1 INTRODUCTION

In order to meet their energy needs, different countries demand diverse types and quantities of energy sources. Each country uses a different variety and proportions of energy sources, characterizing a dynamic energy mix. Researchers and policy-makers look at the energy mix to deal with energy issues and climate change. The energy mix is crucial to determine important aspects of energy economics, such as energy efficiency, energy intensity[1], energy security, and carbon intensity of a country, thus, also impacting climate change policies.

Alterations in the composition of the energy mix in the long run define the concept of energy transition(s). Grübler (2004: 163) proposes a definition of energy transitions "in terms of three interdependent characteristics: quantities (growth in amounts of energy harnessed and used), structure (which types of energy forms are harnessed, processed, and delivered to the final consumers, as well as where these activities take place), and quality (the energetic and environmental characteristics of the various energy forms used)". Moreover, energy transition processes "can be understood as a succession of both, intended disruptive changes and incremental adaptation processes, along a specific change path" (Binder et al., 2017: 1).

The shape and pace of future transitions have been addressed looking at transitions in the past (Fouquet and Pearson, 2012; Rubio and Folchi, 2012; Bennett, 2012; Pearson and Foxon, 2012; Allen, 2012; Steinmueller, 2013; Rosenbloom and Meadowcroft, 2014; Fouquet, 2016; Napp et al., 2017). Currently, we are in the process of a new energy transition (i.e., to a low carbon energy

[1] Gales et al. (2007) already showed that "the transition from traditional energy carriers to modern ones therefore implied a decrease of energy intensity in any country". In general, the transition towards higher quality energy carriers (which have superior capacity to do useful work) imply an improvement in energy intensity. For instance, while the Chinese economy grew nearly 7% in 2017, its energy consumption increased just by 3.5%, while its emissions increased by just 1.7% (or 150 Mt) thanks to continued renewables deployment and faster coal-to-gas switching (IEA, 2018). As a consequence, the energy intensity of China declined.

system), fostered by the social demand for change in the energy paradigm. Contrary to energy transitions in the past, which essentially responded to techno-economic forces, the unfolding one also includes ecological motivations. This new path will entail a substantial change in energy mixes all over the world.

Even though transformations of the energy structure determine energy transitions, the diversification of energy mixes per se has not been studied from a long-term comparative perspective, making use of concentration indicators. We know that technological innovations have allowed societies to use new energy sources. As a result, the availability of varied energy sources has increased, that is, there are more diverse energy options in recent times, than there have been ever before. This does not necessarily means that all countries have followed the same diversification path or have chosen the same options, but, there exists a general notion about the energy mixes becoming more diversified in recent times. This tends to ignore the different traditional forms of energy that were available in the past (draft power, wind, water, and firewood), which allowed a variety of energy mixes with large diversification of sources in past centuries. The interaction between the transformations in energy mixes and successive energy transitions also requires further investigation.

The energy ladder hypothesis states that as incomes rise the shares of higher quality energy carriers increase. Higher quality energy implies carriers that are more productive, cleaner, and more flexible (Cleveland et al., 2008; Stern, 2010). Burke (2013) carried out a detailed quantitative analysis of the energy mix-income relationship. Based on an econometric analysis of 134 countries for the period 1960–2010, he shows that economic development results in an overall substitution from the use of biomass to fossil fuels, and then increasingly to primary electricity.

The energy ladder hypothesis seems to imply a one-way path toward increasing energy mix diversification over time, as countries become richer. That is partly so, given that the lower quality energy sources tend to remain in the energy basket even if only with a minority share. Yet, it remains unclear whether the energy ladder is a theoretical myth or an empirical truth (van der Kroon et al., 2013). As a matter of fact, countries have had disparate experiences depending, among other things, on their energy endowment (this entails different comparative advantages and costs of the energy sources in each country), and the amount of energy consumed, in other words, it depends on the national energy supply and demand.

We only have anecdotal evidence regarding when (or whether or not) the energy mixes become more diversified, (when that happened) whether it was an irreversible process or not, whether all countries followed similar paths or not, whether the levels of diversification of the energy mixes have converged over time or not, or about whether diversification of the energy mixes took place at the same time everywhere, or not.

A small body of evidence (Marcotullio and Schulz, 2007; Rubio and Folchi, 2012) suggests that countries consuming large amounts of energy have behaved differently from small energy consumers in the process of altering their energy mixes, that is, in their energy transitions. Rubio and Folchi (2012), using Latin American data, have showed that small energy consumers had earlier and faster transitions than larger energy consuming countries did. Henriques and Sharp (2015) found a quick transition from firewood to coal in Denmark, a small energy consuming country, too. Following this reasoning, the article starts from the hypothesis that large and small energy consumers' baskets tend to change differently, which, in turn, will imply that the degree of concentration of the energy mixes evolved with different patterns over time, depending on the scale of energy consumption.

In addition to addressing these issues, the approach of our research to the evolution of the diversification of energy mix over the long term may be also useful for shedding some light on other crucial questions, such as whether it was easier to alter the energy mix in the past or in recent times. In other words, how quickly can an energy mix be altered? Is there a different speed, depending on the level of development or the size of the country? But, before answering all these questions with our empirical analysis, we should wonder, would a country always prefer energy mix diversification to concentration? What are the benefits and costs of diversification?

The importance of a varied energy mix is that diversification is one of the drivers of energy security. On the contrary, energy mix concentration is used as an indicator of energy vulnerability (the higher the concentration, the greater the vulnerability).[2] Energy diversity lies in "an evenly balanced reliance on a variety of mutually disparate options" (Stirling, 2010: 1622). The logic behind promoting diversity is that "it is better to be exposed to several risks with limited consequences than to one risk where the probability of failure is weak, but that failure has unbearable consequences for the economies" (Llerena and Llerena, 1993: 230). However, energy diversification – in its various facets – does not prevent energy risks from occurring, but reduces the social and economic impact in case of risk contingencies and provides alternatives to respond to a potential interruption in the energy supply (IEA, 1985: 90), or to a sudden increase in energy prices (conditioned to fuel substitutability).[3]

The preceding explanation justifies recommendations to increase energy diversification (of primary energy sources, suppliers and transport routes[4]) for countries, among other strategies, in order to enhance their energy security. Some examples include those from Churchill, such as "Safety and certainty in oil lie in variety and variety alone" (Yergin, 2006), to international and

[2] For a detailed explanation of energy vulnerability, see Escribano (2008).

[3] Supply continuity and affordable prices matter in the short term. However, decisions related to the energy we consume and a diversification strategy require a long-term perspective. Those decisions will determine the energy transitions in the long run.

[4] These are the most common aspects of energy diversity, but, additionally, some other diversity parameters affect the energy security policies, that is, technologies, infrastructures, industrial interests, regulatory issues, manufacturers, and workforces (Stirling, 2010).

European institutions such as the IEA (1993) and the European Commission (2001: 2; and many subsequent documents).

However, we should bear in mind that if the energy mix concentration is based on a domestically produced source(s), concentration would not entail a high risk. In that case, an energy security strategy based on diversification of the energy sources could be useless or even counterproductive if, after the process, we depend more on foreign energy resources. Furthermore, the more our supply relies in non-renewable energies, the more critical the concentration of the energy mix is, as a matter of resource depletion.

Yet diversification is also a tool for environmental purposes, and “policies which minimize energy consumption and encourage diversity represent the best long-term sustainability strategy” (Templet, 1999: 232). Decarbonization will require altering the current energy mix. Most of the literature directly link decarbonization with diversification of the energy system. In fact, some works point at the potential of energy mix diversification “as an instrument of emissions mitigation” (de Freitas and Kaneko, 2011: 1466). Therefore, it is not unexpected that the EU 2020 climate and energy package, as well as the Paris Agreement (among others), focus on diversifying the energy mixes toward others with a greater proportion of clean energies. However, the assumptions behind such connexion are hardly ever made explicit. In brief, the following assumptions are required to link decarbonization with diversification:

1. A pre-existing energy system already in place mostly comprised of fossil fuels.
2. Multiple higher-quality energy sources will enter the system (following the energy ladder hypothesis lower-carbon or carbon-free), displacing fossil fuels’ pre-eminence.
3. Typically, fuels do not substitute each other but tend to be added to the mix over time. For an energy transition to occur, the old energy carrier may remain relatively stable (in absolute terms) while the new technology expands faster,

4. As a consequence of the above, this tend to be a slow process

If all the assumptions hold, decarbonization will be a direct result of the increased diversification of the energy systems within a relatively long-time frame. Yet, we align more with the idea that steps of the ladder may be skipped in individual countries (Rubio and Folchi, 2012; Marcotullio and Schulz, 2007)-as Portugal and Sweden make evident in this paper- thus making possible faster transitions and different diversification paths.

Moreover there are other potential gains of diversification in terms of competition, innovation (this is a key question while dealing with energy transitions)[5], adapting to different local conditions (cultural, ecological, geopolitical, geophysical, etc.), and of reconciling conflicting socioeconomic interests (Stirling, 2010). On the other hand, diversity may involve costs and trade-offs, such as performance penalty of marginal options, transaction costs, coherence, accountability, standardization, and economies of scale (Stirling, 2010), as well as political, social and environmental costs.

In sum, when we deal with energy diversity, we are dealing with vulnerability (energy security), sustainability, as well as many other features related to energy systems. A diversification strategy might not be the best solution in a static economic analysis (i.e., in terms of costs and economic efficiency), but it is, in general, the best option in a dynamic environment. The optimal level of diversification will depend on the features of each country's energy system (but we will not address this question in this paper).

All this makes it particularly insightful to analyze the diversification paths of the energy mixes of different countries in the long term. In order to answer the questions and verify the

5 Grubb et al. (2006) explore the relationship between the transition to a low carbon energy system (supported by the deployment of renewable technologies) and the diversity and security of the electricity system in the United Kingdom. For a more detailed explanation of transitions to sustainable energy and source diversity, see Stirling (2008) and Mitchell (2010, chapter 3).

hypothesis posed above, we propose a synthetic indicator that allows one to compare and contrast the evolution of the composition of the primary energy baskets of eight European countries over the last two centuries, and quantitatively analyze the degree of concentration (versus diversity) of their energy mixes throughout the period.

The rest of the paper is organized as follows: the next section explains the data sources and the methodology used based on concentration measures. The subsequent section focuses on the Energy Mix Concentration Index analysis and the results obtained. The article ends with a few concluding remarks.

2 MATERIAL AND METHODS

Some of the longest and more consistent series of primary energy consumption belong to eight European countries, and cover the period from 1800 to 2010, for most of them[6]. The historical database was developed over the past fifteen years by a number of energy researchers, for Sweden (Kander, 2002), Spain (Rubio, 2005), Italy (Malanima, 2006), United Kingdom (Fouquet, 2014), Netherlands (Gales et al., 2007), and Portugal (Henriques, 2011). The results have been synthesized and the list of countries has been expanded to include Germany and France in Kander et al. (2014).[7] This makes the database internally coherent, using the same methodologies across countries and energy sources.

The energy data for these eight countries consider the full set of energies, both, traditional and modern, and refers to primary energy supply. The database includes food for men and working

[6] For Italy, Portugal and Spain, from mid-19th century.

[7] There exist an alternative set of data for England and Wales by Warde (2007). We have run our empirical analyses with both, Warde (2007) and Fouquet (2014), datasets. The results are comparable but only those corresponding to Fouquet's data are shown in the paper.

animals, firewood, traditional wind and water used in wheels and mills, and peat, recognized as traditional (also called "organic") energy sources. Modern energy sources refer to the commercial resources developed after the industrial revolution, namely, mineral coal, petroleum, natural gas, and the primary forms of generating electricity, such as hydroelectricity, nuclear energy, and renewable energies (wind power, solar, geothermal, etc.).

Widening the scope beyond commercial energy sources has proven to make important differences in interpreting long-term trends on most aspects of the relationships among the economy, the environment, and energy consumption (Kander, 2005; Gales et al., 2007; Bartoletto and Rubio, 2008; Bertoni et al., 2009). Given the importance of traditional energy sources up to well into the 20th century, any attempt to measure the degree of concentration of the energy mix in the long run without including them will be flawed. Moreover, considering traditional energies is the only way to take into account the first energy transition, from organic-based energy sources to coal.

These eight European countries can be grouped into two categories according to their sizes and their economic and energy use histories. Four of these countries were large energy consumers, and happened to be *early comers*, both by energy standards – with coal as their dominant energy resource throughout the 19th century – and by their economic histories as advanced nations in the industrial processes. These four countries are the United Kingdom, France, Germany, and the Netherlands. The other four countries, situated at the European periphery, used to be small energy consumers and are often referred to as *latecomers*, both energetically – with firewood dominating their energy baskets until the 20th century – and economically. These four countries are Italy, Portugal, Spain, and Sweden.

These assertions about the early comers and the latecomers, are well documented both in the economic history literature (Gerschenkron, 1962; Kuznets, 1966; Sylla and Toniollo, 1992), and the energy history literature (Gales et al., 2007; Kander et al., 2014). Table 1 presents the summary statistics of energy consumption for early comers versus latecomers.

Table 1: Energy consumption of early comers and latecomers (total, per capita)

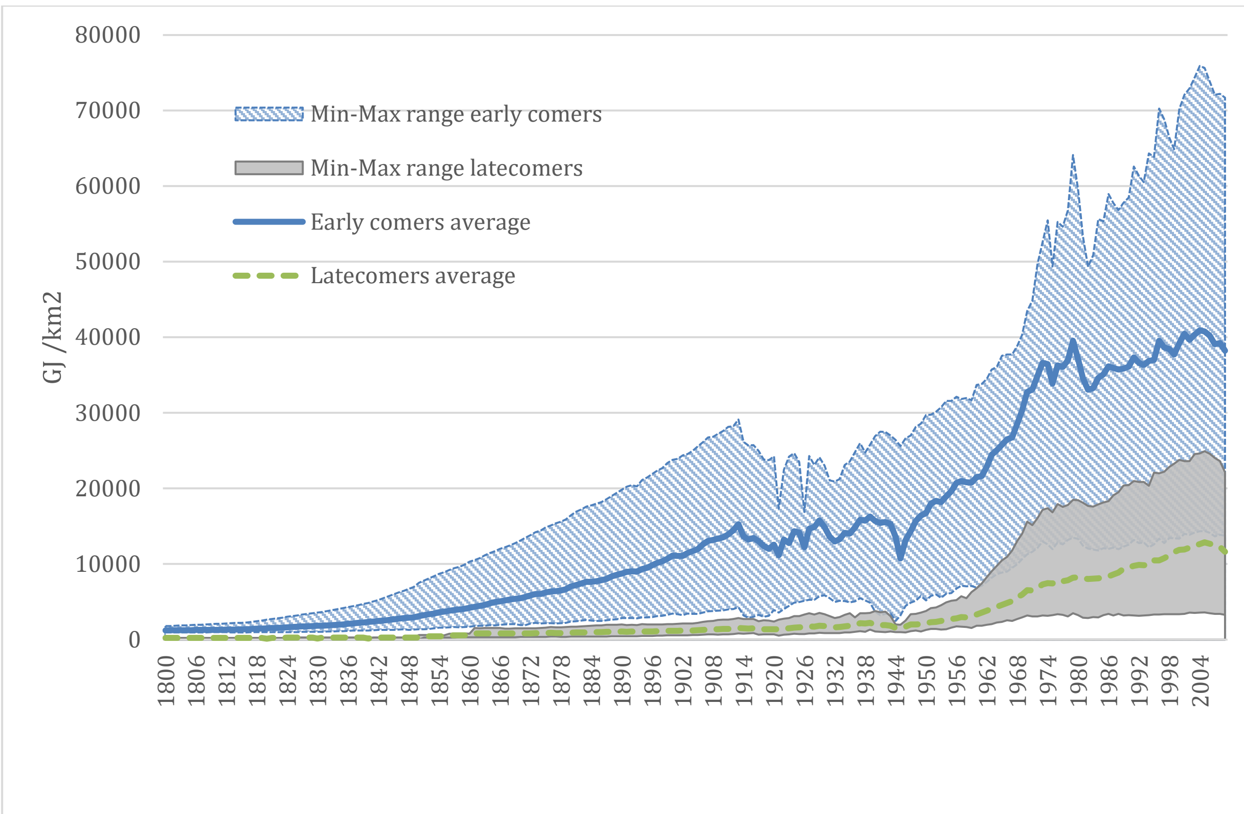
	Total energy consumption (PJ)		**Per capita energy consupmtion (MJ/hab)**	
	Early comers	*Latecomers*	*Early comers*	*Latecomers*
1870-1913	2511,9	324,8	68,2	26,1
1920-1938	3705,7	509,2	85,1	33,2
1950-1973	5953,2	1303,9	119,7	62,1
1973-2010	7952,8	3041,1	153,9	112,5
1800-2010	3429,7	1068,1	79,9	52,5

Sources and notes: unweighted average of energy consumption. Data from Kander et al. (2014) except for the United Kingdom, which belongs to Fouquet (2014), include pre-modern and modern energy sources (i.e., food for men and working animals, firewood, traditional wind and water used in wheels and mills, peat, mineral coal, petroleum, natural gas, and the primary forms of generating electricity such hydroelectricity, nuclear energy, and renewable energies such as wind power, solar, geothermal, etc.).

Are these differences statistically different? Using an unpaired two-sample t-test with unequal variation (Snedecor and Cochran, 1989) we can determine that for the entire period from 1800 to 2010, there is a statistically significant difference between the mean of the total energy consumption for early comers (M=3429.7 PJ, sd= 3593.2) and latecomers (M=1068.2PJ, sd= 1582.9); t(1209.34)=17.9, p>0.0001. The same is true for the means of the energy consumption per capita, which is significantly higher for early comers (M= 79.9 MJ/hab, sd=52.5) than for latecomers (M=52.4 MJ/hab, sd 43.1); t(1491.66)=11, p<0.0001. In both cases, we have sufficient evidence to reject the null hypothesis that the means are the same, and accept the alternative hypothesis that the latecomers had smaller means than the early comers did.

We also need to point out that the crucial difference relies in the amount of energy injected to the territory. This is so because in the pre-modern times, energy was very much restricted to the amount of land capable to feed humans, animals and provide firewood. An organic based economy faces numerous limits to its expansion, as argued by Wrigley (2004: 31). Comparing the amount of energy per square kilometre it becomes obvious that the early comers escaped the organic limitations imposed to energy consumption far earlier than the latecomers did, as shown in Figure 1.

Figure 1: Energy consumption of early comers and latecomers per km²



Sources and notes: unweighted average of energy consumption per km^2; min-max range represents the range between the maximum and the minimum energy consumption per km^2 among the countries in each group. Data from Kander et al. (2014) except for the United Kingdom, which belongs to Fouquet (2014), include pre-modern and modern energy sources (i.e., food for men and working animals, firewood, traditional wind and water used in wheels and mills, peat, mineral coal, petroleum, natural gas, and the primary forms of generating electricity such hydroelectricity, nuclear energy, and renewable energies such as wind power, solar, geothermal, etc.). Present day borders, surface data from CIA Factbook.

In order to test our initial hypothesis and answer the questions posed in the introduction, some sort of a quantitative index of concentration of the energy mix is needed.[8] Some of the most advanced research activity on diversity and concentration has taken place in the area of ecology. Nevertheless, contributions also come from other disciplines in the field of natural and social sciences, such as financial management and energy economics.

According to the research work of Stirling (1998: 39-40; 2010: 1625-26), diversity entails three properties, namely variety, balance and disparity. In the analysis of the energy mix, variety corresponds to the number of different options – energy carriers – in a system, balance concerns the share of each source in the energy mix, and disparity is related to the different nature and characteristics of each energy source.

According to this author, the three properties are necessary and independently partial (Stirling, 1998) since they are all "holistic system-level properties" (Stirling, 2010: 1622). However, most of the analysis omits one or two of them. In general, the analyses of diversity in the energy mix tend to focus on balance and variety, since disparity is a qualitative and context-dependent facet of diversity.

We stick to the dual concept indicators that consider balance and variety features. The reason for dismissing disparity in our analysis is that the characteristics and the performance of energy sources change over time as energy technologies and societies evolve. As a consequence, the distance between a pair of options (this is how Stirling measures energy disparity) varies as the performance of those options change. In a dynamic long term analysis, like the one we conduct, it is impracticable to include disparity. Furthermore, in the very same moment, various countries – with their particular energy systems – will face different energy characteristics depending on their

[8] A classification including concentration and other types of energy indicators is provided in García-Verdugo and Muñoz (2012).

technical, economic, and social features (level of technological innovation, resource quality and depletion, operational integration, etc.). Nevertheless, we agree that it would be neglectful to omit disparity dimension while dealing with future energy strategies and planning. In that case, it would be necessary to take into account all factors, dimensions, properties, and agents involved.

In the field of energy economics, as well as in ecology, the most common dual concept concentration indicators are based on the Herfindahl-Hirschman Index (in ecology, the Simpson Index) and the Shannon-Wiener Index.[9]

The Herfindahl-Hirschman Index (HHI)[10] commonly applies to market concentration analysis. It is measured by the sum of the squares of the market shares of each energy source in any given period, which corresponds to the formula:

$$HHI_t = \sum_i^t p_i^2 \ [1]$$

where p_i is the share of the energy source i in the energy mix. Smaller values of the HHI indicate greater diversification, with 0 being the minimum concentration and 1 being the maximum concentration (in case the shares are expressed as fractions, where the aggregation of all the portions sum one i.e., 10% would be considered as 0.1)[11].

[9] A review of the "dual concept" (as well as the "mono concept") indexes of non-parametric measures of ecological diversity can be found in Stirling (1998).

[10] The paternity of this index is shared by economists Orris C. Herfindahl and Albert O. Hirschman. In 1945, Hirschman (in *National Power and the Structure of Foreign Trade*. University of California Press,) proposed an index of trade concentration consisting of the square root of the sum of the squares of the market share of each country in the market. For his part, in 1950, Herfindahl (in his doctoral dissertation, *Concentration in the steel industry*, Columbia University) proposed an index for measuring the firms' concentration in the steel industry, which was computed in the same way as the Hirschman index, but without the square root that is, the sum of squares of firm sizes, all measured as percentages of total industry size. In Hirschman (1964) he claimed the authorship of the index.

[11] Sometimes, the shares are expressed as percentages –i.e. 10% would be considered as 10–. In this case, the maximum concentration would be 10,000.

The Shannon-Wiener Index (SWI), or just Shannon Index[12], is also known as a measure of entropy. It is expressed as the market share multiplied by the natural logarithm (originally normal log, not Napierian) of the market share for each fuel in the market summed together.

$$SWI_t = -\sum_i^t p_i \ \ln(p_i \ ) \ [2]$$

where ρ_i represents the proportion of the total mix supplied by fuel i. The minimum value that the SWI can produce is zero, which occurs when only one fuel is consumed. This would be the case of maximum concentration in the energy mix. High values imply high diversity, but SWI has no upper limit (since new options would increase the potential values of the SWI).

This last characteristic is the main reason why we decided to use the HHI instead of the SWI. The potential range of the SWI values increases with the number of market sources (or participants), which "undermines the usefulness of the index for comparison across markets or countries" (Le Coq and Paltseva, 2009: 4475). As the United Kingdom Department of Trade and Industry (DTI, 2005: 6) and the Department for Business Enterprise and Regulatory Reform (BERR, 2008: 30) remark, the SWI "can be used to see how diversity of a particular market is changing over time. It should not be used to compare different markets with each other." This is an important technical consideration for a cross-country study like the one we perform.

Moreover, HHI puts relatively more weight on the influence of larger sources (or partner supplies), while the SWI places a greater emphasis on smaller source (or partner supplies).[13] Since we deal with energy transitions, we focus on the major energy sources in the energy systems.

[12] C. E Shannon developed his mathematical formulation in 1948, in "A mathematical theory of communication", *The Bell System Technical Journal* 27 (3): 379–423 & 27 (4): 623–656 (available at: https://www.bell-labs.com/our-research/bell-labs-journals/seminal-works/). Later, in 1964, the SWI was presented in Shannon, C.E. and Weaver, W. "The mathematical theory of communication", *The University of Illinois Press*, Urbana.

[13] For a detailed comparison and discussion of advantages and disadvantages of both indicators, see Stirling (1998) page 50 and following.

Consequently, we find the HHI to be more appropriate. In any case, when simultaneously both indicators are applied to the same variables, the results of both measures are consistent and present similarities (van Hove, 1993; Grubb et al., 2006; Kruyt et al., 2009).

Finally, in the field of energy security and energy economics, the HHI is more widespread. Indeed, the IEA (2007: 54) states that "HHI is a well-established measure of market concentration commonly used by governments". Some examples are Neff (1997), EIA (1999), Sen (2003), Blyth and Lefevre (2004), Liston-Hayes and Pilkington (2004), Fischer (2005), IEA (2007), Gupta (2008), Doane et al. (2008), Jun et al. (2009), Le Coq and Paltseva (2009), US Department of Justice and the Federal Trade Commission (2010), US FERC (2013, and preceding and following orders and analysis), Muñoz et al. (2015), Mason (2015), Chernenko (2015), Genc (2016), Lanz and Rausch (2016), Gupta (2016), CNMC (2017).

Accordingly, in this paper, the concentration of the energy mix in a given year has been calculated using the HHI, and we named it Energy Mix Concentration Index (EMCI). For each country, we built a matrix containing the share of each energy source in the total energy consumption of every year from 1800 to 2010, for the selected countries. For our calculations the energy carriers are aggregated at the upper level possible following the classification originally made in Kander et al. (2014): food, fodder, firewood (biomass), direct water/wind/sun (prime movers or heaters), coal, oil, natural gas and primary electricity (from hydro, geothermal generators, wind power, photovoltaic and nuclear power).

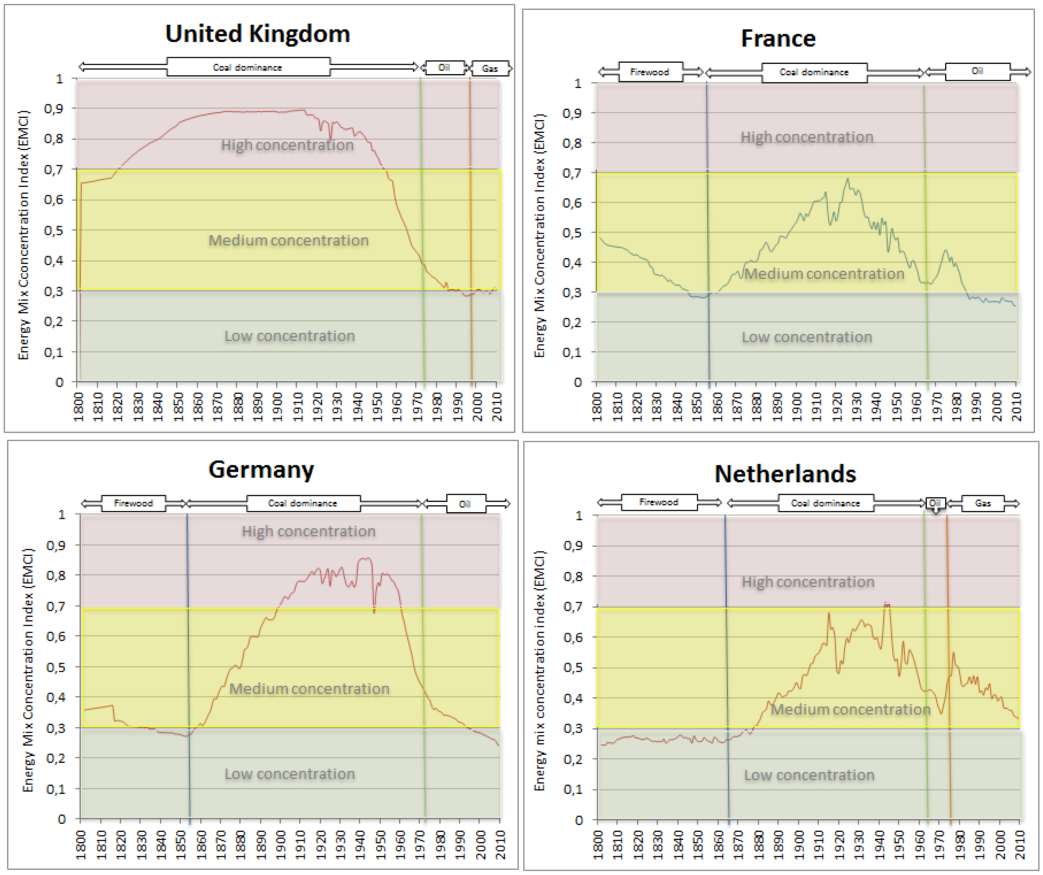
3 RESULTS AND DISCUSSION

Applying the HHI to the composition of the energy mix, we obtain the yearly EMCI over the last 200 years for these eight European countries[14]. The respective EMCI are plotted in Figure 2 for United Kingdom, France, Germany, and the Netherlands, and in Figure 3 for Italy, Portugal, Spain, and Sweden. The smaller (larger) the EMCI is, the more diversified (concentrated) the energy mix turns out to be.

The vertical lines in each country graph mark the year in which the previous prevalent primary energy source gives way to the next dominant source, which we identify as well. The figures also include an intuitive classification between low, medium, and high concentration according to the theoretical distribution of the EMCI, with the lower third of the index been classified as low concentration of the energy mix (i.e., high diversification) and the values falling on the upper third corresponding to high concentration of the energy mix (i.e., low diversification).

Figure 2: EMCI, dominant fuel, and year of transition for four European early comers, from 1800 to 2010

[14] For methodological details and the calculation process step by step, see the companion paper in MethodsX.



Sources and notes: data from Kander et al. (2014) except for the United Kingdom, which belongs to Fouquet (2014), include pre-modern and modern energy sources (i.e., food for men and working animals, firewood, traditional wind and water used in wheels and mills, peat, mineral coal, petroleum, natural gas, and the primary forms of generating electricity such hydroelectricity, nuclear energy, and renewable energies such as wind power, solar, geothermal, etc.). EMCI measured by a HHI. The smaller (larger) the EMCI is, the more diversified (concentrated) the energy mix. The vertical lines mark the year in which the previous prevalent energy source gives way to the next dominant source.

The countries in Figure 2 exhibit some common features for the early comers, which turn out to be some of the largest energy consumers in Europe. They made an early transition from firewood to mineral coal, linked to their economic transformation from an agricultural economy to an industrial one. In fact, according to these data, the United Kingdom entered the 19th century with coal already as the prevalent energy source. France, Germany, and the Netherlands entered the coal era by mid-19th century. These four early comers remained under coal dominance for over a century.

For all of them, the transition from firewood to coal implied an increasingly concentrated energy mix, as coal took larger shares of their energy basket in order to feed their growing energy requirements. This is particularly marked in the United Kingdom and Germany, the leading countries in the continent during the First and Second Industrial Revolutions, respectively.

From a theoretical point of view, we should infer United Kingdom and Germany faced a quite high-risk exposure for long time due to their high coal concentration. However, since their coal consumption was mainly based on a domestic supply, they did not really sustain such a high risk, nor compromised their economic development. Thus, the United Kingdom and Germany cases demonstrate it is possible and compatible an increasing economic growth with a highly concentrated energy mix in the long run. The key to this compatibility is the resource endowment. It is not the aim of this paper but, this reveals in order to carry out an energy security analysis, we should include the dimension of energy dependence as well. This topic deserves future research.

The four countries also share the dates and effects on diversification of the transition from coal to oil. Petroleum became the prevalent energy source for all of them between the mid-1960s and early 1970s, right before the oil crisis. The entrance and eventual prominence of oil in their energy baskets implied greater diversification of their energy mixes in general terms. For sure, other sources participated in the diversification of the energy mix over the second half of the 20^{th} century, most notably hydroelectricity, nuclear, and natural gas, but the battle between coal and oil as principal energy sources prevailed.

The shifts in energy consumption patterns and the dominance of one or another fuel are highly conditioned to the countries' energy endowments. It explains the noteworthy concentration of the energy mix of the United Kingdom and Germany, based on coal. In fact, the United Kingdom and Germany have been the two major coal producers in the European continent until 1970[15] (excluding the USSR and the Russian Federation, which became the greater producers in Eurasia from the second half of the 20th century onward).

The first oil crisis brought about some differences among the early comers' energy mixes. While the United Kingdom and Germany continued to diversify their energy mixes, France and the Netherlands had a short phase of increasing concentration before exhibiting further diversification that extends to the 21st century. These transitions were driven by revolutionary economic and technological changes, but most of the European countries do not have significant reserves of oil (of the selected countries only the United Kingdom does have a relevant role as an oil producer from the late seventies onward).

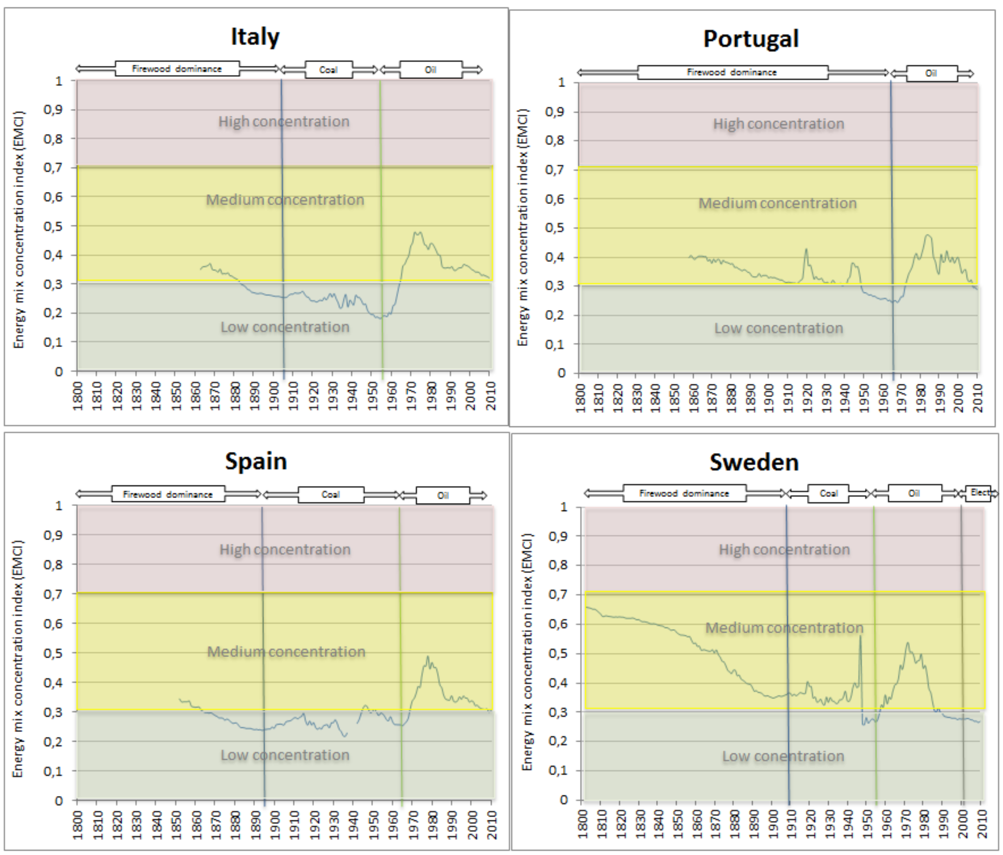
A further difference is that in two cases, namely, the United Kingdom, and most notably, the Netherlands, endured a further transition where natural gas replaced oil as the prevalent energy source. In fact, the transition to natural gas was relatively fast. In the Netherlands natural gas supplied 50% of the total primary energy by 1971, a little bit more than a decade after the discovery of the giant Groningen field in 1959, becoming the major gas producer in the continent until the mid-nineties (again excluding the USSR and Russian Federation). For its part, the United Kingdom has been at the top of the gas production in Europe (together with Norway and the Netherlands) from the mid-seventies until now.

The latecomer group of European peripheral countries in Figure 3 shares some features of their own. They arrived some 50 years later than the early comer group to the coal era, but by the beginning of the 20th century, peripheral Europe had made its transition to coal. An exception must be made for Portugal, the poorest country of the lot, which took much longer to abandon firewood

[15] Then, Germany kept the leading position for two more decades, but Poland reached the second position as the most prominent coal producer in 1971, and then rose to the first one in the nineties.

as the predominant fuel and leapfrogged straight into oil by the mid-sixties. Coal never dominated the Portuguese energy basket. For the rest of peripheral Europe, coal reigned over the first half of the 20th century, but around the mid-1950s (Portugal by mid-1960s) oil became the major energy source.

Figure 3: EMCI, dominant fuel, and year of transition for four European latecomers, from the 1850s to 2010



Sources and notes: As in Figure 2.

The transition from firewood to coal implied a larger diversification of their energy baskets, that is, a smaller EMCI, while the oil supremacy that began around 1960 conveyed an increasing concentration of their energy mixes, reaching maximum EMCI levels in between the oil crises of 1973 and 1979. In any case, none of these countries reaches high concentration indices along the full period. On the contrary, they show medium and low concentration of their energy baskets, and particularly low in the Mediterranean countries until the sixties, and now again at the down of the 21st century.

The events of the 1970s made evident the need for reducing their concentration away from oil, and the four countries pursued energy mix diversification strategies, particularly fast in the case of Sweden. The oil shocks opened a period of convergence between early comers and latecomers toward similar levels of diversification at the end of the century. However, in the particular case of industrial sector, Safarzynska (2017) concludes that, as countries grow, they increase both fuel and industrial diversity, but the unique production capacity that the countries develop drives divergence in fuel diversity between countries.

Besides the obvious classification criteria, the latecomers' transit to modern energy sources happened some half a century later than early comer's transition. The differences in the evolution of both groups are striking. Latecomers endured much shorter coal dominance (some 50 years versus over a century of the early comers). Latecomers also shifted earlier to oil as their predominant energy source, with the exception of Portugal, over a decade earlier, probably due to their scant coal resources.

On the other hand, none of the latecomers initiated the transition to the natural gas age yet, although Italy already consumed more natural gas than oil in 2012 and 2016 (according to Eurostat database), what points to a new energy transition in the country. For its part, Sweden leapfrogged the gas era, initiating the transition from oil to primary forms of generating electricity at the beginning of the 21st century (from 2001 to 2008, nuclear energy headed the Swedish energy mix and, from 2009 up to now, renewable energies do it).

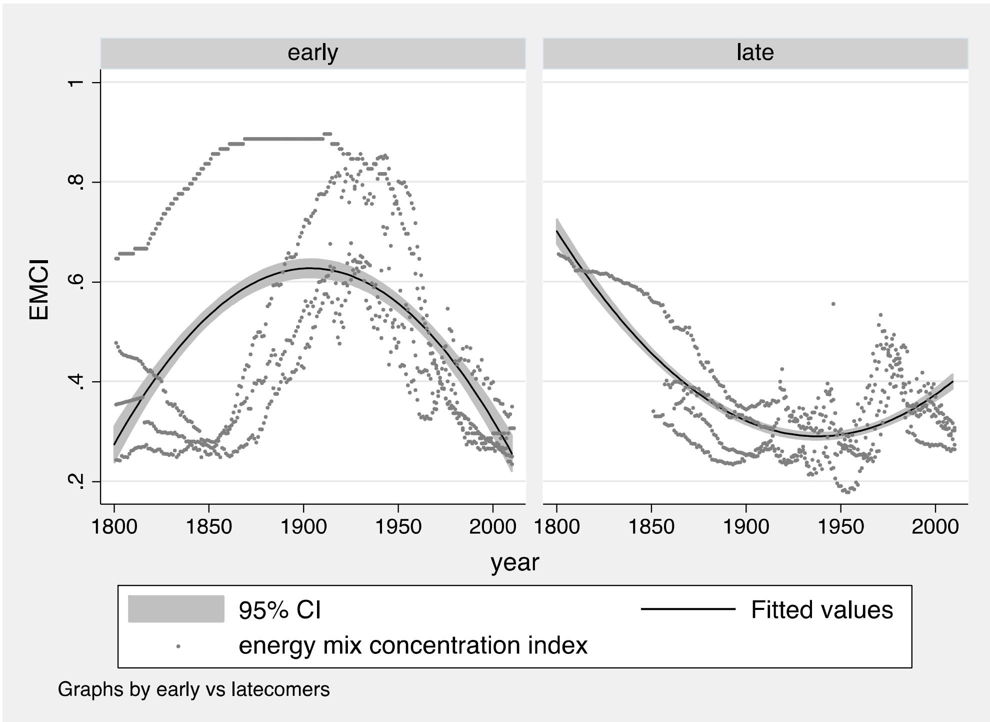
The experience of Portugal and Sweden, skipping some conventional energy eras, is compatible with the fact that developed countries increase their energy diversity by adopting close fuels to those in the mix, while poor countries adopt less connected fuels (Safarzynska, 2017: 38). Nevertheless, most energy transitions “have been, and will likely continue to be, path dependent rather than revolutionary, cumulative rather than fully substitutive” (Sovacool, 2016: 212).

The successive introduction of new energy sources had different impacts on the concentration of the energy mixes of early comers and latecomers. While coal adoption contributed to increasing the energy mix concentration of the large energy consumers (United Kingdom, Germany, France, and the Netherlands) during the 19th century and the early years of the 20th century, the diffusion of coal did imply a larger diversification of the energy basket of the smaller consumers (Italy, Portugal, Spain, and Sweden).

The arrival of oil predominance over the 1950s and 1960s also implied opposite results for the diversification of the energy mixes. Oil predominance had the effect of increasing concentration of the energy baskets of the small consumers, but reduced the level of concentration of the energy baskets of the large energy consumers. Toward the end of the 20th century, however, when the levels of energy consumption per capita leveled out, the concentration index of both groups also equalized in the frontier between low and medium concentration of the energy mix.

Furthermore, these results show very different diversification paths of the energy baskets of European early comers versus latecomers. The early comers achieved the maximum level of concentration during their coal era somewhere in the first half of the 20th century. The latecomers reached the maximum concentration of their energy baskets in the early days of the oil dominance, right about the oil crisis of 1973. These two maximums are not only distant in time and predominant fuel, but also differ in their magnitude. Early comers’ maximum level of energy mix concentration almost doubles the maximum level ever achieved by latecomers. In other words, early comers endured much more concentrated energy baskets than latecomers would ever endure, following a distinct path over time (see Figure 4).

Figure 4: EMCI of European early comers vs latecomers from 1800 to 2010



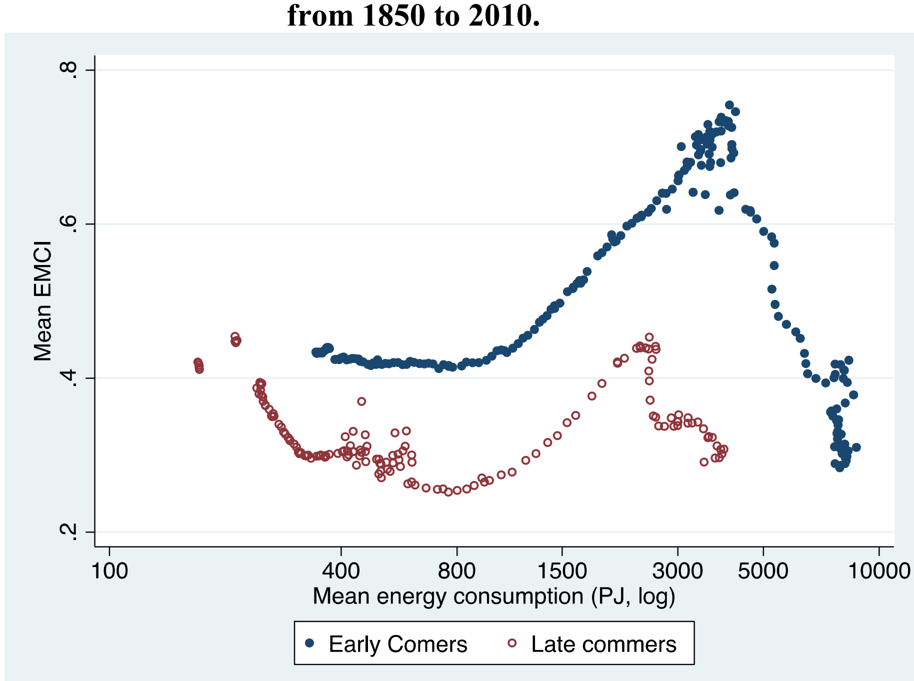
Sources and notes: As in Figure 2. Early comers refer to the United Kingdom, Germany, France, and the Netherlands. Latecomers refer to Italy, Portugal, Spain, and Sweden. Fitted values on a quadratic regression on time.

Energy mix studies, such as van Hove's (1993), Templet (1999) and Safarzynska (2017), are usually based on the last 60 years' experience (post-1950), where the story is one of a continuous and intense diversification effort by the early comers, and a modest diversification by the latecomers, only apparent after 1970. In fact, latecomers end the period with a smaller diversity than early comers do. Yet, the long-term perspective tells quite a different story: the early comers followed an inverted-U path of increasing concentration for over a century, followed by an intense diversification of their energy mixes, achieving by 2010 their most diversified energy basket of the past 200 years, except for the Netherlands. This is not the case for the latecomers, which became more diversified over time but toward the end of the 20th century increased the concentration of their energy mixes (mostly on oil), keeping moderated levels of concentration.

We suspect that there are at least two effects at play in this distinct behavior of early comers and latecomers. One that has to do with the different timing in development, let us call it the "time effect", and another that has to do with the different levels of energy consumption demanded by the countries, a "size effect".

On the one hand, consuming large amounts of energy in the 19th century required a huge concentration of the energy basket since the only modern technology available was coal-based. This is consistent with a strong positive correlation between (total and per capita) energy consumption and EMCI in the 19th century for early comers (0.9, on average, excluding France, that has a weak positive correlation). For its part, smaller consumers could get by with a variety of pre-modern sources to add to a modest consumption of coal. This is also confirmed by a very strong negative correlation between total energy consumption and concentration levels in that century among latecomers (-0.92, on average).

Figure 5. Mean EMCI vs average energy consumption of early comers vs latecomers from 1850 to 2010.



Sources and notes: As in Figure 2. Early comers refer to the United Kingdom, Germany, France, and the Netherlands. Latecomers refer to Italy, Portugal, Spain, and Sweden. Fitted values on a quadratic regression on time.

On the other hand, when the latecomers required larger amounts of energy by the mid-20th century, the array of available energy technologies had widened considerably, and they were already at their lowest concentration levels. In turn, this implied that when latecomers eventually reached the levels of energy consumption that the early comers had achieved some decades earlier, the latecomers did it with a far more diversified energy mix (see Figure 5) despite they had to do it at the expense of a temporary increase in the concentration of their energy mixes but still at lower level than the one endured by the early comers for the same level of energy consumption. Meanwhile, in the 20th century, early comers changed the trend of increasing energy demand based on high concentrated energy mixes for a much more diversified structures (a correlation coefficient of 0.86 for the group corroborates this shift).

4 CONCLUSIONS

We find that the countries analyzed had converged to similar levels of diversification in their energy mixes only from the second half of the 20th century onward, and more crucially, after the oil crises of the 1970s, that is, only for the last quarter of the period under consideration. However, the path toward today's level of diversification of the energy mix diverged from 1800 until the second half of the 20th century.

Early comers followed an inverted-U path of growing concentration (based on mineral coal) for over a century, and later started their diversification processes during the second part of their coal dominance periods. Meanwhile latecomers, –which tended to also be smaller energy consumers, enjoyed historically lower levels of concentration in their energy mixes, and followed a U-path, reaching their maximum levels right about the oil crisis of 1973 (during their oil dominance).

Moreover, early comers' maximum level of energy mix concentration almost doubles the maximum level ever achieved by latecomers. Thus, the process of reducing the energy mix concentration has been far more intense among the early comers. In fact, they end the period with a higher diversity than latecomers do. For some countries, all the early comers but the Netherlands and Sweden, today's degree of diversification is the largest in their energy histories, but it is not the case for the rest of them.

We also find that the alteration of the energy mix took far more time in the 19th century for the early comers, producing a longer coal dominance era (about one century) than the energy baskets of the latecomers (versus half a century). The successive introduction of new energy sources had different impacts on the concentration of the energy baskets of early comers and latecomers. When latecomers eventually achieved the levels of energy consumption of the early comers, they did so with a more diversified energy mix. We explain this as a combined "time effect" and "size effect".

In our sample, energy transitions always occur at mid-to-low concentration levels. Yet, the diversification path followed after a transition takes place differently in the two groups. For instance, the transitions of United Kingdom and Germany from coal to oil preceded a reduction of the concentration of their energy mixes in the following years/decades. While for the latecomers, the path was towards higher concentration once oil took the lead. Nevertheless, in both groups energy transitions always took place at times when their energy mixes were facing mid-to-low concentration levels (EMCI<0.4).

The evidence we present here points to a different behavior of large and small energy consumers, that is, developed and underdeveloped countries, in their energy transitions. Therefore, we verify our initial hypothesis: that size matters at the time of altering the level of concentration of the energy mix. It was more difficult for large consumers than for small consumers to achieve diversification.

This has to do with the strong inertia of some energy systems that have well-established infrastructure on both, the supply and demand sides, and powerful political support due to the tremendous wealth associated with the sale of those fuels. It was the case of coal in the 19th century, or oil and nuclear energy in the 20th centuries. Energy related capital (from energy generating and distributing to energy consuming capital) tend to be long-term investments with long amortization periods. The more vested capital related to energy the larger the energy consumption. Small energy consumers enjoy the advantage conferred by minimum pre-existing investment and the opportunity of leapfrogging in the energy ladder (as shown by the Portuguese and Swedish cases above).

Regarding the ecological impact of the energy transitions and the diversification paths, the good news is that, after carrying out their diversification processes initially relying mostly on fossil fuels, the countries analyzed are reducing their dependence on polluting and non-renewable energy sources (such as coal and oil). The current trend points to a more diverse energy mix with a growing role of cleaner and renewable energies, therefore in a path towards a lower-carbon energy system. But we would like to remember that markets will not follow this path by themselves, governments must lead this process.

The worries about the future of carbon emissions, given the path that developing countries had to follow to achieve the levels of already developed countries, are based in two premises. First, that developing countries (by definition latecomers to modern economies) would require similar amounts of energy to attain similar levels of GDP to those of advanced nations today (the early comers). Second, that developing countries would transit the path of dirtier energies first, so that even if they can obtain similar levels of GDP at lower energy consumption, they will still pollute more.

Our results offer some comfort, because even if developing countries would require as much energy as developed countries did at their time, our results in Figure 5 above point at the fact that the energy sources they use would be from a wider variety (and this is the current general trend). Thus they will pollute less -both in relative and in absolute terms- for the same amount of energy consumed. A more diverse energy mix is positive for carbon emissions at this moment (since the new options come from less contaminant sources). This reasoning is supported by a strong positive correlation between EMCI and carbon emissions in Sweden, Germany, United Kingdom and France from 1970 to 2009 (0.87 correlation coefficient, on average), meaning that the reduction in their concentration levels is clearly associated to a decrease in their CO_2 emissions Though more research would be required to link the true relation between diversification and decarbonisation.

Has diversification been the only trend in the past? We demonstrated it has not been the path for all the countries studied, on the contrary, just for half of them. Would diversification be the definitive trend in the future? Is it desirable above all things? Imagine if we could get hold of a Nikola Tesla's type of ubiquitous, unlimited, and free energy presence in the ether around us. Then, it would make sense to switch to it immediately, giving up lower quality, limited, and more expensive energies, and concentrate as much as possible on this new free, renewable, safe, and clean energy. In fact, the predictions by Creutzing et al. (2017) hint at the potential for high concentrations in photovoltaicin a foreseeable low-carbon energy future.

In such a scenario, and in general, in any other energy transition, our results suggest that small energy consuming countries will be able to make faster transitions than large energy consumers will. All in all, economic and energy transformations are speeding up, and it is presumable that the next energy transitions will be much faster in all cases (e.g., the shift from the oil dominance era to natural gas in the Netherlands and the United Kingdom), and not necessarily linear (such as Portugal and Sweden).

ACKNOWLEDGMENTS

This research was supported by the National Program of R+D+i Projects of the Spanish Ministry of Economy and Competitiveness (Refs.: HAR2014-53825 and HAR2017-86086R). The authors would like to express their gratitude to Roger Fouquet and the researchers who provided valuable comments to our paper at the Energy Economics Iberian Conference (2016), the 41st International Association for Energy Economics International Conference (2018), and the XVIII World Economic History Congress (2018). The comments and suggestions made by two anonymous referees also contributed to improving the final version. All remaining errors or omissions are however our full responsibility.

REFERENCES

Allen, R.C. (2012). “Backward into the future: The shift to coal and implications for the next energy transition”. Energy Policy 50: 17–23.

Bartoletto, S., Rubio, M.d.M. (2008). “Energy transition and CO_2 emissions in Southern Europe: Italy and Spain (1861–2000)”. Global Environment 2, 4681.

Bennett, S.J. (2012). “Using past transitions to inform scenarios for the future of renewable raw materials in the UK”. Energy Policy 50: 95–108.

BERR (2008). *UK Energy Sector Indicators 2008. Department for Business Enterprise and Regulatory Reform (BERR).* URN 08/193.

Bertoni, R., Román, C., Rubio, M.d.M. (2009). “El desarrollo energético de España y Uruguay en perspectiva comparada: 1860–2000”. Revista de Historia Industrial 41 (3): 161–194.

Binder, C.R., Mühlemeier, S., Wyss, R. (2017). “An Indicator-Based Approach for Analyzing the Resilience of Transitions for Energy Regions. Part I: Theoretical and Conceptual Considerations”. Energies 10(36): 1-18.

Blyth, W., Lefevre, N. (2004). Energy security and climate change policy interactions, an assessment framework*. IEA Information paper.* pp. 89. Paris, December 2004.

Burke, P. J. (2013). “The National-Level Energy Ladder and Its Carbon Implications.” *Environment and Development Economics* 18(4): 484-503.

Chernenko, N. (2015). “Market power issues in the reformed Russian electricity supply industry”. Energy Economics 50: 315–323.

Cleveland, C. (Lead Author); D. Budikova (Topic Editor). (2008). ‘Energy quality’. In: *Encyclopedia of Earth*. Eds. Cutler J. Cleveland (Washington, D.C.: Environmental Information Coalition, National Council for Science and the Environment). [First published in the Encyclopedia of Earth February 22, 2007; Last revised November 18, 2008; Retrieved September 18, 2009]. <http://www.eoearth.org/article/Energy_quality>

CNMC (2017). *Informe de supervisión del mercado minorista de electricidad año 2016*. National Commission on Markets and Competition (CNMC in Spanish), IS/DE/041/17, pp. 79.

Creutzig, F., Agoston, P., Goldschmidt, J.C., Luderer, G., Nemet, G. and Pietzcker, R.C., (2017) ‘ The underestimated potential of solar energy to mitigate climate change’ *Nature 2, Nº 17140*

De Freitas, L.C. and Kaneko, S. (2011). “Decomposing the decoupling of CO_2 emissions and economic growth in Brazil”, Ecological Economics 70: 1459–1469

Doane, M.J., McAfee, R.P., Nayyar, A., Williams M.A. (2008). “Interpreting concentration indices in the secondary market for natural gas transportation: The implication of pipeline residual rights”. Energy Economics 30: 807–817.

DTI (2005). *UK energy sector indicators. A supplement to the second annual report on the energy white paper: Our energy future – creating a low carbon economy. UK Department of Trade and Industry*. No URN 05/193, pp. 121.

EIA (1999). *Natural Gas 1998 - Issues and Trends*. DOE/EIA-0560(98). U.S. Energy Information Administration, Office of Oil and Gas, U.S. Department of Energy, Washington.

Escribano, G. (2008). “Entre el mercado y la geopolítica: seguridad de abastecimiento y corredores energéticos en la UE”. Información Comercial Española. Revista de Economía (842), mayo-junio.

European Commission (2001). *Green paper: Towards a European strategy for the security of energy supply, adopted by the European Commission on 29 November 2000*. COM(2000) 769 final, pp. 105. Luxembourg. Office for Official Publications of the European Communities.

Fischer, C. (2005). “On the importance of the supply side in demand-side management”. Energy Economics 27: 165–180.

Fouquet, R. (2014), "Long run demand for energy services: income and price elasticities over 200 years.' Review of Environmental Economics and Policy 8(2) 186-207.

Fouquet, R. (2016). "Historical energy transitions: Speed, prices and system transformation". Energy Research & Social Science, 22: 7–12.

Fouquet, R., Pearson, P.J.G. (2012). "Past and prospective energy transitions: Insights from history". Energy Policy 50: 1–7.

Gales, B., Kander, A., Malanima, P., Rubio, M.d.M. (2007). "North versus South: energy transition and energy intensity in Europe over 200 years". European Review of Economic History 11 (2): 219–253.

Gerschenkron, A. (1962). *Economic Backwardness in Historical Perspective. A Book of Essays.* Cambridge: Harvard University Press.

García-Verdugo, J., Muñoz, B. (2012). Energy dependence, vulnerability and the geopolitical context. A quantitative approach to energy security. In Marin Quemada et al. (Eds.), Energy Security for the EU in the 21st Century: Markets, Geopolitics and Corridors. Routledge, Oxon & New York, 37–53.

Genc, T.S. (2016). "Measuring demand responses to wholesale electricity prices using market power indices". Energy Economics 56: 247–260

Grubb, M., Butler, L., Twomey, P. (2006). "Diversity and security in UK electricity generation: The influence of low-carbon objectives". Energy Policy 34: 4050–4062.

Grübler, A. (2004). Transitions in energy use. Encyclopedia of Energy 6, 163–177. Elsevier.

Gupta, E. (2008). "Oil vulnerability index of oil-importing countries". Energy Policy 36: 1195–1211.

Hirschman, A. O. (1964). "The Paternity of an Index". The American Economic Review, 54 (5): 761.

Henriques, S.T. (2011). Energy transitions, economic growth and structural change: Portugal in a Long-Run Comparative Perspective. Thesis, published in Lund Studies in Economic History, 54. Lund University. Lund.

Henriques, S.T., Sharp, P. (2015). "The Danish agricultural revolution in an energy perspective: a case of development with few domestic energy sources". Economic History Review (early view online: DOI: 10.1111/ehr.12236).

IEA (1985). *Energy technology policy.* International Energy Agency, pp. 123. Organisation for Economic Co-operation and Development, Paris.

IEA (1993). *Shared goals, adopted by IEA Ministers at their 4 June 1993 meeting in Paris.* International Energy Agency, Organisation for Economic Cooperation and Development.

IEA (2007). *Energy security and climate policy: Assessing interactions*. International Energy Agency, pp. 145. Organisation for Economic Co-operation and Development, Paris.

Jun, E., Kim, W., Chang, S.H. (2009). "The analysis of security cost for different energy sources". Applied Energy 86 (10): 1894–1901. Elsevier Ltd.

Kander, A. (2002). Economic Growth, Energy Consumption and CO_2 Emissions in Sweden 1800-2000. Thesis, published in Lund Studies in Economic History, 19. Lund University. Lund.

Kander, A. (2005). "Baumol's disease and dematerialization of the economy". Ecological Economics 55 (1): 119–130. http://dx.doi.org/10.1016/j.ecolecon.2004.10.008.

Kander, A., Malanima, P., Warde, P. (2014). Power to the People: Energy in Europe over the Last Five Centuries. Pricenton University Press.

Kuznets, S. (1966) , *Modern Economic Growth: Rate, Structure and Spread*, New Haven: Yale University Press.

Kruyt, B., van Vuuren, D. P., De Vries, H. J. M., Groenenberg, H. (2009). Indicators for energy security. Energy Policy 37, 2166–2181.

Lanz, B., Rausch, S. (2016). "Emissions Trading in the Presence of Price-Regulated Polluting Firms: How Costly Are Free Allowances?". Energy Journal 37 (1): 195-232.

Le Coq, C., Paltseva, E. (2009). "Measuring the security of external energy supply in the European Union". Energy

Policy 37: 4474–4481.

Liston-Hayes, C., Pilkington, A. (2004). “Inventive Concentration: An Analysis of Fuel Cell Patents”. Science and Public Policy 31 (1): 15–25.

Llerena, D., Llerena, P. (1993). “Diversity and Valorization of the Electricity-generation Technologies in the European Community”. Utilities Policy, July: 223–232. Butterworth-Heinemann Ltd.

Malanima, P. (2006). Energy consumption in Italy in the 19th and 20th centuries: a statistical outline. Consiglio nazionale Delle Ricerche. Istituto Di Studi Sulle Societa del Mediterraneo, Naples.

Marchetti C. (1977). “Primary Energy Substitution Models: On the Interaction between Energy and Society”. Technological Forecasting and Social Change 10: 345–356.

Marcotullio, P. J., Schulz, N. B. (2007). “Comparison of energy transitions in the United States and developing and industrializing economies”. World Development 35 (10): 1650–1683.

Mason, C.F. (2015). “Concentration Trends in the Gulf of Mexico Oil and Gas Industry”. Energy Journal 36 (Adelman Special Issue): 215-236.

Mitchell, C. (2010). The Political Economy of Sustainable Energy. Palgrave, London. ISBN 978–0–230–24172–5.

Muñoz, B., García-Verdugo, J., San-Martín, E. (2015). “Quantifying the geopolitical dimension of energy risks: A tool for energy modelling and planning”. Energy 82: 479–500.

Napp, T., Bernie, D., Thomas, R., Lowe, J., Hawkes, A., Gambhir, A. (2017). “Exploring the Feasibility of Low-Carbon Scenarios Using Historical Energy Transitions Analysis”. Energies 10(1), 116; doi:10.3390/en10010116.

Neff, T.L. (1997). *Improving Energy Security in Pacific Asia: Diversification and risk reduction for fossil and nuclear fuels. PARES project*, Center for international studies, Massachusetts Institute of Technology, Cambridge USA.

Pearson, P.J.G., Foxon, T.J. (2012). “A low carbon industrial revolution? Insights and challenges from past technological and economic transformations”. Energy Policy 50: 117–127.

Rosenbloom, D., Meadowcroft, J. (2014). “The journey towards decarbonization: Exploring socio-technical transitions in the electricity sector in the province of Ontario (1885-2013) and potential low-carbon pathways”. Energy Policy 65: 670–679.

Rubio, M.d.M. (2005). “Energía, economía y CO_2: España 1850–2000”. Cuadernos Económicos de ICE 2 (70): 51–71.

Rubio, M.d.M., Folchi, M. (2012). “Will small energy consumers be faster in transition? Evidence from the early shift from coal to oil in Latin America”. Energy Policy 50: 50–61.

Safarzynska, K. (2017). “The Implications of Industrial Development for Diversification of Fuels”, Ecological Economics 137: 37–46.

Sen, A. (2003). “Higher prices at Canadian gas pumps: international crude oil prices or local market concentration? An empirical investigation”. Energy Economics 25: 269–288

Snedecor, George W. and Cochran, William G. (1989), *Statistical Methods*, Eighth Edition, Iowa State University Press.

Sovacool, B.K. (2016), “How long will it take? Conceptualizing the temporal dynamics of energy transitions”, Energy Research & Social Science 13: 202–215.

Steinmueller, W.E. (2013). “The pre-industrial energy crisis and resource scarcity as a source of transition”. Research Policy 42 (10): 1739–1748.

Stern, D. I. (2010). “Energy Quality.” *Ecological Economics* 69(7): 1471-1478.

Stirling, A. (1998). “On the economics and analysis of diversity”. Science and Technology Policy Research (SPRU), Electronic Working Papers Series 28, October.

Stirling, A. (2008). Diversity and sustainable energy transitions: multicriteria diversity analysis of electricity portfolios.

In Bazilian, M., Roques, F. (Eds.), Analytical Methods for Energy Diversity and Security. Elsevier, Oxford, 3–29.

Stirling, A. (2010). "Multicriteria diversity analysis: A novel heuristic framework for appraising energy portfolios". Energy Policy 38: 1622–1634.

Sylla, R. and Toniolo, G (1991) Patterns of European Industrialization.The nineteenth century, Francis &Taylor: London

Templet, P. H. (1999). "Energy, diversity and development in economic systems; an empirical analysis". Ecological Economics 30: 223–233.

US Department of Justice and the Federal Trade Commission (2010). *Horizontal Merger Guidelines*. Issued: August 19, 2010, pp.34.

US FERC (2013). *Revised Market Power Analysis*. United States of America Federal Energy Regulatory Commission, 145 FERC 61.079, pp. 5.

Van der Kroon, B., Brouwer, R., van Beukering, P.J.H. (2013). "The energy ladder: Theoretical myth or empirical truth? Results from a meta-analysis". Renewable and Sustainable Energy Reviews 20: 504–513, April.

Van Hove, L. (1993). "Diversification of primary energy consumption in six West European countries. Quantification and analysis by means of measures of concentration", Energy Economics 15 (4): 239–244.

Warde, P. (2007). Energy Consumption in England and Wales 1560-2000. Consiglio Nazionale della Ricerche, Naples. ISBN 978-88-8080-082-8.

Wrigley, E.A., 2004. *Poverty, Progress and Population*. Cambridge University Press, Cambridge.

Yergin, D. (2006). "Ensuring energy security". Foreign Affairs 85 (2): 69–82, March/April.