the technological sophistication of a product as being the average complexity of the countries that produce it; a less sophisticated product can be produced by a less complex country, while a very sophisticated product requires capabilities that will only be present in countries with more complex economies.

$$PCI_{tech,n} = \sum_{i} PR_{i,tech} * PR_{tech,i,n,c} * PCI_{i,n}$$

Where $\mathbf{PCI_{tech,n}}$ indicates the complexity of the technology **tech** in year **n** or the complexity of the cloud of products that compose the technology. $\mathbf{PR_{i,tech}}$ is the relative weight of the sector **i** in the technology **tech** (it is constant in time and space). $\mathbf{PR_{tech,i,n,c}}$ is the relative weight of the technology **tech** in the sector **i** in the year **n** and in the country **c**. $PCI_{i,n,c}$ is the product complexity index of the sector **i** in the year **n**. The PCI is the same for all countries in each year

The metric used at the second parameter, the connectivity, indicates the opportunities in terms of economic diversification that can be achieved through the acquisition of capacities that allow the production of a new product. The distance will be used as a connectivity parameter. By distance, we mean the sum of the proximities connecting the new product with all products that the country does not yet produce or does not export, as defined by Hausmann et al., (2014).

$$d_{tech,n,c} = \frac{\sum_i d_{i,n,c}}{number\ of sectors\ i}$$

Where **d** is the distance between product **i** and the rest of the productive structure in year **n** and country **c**.

$$d_{i,n,c} = \frac{\sum_i proximidade_{j,i,n,c}}{\sum_i proximidade_{j+k,i,c,n}}$$

Where the distance **d** of each sector **i** is the sum of the proximity between sector **i** and each sector that the country does not yet produce **j**, divided by the sum of the proximity of sector **i** with all products, those it already produces **k** and those it still produces does not produce **j**.

Finally, in the third parameter, to measure competitiveness, we used the revealed comparative advantages (RCA) that takes into account both the importance of technology for the sector and the importance of the sector for technology. In a generic notation would be:

$$RCA_{tech,n} = \sum_{i} PR_{i,tech} * PR_{tech,i,n,c} * RCA_{i,n,c}$$

Where $\mathbf{RCA_{tech,n}}$ represents the RCA of the technology **tech** in year **n** in country **c**. $\mathbf{PR_{i,tech}}$ is the relative weight of the sector **i** in the technology **tech** (it is constant in time and space). $\mathbf{PR_{tech,i,n,c}}$ is the relative weight of the technology **tech** in the sector **i** in the year **n** and in the country **c**. $\mathbf{RCA_{i,n,c}}$ is the RCA of sector **i**, in year **n** e in the country **c**.

3.3 Case study

Description

To illustrate the methodology developed we apply it to the case of wind power deployment in Portugal, a fast follower in the implementation of the technology. We compare the results with the same parameters for three countries that have also a high level of technology deployment: Denmark, Spain and Germany. It was made to avoid the idiosyncrasies of the country bringing some biases for the results.

The identification of the industrial products involved in the technology deployment has three steps. The initial step was to identify the manufacturing sectors that compose the technology value chain in the work of Wind(2010). In a second step, sector specialists confirmed these sectors. The third step was to match this set of products with the literature, specifically the work of (Cai et al., 2017). The core sectors for wind deployment classified according to HS (Harmonized System[3]) and NACE (Statistical Classification of Economic Activities in the European Community) are presented in table 3.

Table 3 - Main products to wind power generation

Core product		HS – 4 digits	CAE R3	PRODCOM	HS – 6 digits
		Code	Code	Code	Code
Blade		7019	2314	23141170	701931
Turbines		8412	2811	28112400	841290
Gearbox		8483	2815	28152270	848340
				28152330	848320
Bearing		8482		28152450	848210
Tower		7308	2511	25112200	730820
Generator		8501	2711	27112610	850230
Yaw angle adjustment system		8428	2822	28221470	842612
Break system		8708	2932	29323020	870831
Electronic equipment	Board	8730	2712	27123203	853710
	Oscilloscope	9028	2651	26514520	902830
	Multimeters	9030			
	Electricity meter				
	Other meters	9032			
	Automatic regulator				

Data

There are two types of data, one for calculation of the relative weight of each product in the technology and the relative weight of technology in the sectorial production and another for the calculation of the parameters. Table 4 combined with figure 3 shows the main data sources. For the vector of relative weights of the sector in technology we use the same vector of(Cai et al., 2017), the author kindly provided the vector upon request. Elaborating these vectors is a process that requires access to detailed wind energy projects costs that were unavailable for use in the Portuguese context.

The data for assessing the weight of the technology in the sector required a three-step calculation. The starting point was the additional installed capacity each year in the country with data from IRENA (2021). Then the amount of technology installed in that year and country

[3] Harmonized System is a product classification used in international trade used by the custom authorities worldwide.

was multiplied by the vector of relative weights of the sector in technology, as it was necessary to understand how much of each product was required for the deployment. The second stage was to evaluate the size of the sector in the country and year. The work of Cai et al., (2017) uses the PRODCOM database from EUROSTAT. In that database, there is information about the production, imports, and exports of each product (with an 8 digits detailed classification) in each country with some missing points. Unfortunately, there are not enough data for Portugal. For the Portuguese context, the data came from the Portuguese statistical bureau (INE), correspond to the period between 2008[4] and 2017 in two different databases, one for production, the statistics of industrial production, and another of the international trade (INE, 2009, 2010, 2019, 2020, 2011, 2012, 2013, 2014, 2015, 2016, 2017, 2018). Data for Germany, Denmark, and Spain[5], which are used for comparative purposes, comes from the PRODCOM database (EUROSTAT, 2021).
After the second step, we had a proxy of the total amount of product that was used by the technology in each year. The third step was to make the quotient of that and the total available products in that year (production plus imports minus exports). The result is the relative weight of the technology in each product.
The data for parameters asses were from the Dataverse (The Growth Lab at Harvard University, 2019), this database is largely used at economic complexity for example in Hausmann et al., (2014). For Portugal, we use the four digits of sectorial granularity, at that table, the RCA, PCI, and distance are provided for products, years, and countries, the database was "filtered" using R. For Germany, Denmark, and Spain, as the data at PRODCOM were available, with minor missing points, they were used allowing six digits of sectoral granularity. However the tables with six digits in Dataverse have no information about PCI and distance, we use Python to calculate them using codes from (Simoes, 2020).

Table 4 - Data source and treatments

Data for relative weight calculation		**Data for parameters**			
Sector in technology	**Technology in sector**	**Portugal**		**Germany, Denmark and Spain**	
Cai (personal communication)	See figure 3	Source	Data	Source	Data
		Dataverse HS - 4 DIGITS TABLES	PCI, RCA, DISTANCE subsets using R	Dataverse HS - 6 DIGITS TABLES	Export, Import and RCA, subsets using R - PCI and distance calculated in Python.

Finally, to summarize the process of data collection and calculation, figure 3 shows the starting point for each country: the additional installed capacity. The second step was to identify the demand for each product based on technology deployment. The third was to compare this demand with the internal availability of the product to find the relative weight of the technology in the sector.

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[4] The previous repots of the industrial production classifies the products by the CAE 2.1. After 2008, the reports classifies them in CAE 3. At this stage, this research avoid the matching, it could be done in a latter stage.

[5] For those countries the missing points were less relevant than in Portugal and we opt to doesn't include two products that represent less than 5% of the value chain because they have too many missing points. We clean the datasets by doing extrapolations when the missing point were just one in the tails and interpolation when the missing points have valid points in both sides, for Denmark, product 25110 we considers just the production because the exports were greater than the production plus the imports. When the country has not a positive variation in the wind energy installed capacity, the year were not considered, this is the case of Denmark in 2007 and Spain in 2014.

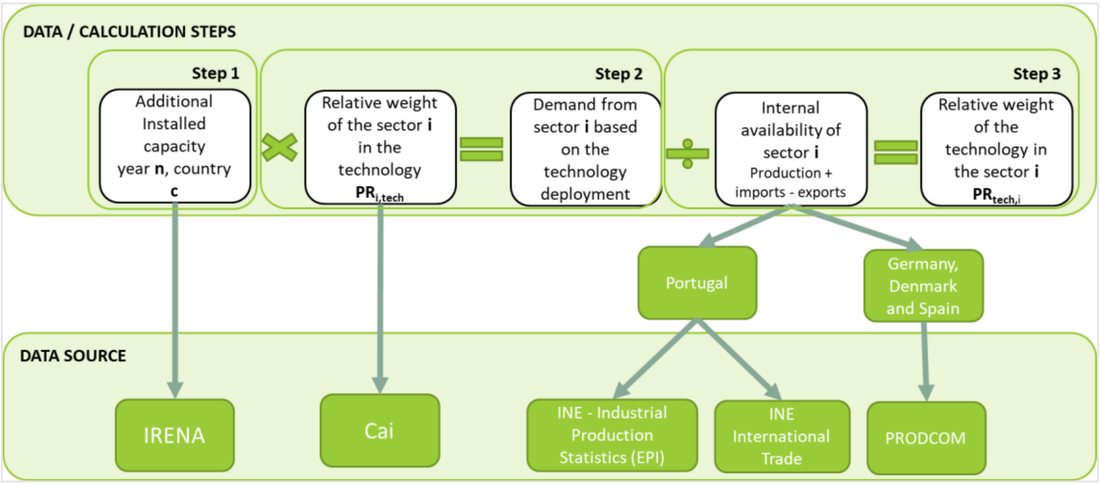

Figure 3 - Methodological steps

4. Results of methodology application

This section presents the results of the application of the method described above for assessing the effects of a renewable energy technology deployment in the industrial structure.

4.1 Technological Sophistication

In order to assess the impact that the cloud dynamics have on the industrial structure ~~in~~ terms of sophistication, it is important to understand how the sophistication of the cloud has evolved and also how the sophistication of the fabric as a whole has evolved. In a way, this assessment of the technological sophistication of the industrial structure as a whole and the dynamics of the technological sophistication of the cloud indicate~~.~~

The dynamics of the sophistication of technology between 2008 and 2018 shows a decrease in as shown in figure 4. This process can be explained by two movements in the composed indicator, the technological sophistication can be decreasing in the sectors of the technology as a whole and/or the relevance of the technology in the sectors can be changing and affecting the dynamics of the indicator

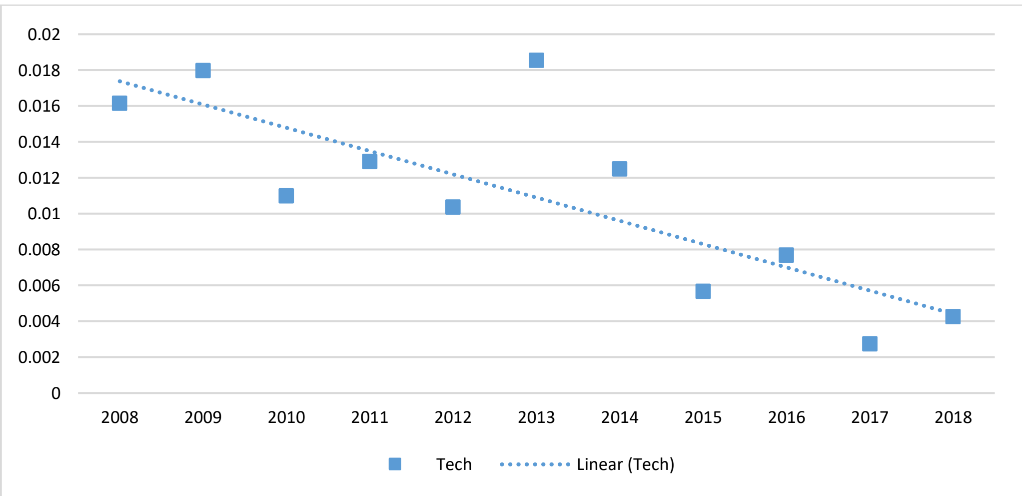

Figure 4 - Portugal - 2008-2018 - Sophistication of the wind technoloogy value chain (manufacturing phase)

The first movement is observed in figure 5 by the variation in the vertical axis. The total reduction in the average technological sophistication of the sectors that are in the cloud of products was 9%. The movement, the variation in the horizontal axis is more clear. Figure 5 represents the sophistication (PCI) of each sector in the vertical axis and the relevance of the technology for the sector in the horizontal axis. The size of the circles indicates the relevance of the sector to the technology.

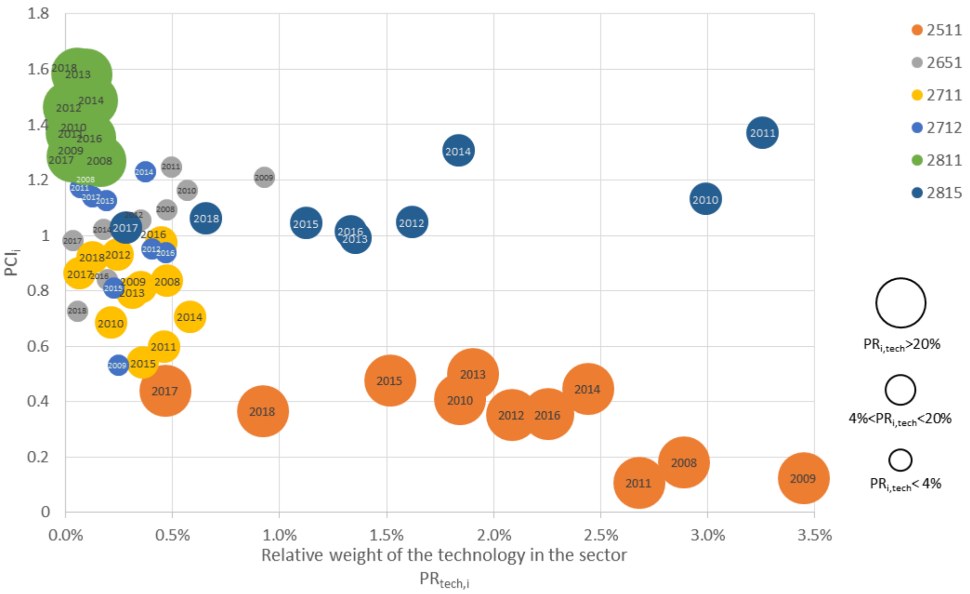

Figure 5 - Portugal - 2008-2018 - Dynamics of PCI and relative weight of technology in the sector by products

Note: the sectors 2822, 2314, and 2932 are not plotted in figure 5 to keep its readability.

The second movement in the decrease of the technological sophistication indicator is the reduction of the relevance of the technology for the sector as a whole. In this case, the relevance is decreasing as well. It is worth highlighting that the technology is more relevant to the sector of glass fibre than to the other sectors.

Besides these two phenomena, decreasing complexity of the products and the relevance of them to the sectors, the pace of installation of the wind energy is also an explicative variable as can be shown in figure 6. Even looking for an in-deep analysis of structural industrial changes, some aspects can be beyond this approach, for example, the processes started in some products could continue even if the internal demand decreases due to exports, see box 1.

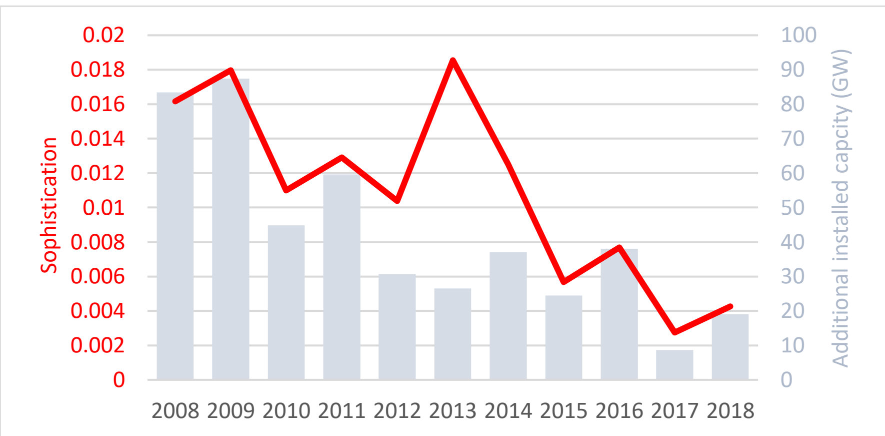

Figure 6 - Portugal - 2008-2018 - Sophistication of wind energy value chain and wind energy deployment

Box 1 . The case of the Wind-powered generating (850231-HS)- Portugal

If we analise the process of the product 850231 we can see a process of international trade role transformation. This product is used exclusively in the value chain of the wind energy deployment. During the last 20 years, Portugal goes from an importer position to an exporter position, as shown in Figure 7. At the same time, the pace of wind energy technology deployment in Portugal had an increase and a decline. Our approach is unable to capture this kind of structural effect of energy deployment.

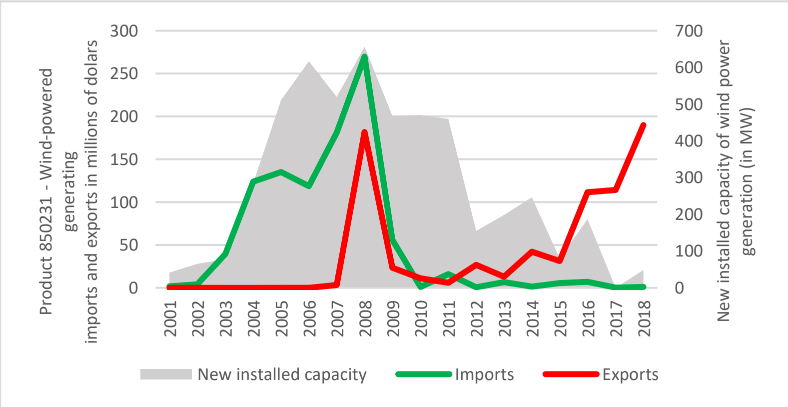

Figure 7 - Portugal - 2001-2018 - Imports and Exports of product 850231 and wind technology deployment

The strong correlation (72% in Portugal) between the cloud sophistication and the pace of wind energy installation is a process that can be observed in other territorial contexts as well. In the case of Denmark and Spain for example, figure 8 and 9. In these countries, the correlation is lower, 42% and 21 % but is still possible to observe a similarity between the sophistication that the technology represents for the industrial sector and the pace of energy deployment technology.

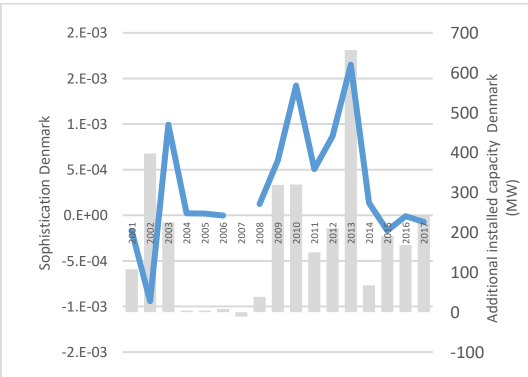

Figure 9 -- Denmark - 2001-2018 - Sophistication of wind technology value chain and wind energy new installed capacity

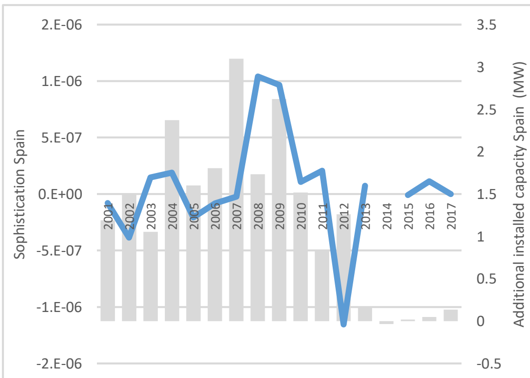

Figure 8 Spain - 2001-2018 - Sophistication of wind technology value chain and wind energy new installed capacity

4.2 Connectivity with the rest of economy

During a process of diversification of an economy, the distance between each new product and the rest of the economy tends to decrease because new products mean the acquisition of new capabilities and new “open doors”. Our data suggest not an inverse but direct relation between the implementation of the technology and the distance between the product and the rest of the economy. The reason for explaining the direct relationship between the distance of the products and the energy technology deployment could be a more or less related diversification process. For example, few new products are being produced due to the deployment of the technology or the new products are close from those already produced, so the diversification process is less relevant. This analysis has not taken into account the debate about related or unrelated diversification, however, it could be considered in further research.

The connectivity of the cloud is decreasing during the horizon of analysis. It is also much related to the pace of implementation with a correlation of 75%.

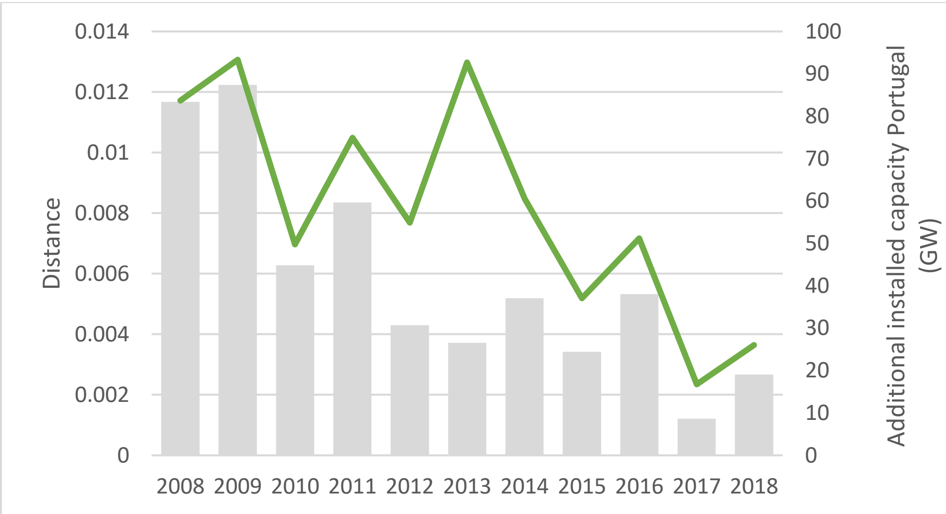

Figure 10 - Portugal - 2008-2018 - Connectivity of wind technology value chain and wind technology new installed capacity

The other countries present similar dynamics, for example, Germany presents an 84% of correlation between the distance of the technology from the rest of the economy and the pace of technology deployment. In Denmark, the correlation is about 69% and 61% in Spain.

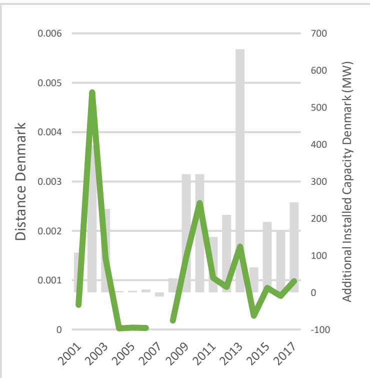

Figure 13 – Denmark 2001-2017 - Connectivity of wind technology value chain and wind technology new installed capacity

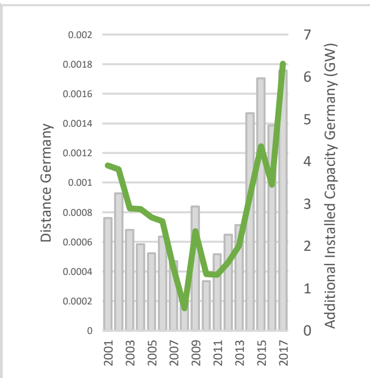

Figure 11 - Germany - 2001-2017 - Connectivity of wind technology value chain and wind technology new installed capacity

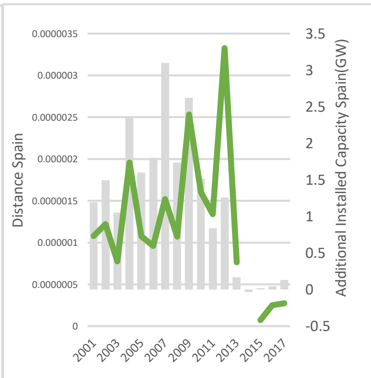

Figure 12 - Spain - 2001-2017 - Connectivity of wind technology value chain and wind technology new installed capacity

4.3 Competitiveness

At a first look, the cloud seems to decrease the competitiveness of the Portuguese economy due to the decreasing tendency of the curve in figure 14. However, again this information combined with the pace of deployment of the technology shows and strong correlation between the variables. This could suggest that the deployment of the technology induces a competitiveness increase mainly in the installation phase. This result was expected because we consider the manufactured products only.

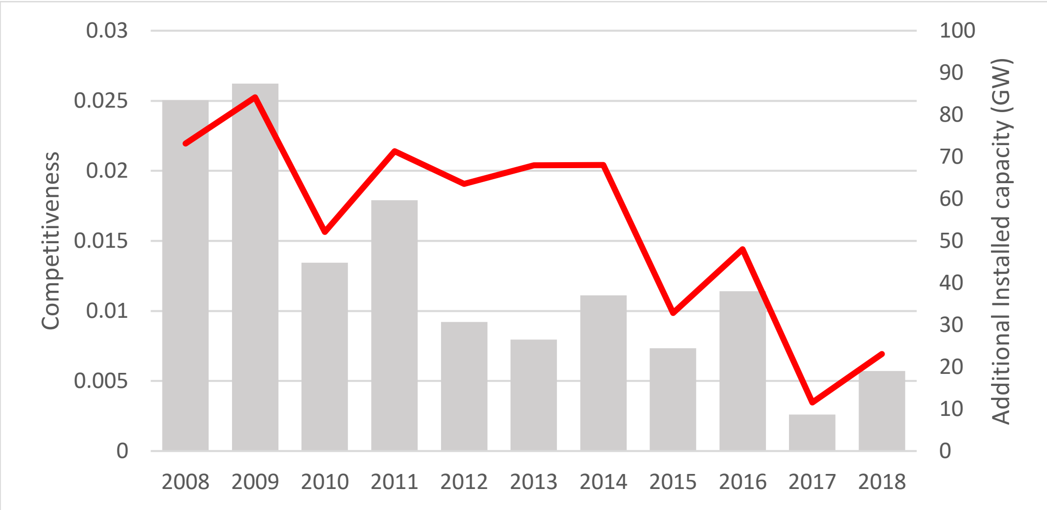

Figure 14 - Portugal - 2008-2018 - Competitiveness of wind technology value chain and wind technology new installed capacity

The hypothesis of strong correlation is corroborated by the observation of the German case. There, the correlation between the competitiveness and the additional installed capacity is 85%, Figure 15.

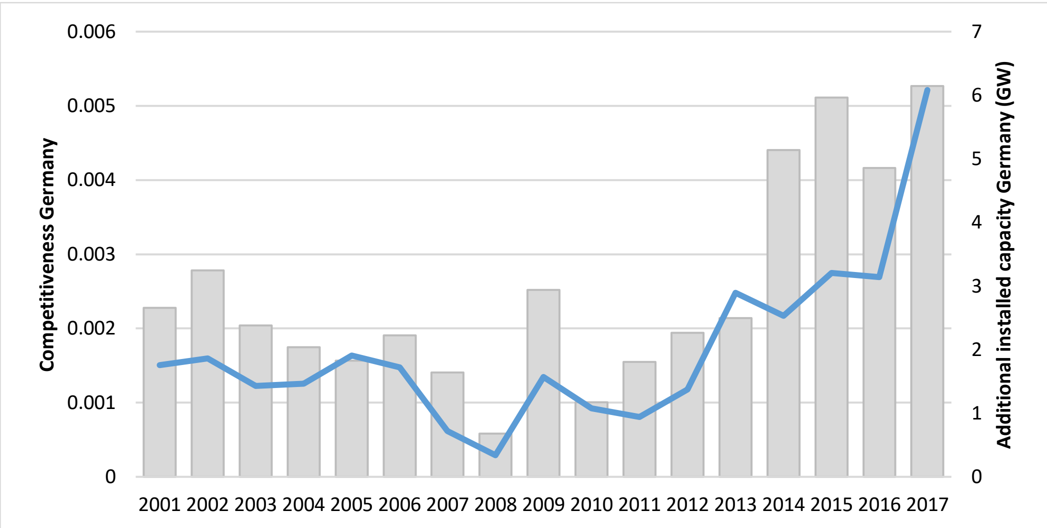

Figure 15 - Germany - 2001-2017 - Competitiveness of wind technology value chain and wind technology new installed capacity

In this case, with more observed years is still more evident the similarity between the pace of installation of technology and the competitiveness of the industrial sector presumable associated with the technology.

5. Discussion and conclusion

Renewable energy technologies are crucial for the sustainability transition, but the perception about the socioeconomic effects in employment and in the industrial structure will be decisive for their social acceptability (Andersen et al., 2020; Vona, 2019). This paper proposes a novel methodology to measure the industrial effects of the deployment of renewable energy technologies that go beyond changes in employment. To measure these effects the research had to address two main problems. First of all, how can these impacts be measured? Second what precisely should to be measured?

Concerning the first problem, the basic assumption is that the implementation of a new technology causes a change in the industrial structure. This change can be measured through the effects that the additional installed capacity induces in the activity of the sectors that compose the value chain of the new technology. However, contrary to previous research and supported by the economic complexity literature, we argue that the products that compose the value chain of a technology are heterogeneous, as they need different capabilities to be produced. Such product heterogeneity implies that the changes in the production of different products can lead to different effects in the industrial structure. Therefore, we propose three dimensions along which to measure the impact of changes on the level of production of existing products, or the introduction of new products, in the structure of industrial sectors: sophistication, connectivity, and competitiveness.

Concerning the second problem, we argue that what should be measured is not the sectoral change as a whole, but the dynamics of a cloud that represents the set of products effectively involved in the technology. The sectors have to be represented more precisely, in the proportion that the technology really affects them. For this, we propose a method to weight the sector, which requires assessing the relevance of the sector to the technology (constant by year and country) and the relevance of the technology for the sector (dynamic in time and space).

We apply this methodology to the case of wind energy technology, for which it is already possible to obtain evidence on industrial effects in several countries. The results show that the sophistication of the cloud of products involved in the technology follows the pace of technology implementation in the country. This direct relation indicates that an increase in the deployment of the technology could contribute to the sophistication of the industrial structure. The results also suggest that the major effects in terms of increase in technological sophistication occur in the initial phase of technology deployment. This was expected since the analysis focused on the manufacturing part of the technology value chain.

As for competitiveness, we similarly observe a direct relationship between the variation in the technology deployment and in the competitiveness of the cloud of products. This result can be understood as an indication that the technology deployment could contribute to an increase in the competitiveness of the industrial structure in a country.

In what concerns connectivity the results show a direct relationship between the deployment of the technology and the distance between the cloud of products and the rest of the economy. Contrary to the initial expectations the evidence reveals that when technology deployment increases, connectivity decreases. This result raises questions regarding our expectation that technology deployment would drive the introduction of new unrelated products, which would drive new unrelated diversification opportunities. However, the effect observed may be explained by the characteristics of the wind energy technology. As technologies differ concerning the nature of the products that compose their industrial value chain (Hidalgo et al, 2018), the deployment of other technologies might produce a different pattern. Future research on other technologies may reveal a greater role for unrelated diversification.

The paper offers a new contribution to assess the socio-economic impacts of renewable energy technologies, proposing an analytical framework and tools to measure their still overlooked transformation effects upon the industrial structure. Thus it adds to a recent stream of research in sustainability transitions that highlights the need to understand the transformative effect of the sustainable technologies (Fontes et al, 2021; Köhler et al., 2019). It advances in the measurement of these effects by linking with the economic complexity literature, which enables us to bring the concept of product heterogeneity into the analysis. This conceptual approach allows us to start understanding how the different features of the products can induce specific transformative effects: changes on the product sophistication can have an impact on the complexity of economy; changes on product competitiveness can have an effect on the country's relative position in international trade; changes on product connectivity can influence the diversification pathways. In addition, the parameters defined in this work somehow dialogue with the suggestion of Balland et al. (2022) about the importance of combining complexity and relatedness analysis, which are not yet studied in tandem but are two perspectives to observe the same phenomena.

The case of onshore wind energy technology permitted to test the usefulness of the methodology. But the analysis still has some limitations. The results provide some evidence that the renewable energy technology deployment have transformative effects on the industrial structure of a country, and that these effects are largely consistent across countries with different structures. However, a low national content in the technology installation could affect the intensity of that process. On the other hand, the methodology was only applied to the case of one technology. Its application to other different technologies could provide additional insights about the specific characteristics of the technologies that may affect their impact upon the industrial structure of a country. It would also contribute to improve the methodology and to enable a generalization of the findings, strengthening its potential role as an instrument to support policy decisions.

The results have implications for industrial policy in sustainability transitions. We offer evidence that the dynamics of the sophistication and of the competitiveness of the technology value chain are positively related with technology deployment. This can contribute to increase the awareness of the economic actors not just of the urgency and relevance but also the benefits of the sustainable transition.

References

Andersen, A. D., & Gulbrandsen, M. (2020). The innovation and industry dynamics of technology phase-out in sustainability transitions: Insights from diversifying petroleum technology suppliers in Norway. *Energy Research & Social Science*, *64*, 101447. https://doi.org/10.1016/J.ERSS.2020.101447

Andersen, A. D., Steen, M., Mäkitie, T., Hanson, J., Thune, T. M., & Soppe, B. (2020). The role of inter-sectoral dynamics in sustainability transitions: A comment on the transitions research agenda. *Environmental Innovation and Societal Transitions*, *34*, 348–351. https://doi.org/10.1016/J.EIST.2019.11.009

Balland, P.-A., Broekel, T., Diodato, D., Giuliani, E., Hausmann, R., O'Clery, N., & Rigby, D. (2022). The new paradigm of economic complexity. *Research Policy*, *51*(3), 104450. https://doi.org/10.1016/J.RESPOL.2021.104450

Bergek, A., Hekkert, M., Jacobsson, S., Markard, J., Sandén, B., & Truffer, B. (2015). Technological innovation systems in contexts: Conceptualizing contextual structures and interaction dynamics. *Environmental Innovation and Societal Transitions*. https://doi.org/10.1016/j.eist.2015.07.003

Bergek, A., Jacobsson, S., Carlsson, B., Lindmark, S., & Rickne, A. (2008). Analyzing the functional dynamics of technological innovation systems: A scheme of analysis. *Research Policy*, *37*(3), 407–429. https://doi.org/10.1016/J.RESPOL.2007.12.003

Boschma, R., Minondo, A., & Navarro, M. (2012). Related variety and regional growth in Spain. *Papers in Regional Science*, *91*(2), 241–256. https://doi.org/10.1111/j.1435-5957.2011.00387.x

Brown, J. P., Pender, J., Wiser, R., Lantz, E., & Hoen, B. (2012). Ex post analysis of economic impacts from wind power development in U.S. counties. *Energy Economics*, *34*(6), 1743–1754. https://doi.org/10.1016/j.eneco.2012.07.010

Cai, M., Cusumano, N., Lorenzoni, A., & Pontoni, F. (2017). A comprehensive ex-post assessment of RES deployment in Italy: Jobs, value added and import leakages. *Energy Policy*, *110*(August 2016), 234–245. https://doi.org/10.1016/j.enpol.2017.08.013

Connolly, K. (2020). The regional economic impacts of offshore wind energy developments in Scotland. *Renewable Energy*, *160*, 148–159. https://doi.org/10.1016/j.renene.2020.06.065

EUROSTAT. (2021). *PRODCOM - Statistics on the production of manufactured goods*. https://ec.europa.eu/eurostat/web/prodcom/data/database

Fontes, M., Bento, N., & Andersen, A. D. (2021). Unleashing the industrial transformative capacity of innovations. *Environmental Innovation and Societal Transitions*, *40*(November 2020), 207–221. https://doi.org/10.1016/j.eist.2021.07.004

Gala, P., Camargo, J., Magacho, G., & Rocha, I. (2018). Sophisticated jobs matter for economic complexity: An empirical analysis based on input-output matrices and employment data. *Structural Change and Economic Dynamics*, *45*, 1–8. https://doi.org/10.1016/j.strueco.2017.11.005

Gao, J., Jun, B., Pentland, A. 'Sandy', Zhou, T., & Hidalgo, C. A. (2021). Spillovers across industries and regions in China's regional economic diversification. *Regional Studies*, 1–

16. https://doi.org/10.1080/00343404.2021.1883191

Geels, F. W. (2002). Technological transitions as evolutionary reconfiguration processes: a multi-level perspective and a case-study. *Research Policy*, *31*(8–9), 1257–1274. https://doi.org/10.1016/S0048-7333(02)00062-8

Gouveia, J. P., Dias, L., Martins, I., & Seixas, J. (2014). Effects of renewables penetration on the security of Portuguese electricity supply. *Applied Energy*, *123*, 438–447. https://doi.org/10.1016/j.apenergy.2014.01.038

Graziano, M., Lecca, P., & Musso, M. (2017). Historic paths and future expectations: The macroeconomic impacts of the offshore wind technologies in the UK. *Energy Policy*, *108*(November 2016), 715–730. https://doi.org/10.1016/j.enpol.2017.06.042

Hanson, J. (2018). Established industries as foundations for emerging technological innovation systems: The case of solar photovoltaics in Norway. *Environmental Innovation and Societal Transitions*, *26*, 64–77. https://doi.org/10.1016/J.EIST.2017.06.001

Hausmann, R., Hidalgo, C., Bustos, S., Coscia, M., Chung, S., Jimenez, J., Simoes, A., & Yildirim, M. (2014). *Atlas of Economic Complexity_Part_I*. https://growthlab.cid.harvard.edu/files/growthlab/files/atlas_2013_part1.pdf

Hidalgo, C. A. (2021). Economic complexity theory and applications. *Nature Reviews Physics*, *3*(2), 92–113. https://doi.org/10.1038/s42254-020-00275-1

Hidalgo, C. A., Balland, P.-A., Boschma, R., Delgado, M., Feldman, M., Frenken, K., Glaeser, E., He, C., Kogler, D. F., Morrison, A., Neffke, F., Rigby, D., Stern, S., Zheng, S., & Zhu, S. (2018). The Principle of Relatedness. In A. J. Morales, C. Gershenson, D. Braha, A. A. Minai, & Y. Bar-Yam (Eds.), *ICCS: International Conference on Complex Systems Unifying Themes in Complex Systems IX* (Vol. 2, Issue July, pp. 451–457). Springer International Publishing. https://doi.org/10.1007/978-3-319-96661-8_46

Hidalgo, & Hausmann, R. (2009). The building blocks of economic complexity. *Proceedings of the National Academy of Sciences of the United States of America*, *106*(26), 10570–10575. https://doi.org/10.1073/pnas.0900943106

Hidalgo, Winger, B., Barabási, A. L., & Hausmann, R. (2007). The product space conditions the development of nations. *Science*, *317*(5837), 482–487. https://doi.org/10.1126/science.1144581

IEA. (2021). *Net Zero by 2050 A Roadmap for the*. 222.

INE. (2009). *Estatísticas da Produção Industrial 2008_EPI*.

INE. (2010). *Estatísticas da Produção Industrial 2009_EPI*.

INE. (2011). *Estatísticas da Produção Industrial EPI_2010_1*.

INE. (2012). *Estatísticas da Produção Industrial EPI_2011*.

INE. (2013). *Estatísticas da Produção Industrial EPI_2012*.

INE. (2014). *Estatísticas da Produção Industrial EPI_2013*.

INE. (2015). *Estatísticas da Produção Industrial EPI_2014*.

INE. (2016). *Estatísticas da Produção Industrial EPI_2015*.

INE. (2017). *Estatísticas da Produção Industrial EPI_2016*.

INE. (2018). *Estatísticas de Produção Industrial EPI_2017*.

INE. (2019). *Estatísticas de Produção Industrial EPI_2018*. https://www.ine.pt/ngt_server/attachfileu.jsp?look_parentBoui=408790016&att_display=n&att_download=y

INE. (2020). *Estatísticas de Produção Industrial Epi_2019*. https://www.ine.pt/ngt_server/attachfileu.jsp?look_parentBoui=467893432&att_display=n&att_download=y

IPCC. (2018). Summary for Policymakers. In: Global Warming of 1.5°C. In *Intergovernmental Panel on Climate Change (IPCC)*. https://doi.org/http://www.ipcc.ch/publications_and_data/ar4/wg2/en/spm.html

IRENA. (2019). *Global Energy Transformation: A Roadmap to 2050*. https://www.irena.org/publications/2019/Apr/Global-energy-transformation-A-roadmap-to-2050-2019Edition

IRENA. (2021). *IRENA Statistics time series - Query Tool*. [Banco de Dados].

Jenniches, S. (2018). Assessing the regional economic impacts of renewable energy sources - A literature review. *Renewable and Sustainable Energy Reviews*, *93*(May), 35–51. https://doi.org/10.1016/j.rser.2018.05.008

Kandrot, S., Cummins, V., Jordan, D., & Murphy, J. (2020). *Economic and employment impacts of offshore wind for Ireland: A value chain analysis*. https://doi.org/10.1080/15435075.2020.1791874

Köhler, J., Geels, F. W., Kern, F., Markard, J., Onsongo, E., Wieczorek, A., Alkemade, F., Avelino, F., Bergek, A., Boons, F., Fünfschilling, L., Hess, D., Holtz, G., Hyysalo, S., Jenkins, K., Kivimaa, P., Martiskainen, M., McMeekin, A., Mühlemeier, M. S., … Wells, P. (2019). An agenda for sustainability transitions research: State of the art and future directions. *Environmental Innovation and Societal Transitions*, *31*, 1–32. https://doi.org/10.1016/J.EIST.2019.01.004

Lee, I., Jang, S., Chung, Y., & Seo, H. (2021). Economic spillover from renewable energy industries: an input-output analysis. *International Journal of Green Energy*, 1–9. https://doi.org/10.1080/15435075.2021.1963258

Lund, P. D. (2009). Effects of energy policies on industry expansion in renewable energy. *Renewable Energy*, *34*(1), 53–64. https://doi.org/10.1016/j.renene.2008.03.018

Makešová, M., & Valentová, M. (2021). The concept of multiple impacts of renewable energy sources: A critical review. *Energies*, *14*(11). https://doi.org/10.3390/en14113183

Mäkitie, T., Andersen, A. D., Hanson, J., Normann, H. E., & Thune, T. M. (2018). Established sectors expediting clean technology industries? The Norwegian oil and gas sector’s influence on offshore wind power. *Journal of Cleaner Production*. https://doi.org/10.1016/j.jclepro.2017.12.209

Mamkhezri, J., Malczynski, L. A., & Chermak, J. M. (2021). Assessing the economic and environmental impacts of alternative renewable portfolio standards: Winners and losers. *Energies*, *14*(11). https://doi.org/10.3390/en14113319

Markard, J. (2018). The next phase of the energy transition and its implications for research and policy. *Nature Energy*, *3*, 628–633.

Markard, J., & Hoffmann, V. H. (2016). Analysis of complementarities: Framework and examples from the energy transition. *Technological Forecasting and Social Change*, *111*, 63–75. https://doi.org/10.1016/j.techfore.2016.06.008

Mealy, P., & Teytelboym, A. (2020). Economic complexity and the green economy. *Research Policy*, 103948. https://doi.org/10.1016/J.RESPOL.2020.103948

Mu, Y., Cai, W., Evans, S., Wang, C., & Roland-Holst, D. (2018). Employment impacts of renewable energy policies in China: A decomposition analysis based on a CGE modeling framework. *Applied Energy*, *210*(October 2017), 256–267. https://doi.org/10.1016/j.apenergy.2017.10.086

Oliveira, C., Coelho, D., Pereira Da Silva, P., & Antunes, C. H. (2013). How many jobs can the RES-E sectors generate in the Portuguese context? *Renewable and Sustainable Energy Reviews*, *21*, 444–455.

Pegels, A., & Lütkenhorst, W. (2014). Is Germany's energy transition a case of successful green industrial policy? Contrasting wind and solar PV. *Energy Policy*, *74*(C), 522–534. https://doi.org/10.1016/J.ENPOL.2014.06.031

Pinheiro, F. L., Alshamsi, A., Hartmann, D., Boschma, R., & Hidalgo, C. A. (2018). *Shooting High or Low: Do Countries Benefit from Entering Unrelated Activities?* http://arxiv.org/abs/1801.05352

Sandén, B. A., & Hillman, K. M. (2011). A framework for analysis of multi-mode interaction among technologies with examples from the history of alternative transport fuels in Sweden. *Research Policy*, *40*(3), 403–414. https://doi.org/10.1016/J.RESPOL.2010.12.005

Simoes, A. (2020). *ps_calcs*.

Stephan, A., Bening, C. R., Schmidt, T. S., Schwarz, M., & Hoffmann, V. H. (2019). The role of inter-sectoral knowledge spillovers in technological innovations: The case of lithium-ion batteries. *Technological Forecasting and Social Change*, *148*, 119718. https://doi.org/10.1016/j.techfore.2019.119718

Stephan, A., Schmidt, T. S., Bening, C. R., & Hoffmann, V. H. (2017). The sectoral configuration of technological innovation systems: Patterns of knowledge development and diffusion in the lithium-ion battery technology in Japan. *Research Policy*, *46*(4), 709–723. https://doi.org/10.1016/J.RESPOL.2017.01.009

Surana, K., Doblinger, C., Anadon, L. D., & Hultman, N. (2020). Effects of technology complexity on the emergence and evolution of wind industry manufacturing locations along global value chains. *Nature Energy*, *5*(10), 811–821. https://doi.org/10.1038/s41560-020-00685-6

The Growth Lab at Harvard University. (2019). *'International Trade Data (HS, 92)'*. https://doi.org/10.7910/DVN/T4CHWJ

Valentine, S. V. (2011). Emerging symbiosis: Renewable energy and energy security. *Renewable and Sustainable Energy Reviews*, *15*(9), 4572–4578. https://doi.org/10.1016/J.RSER.2011.07.095

van der Loos, A., Normann, H. E., Hanson, J., & Hekkert, M. P. (2021). The co-evolution of innovation systems and context: Offshore wind in Norway and the Netherlands. *Renewable and Sustainable Energy Reviews*, *138*, 110513. https://doi.org/10.1016/J.RSER.2020.110513

Vona, F. (2019). Job losses and political acceptability of climate policies: why the ‘job-killing’ argument is so persistent and how to overturn it. *Climate Policy*. https://doi.org/10.1080/14693062.2018.1532871

Wei, M., Patadia, S., & Kammen, D. M. (2010). Putting renewables and energy efficiency to work: How many jobs can the clean energy industry generate in the US? *Energy Policy*, *38*(2), 919–931. https://doi.org/10.1016/J.ENPOL.2009.10.044

Wind, I. (2010). HS Codes and the Renewable Energy Sector. In *ICTSD Programme on Trade and Environment* (Vol. 01). https://www.ictsd.org/downloads/2010/01/hs-codes-and-the-renewable-energy-sector.pdf