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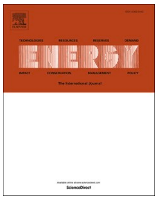

Interaction between renewable energy consumption and dematerialization: Insights based on the material footprint and the Environmental Kuznets Curve

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ABSTRACT

This paper investigates the effect of renewable energy consumption on material consumption, considering the relationship between Material Footrprint and Gross Domestic Product (GDP), and testing the assumptions of the Environmental Kuznets Curve. A STIRPAT variation is used to specify a model relating the Material Footprint to renewable energy consumption and GDP. The effect is tested for the Material Footprint of fossil fuels and for the Material Footprint of the other categories. The analysis is applied to the seven European countries with the highest proportion of renewable energy consumption.

The model estimation shows that the relationship between GDP and Material Footprint follows an inverted N-shaped form, and that the renewable energy favours the reduction of the material consumption of fossil fuels. However, there is a positive effect between the renewable energy consumption and the Material Footprint of the other categories beyond fossil fuels.

These results must be interpreted considering the context, as the development of renewable energy coincides with the effects of the 2008 crisis, which may distort the relation between the variables. To pose dematerialization scenarios, it seems necessary to consider reducing energy consumption even if it comes from renewable sources.

1. Introduction

The replacement of fossil energy sources is one of the main challenges today. The main reason is their high impact on the environment. However, it should not be forgotten that their availability is becoming increasingly limited [1]. This year marks the 50th anniversary of the report "The Limits to Growth" [2], which warned about the problems related to the limited stock of resources. At the same time, the war in Ukraine is creating supply problems that have led to major tensions in the energy sector. In this context, the focus on the availability of energy resources is gaining interest and opens the door to analyses combining energy and material consumption. Although energy generation is a very important source of material resource consumption, it is not common for both issues to be analysed together. However, there are important commonalities between energy transition and dematerialization objectives [3]. On the other hand, much research investigates the interaction between economic development and/or growth and environmental impact, finding evidence of both a negative and positive relation between these variables [4–13]. However, one issue on which there is some consensus is that technological improvements lead to a reduction in environmental impact [13–18].

In the field of energy, technological progress can be measured in many ways and manifest itself as improvements in the efficient use of existing resources or as the substitution of these by more sustainable technologies. Thus, renewable energy plays a very important role, as it is a technological change that makes it possible to replace fossil energy sources, especially in electricity generation.

Following the line of different research studies that analyse the effect of renewable energies on environmental impact [7,14,15,17,18], but not specifically through material consumption indicators, this article aims to analyse the effect of renewable energy on material consumption. The development of renewable energy sources leads to new needs for materials, so the transition to renewable energy sources may hinder dematerialization processes [19–21]. Material consumption provides

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both an insight into the pressure on an economy's natural resource stock and an approximation of its environmental impact [22,23]. In addition, because technological progress is often linked to economic growth [16, 24], the study of the interaction between these variables is incorporated into the analysis. For this purpose, the Gross Domestic Product (GDP) in constant 2015 dollars, obtained from the World Bank database, is used. As an indicator of material consumption, the Material Footprint is used, a measure obtained through the Material Flow Analysis methodology that indicates the consumption of resources required by a given economy to satisfy its domestic demand, regardless of where it is actually produced [23,25–31]. In this way, not only the effect on the internal environmental impact is analysed, but also the environmental impact related to the country as a whole, making it possible to eliminate the effect generated by the relocation of production activities [12,23,30, 32]. The Material Footprint data is obtained from the Global Material Flows Database [33]. To determine the effect of renewable energy, the consumption of primary energy from renewable sources is used. It is considered more appropriate to use primary energy consumption than other possible measures such as installed capacity, which might have a less direct effect on material consumption. So, renewable energy is defined as solar, wind, geothermal and biofuels, excluding hydropower. It is excluded because this energy source tends to have a high degree of environmental impact and consumption of material resources. Data are taken from BP Statistical Review of World Energy 2021.

The analysis is carried out on a set of seven countries that represent the countries with the highest percentage of primary energy consumption from fossil fuels in total primary energy consumption: Denmark, Germany, Finland, Portugal, Spain, Sweden and United Kingdom. These countries have a high level of development and are therefore suitable for studying hypotheses about the relationship between GDP and material consumption. The period of analysis is from 1990 to 2018. It is not considered appropriate to start the analysis further back in time because renewable energies have experienced most of their development and deployment in the last two decades.

The research is structured in a first part of descriptive analysis of the data, which provides context and allows for the identification of important trends. This is followed by an analysis of the decoupling through the individual coefficient of renewable energy consumption and GDP. Finally, a model is proposed to jointly analyse the effect of renewable energy and GDP on material consumption, or to analyse whether GDP and material consumption maintain a non-monotonic relationship, following the theories of the Environmental Kuznets Curve, which are developed in the methodology. This model and the methodology that supports it are described in depth in the methodological section.

The main contribution of this work is the analysis of the effect of renewable energy on the Material Footprint, combining the field of energy with the field of material consumption. In addition, the study of the relationship between GDP and the Material Footprint in the set of countries with a higher proportion of renewable energy consumption is also of great interest.

2. Methodology and literature review

This section describes the methodological itinerary followed from the methods used to specify the model proposal applied, being the material flow analysis used to obtain the Material Footprint, the IPAT and STIRPAT as the basis of the specified model, to obtain the ecological elasticity and to contrast the hypotheses of the Environmental Kuznets Curve.

2.1. Material Footprint and dematerialization

The methodology of Material Flow Analysis (MFA) is used to obtain the indicators of material consumption. The MFA is based on the theory of socio-economic metabolism to estimate the accounting of material flows [22,23,25,26,31,34]. The basic material flow is Domestic Extraction (DE) which represents all materials extracted from nature that enter the economy in some form [23,27,30].

To obtain an indicator of physical consumption, the Physical Trade Balance (PTB), which is the difference between physical imports and physical exports, must be added to the DE [23,27]. These physical trade flows can be considered from different perspectives. The most widespread is the territorial or production perspective, which simply considers the final weight of the materials that make up imports and exports [12,27,32]. However, using the consumption approach, trade flows also include all materials used in the production process of traded goods, whether or not they are part of the traded goods and regardless of where they are consumed [23,27–29]. The PTB obtained through the consumption method is called the Raw Trade Balance (RTB). The RTB is very useful, as it allows measuring the material consumption that the analysed country displaces to the rest of the world (when its result is positive) or that it receives (when it is negative) [35–37].

This approach provides an indicator of material consumption called the Material Footprint, which indicates the material consumption associated with the final demand of the territory under analysis, even if it is not actually produced there [12,23,29,32]. It is important to note that material consumption is not exactly an indicator of environmental impact. While resource consumption inevitably leads to an environmental impact, this is not directly expressed by indicators such as the Material Footprint [38]. Rather, material consumption indicators provide an approximation of the pressure exerted on natural resources by societies.

To determine more precisely the effect of renewable energy consumption on the Material Footprint, the Fossil Fuels Material Footprint (FFMF) is used, which captures the material consumption of fossil fuels, both directly and indirectly. This means that the consumption of fossil fuels made elsewhere in the world to produce the imports of the analysed country, for example, is included. Using the Material Footprint of fossil fuels avoids distortions caused by other material categories where energy consumption has little effect. At the same time, it is considered interesting to estimate the model for Material Footprint by discounting the FFMF, as the development and deployment of renewable energy related technologies also requires a certain material consumption. The Material Footprint resulting from discounting the FFMF is called Discounted Material Footprint (DMF).

To explain the concept of dematerialization, it is important to first introduce the concept of decoupling. It refers to the situation in which one series grows at a faster rate than another and decouples from it. It is a widely used measure to contextualise the evolution of material consumption in relation to economic growth. Thus, depending on how both growth series evolve, three situations can be described [39–42]: when material consumption increases, but to a lesser extent than GDP, there is relative or weak decoupling; when material consumption decreases and GDP increases or stays the same, there is absolute or strong decoupling. The situation of absolute decoupling is also known as dematerialization, because it implies that the amount of materials consumed by a territory is reduced without it being due to a recessionary period [43].

2.2. IPAT, STIRPAT and ecological elasticity

The IPAT model is one of the first mathematical formulae specifically designed to assess the impact of human societies on the environment. This model is based on the work of Ehrlich and Holdren (1971; 1974) and [44]; who made the first formulations of the IPAT and subsequently came up with the equation specified as the product of three components [45]: population (P), affluence or wealth per capita (A) and technology (T), giving rise to the expression:

$$I = P \times A \times T \tag{1}$$

The strengths of this formulation are its explanatory power and its simplicity, making it easily generalisable [45–47]. However, it is limited because it assumes proportionality between the component factors and, in addition, the known factors determine the unknown factors, so it does not allow testing of hypotheses [45,47]. These limitations are solved by converting the IPAT to a stochastic model, the STIRPAT, whose specification is as follows:

$$I_i = aP^i_b A^i_e T^i_d e_i \tag{2}$$

The coefficient *a* represents the ordinate at the origin, *b, c* and *d* are the coefficients that must be estimated to know the effect of P, A and T on I and *e* is the error term. The subscript *i* indicates that I, P, A, T and e vary between observations [45,48]. An additive model in logarithmic form can be used to facilitate coefficient estimation and hypothesis testing:

$$\log I = a + b(\log P) + c(\log A) + d(\log T) + e \tag{3}$$

The model approached in this way allows to decompose the effect of each individual factor, so that other factors that are considered relevant can also be included [13]. In order to facilitate the specification of the model, it is common to shift the information collected in T to the error term, due to the difficulty of adequately defining the content and scope of this variable [45,48]. This leads to a simpler model (4).

$$\log I = a + b(\log P) + c(\log A) + e \tag{4}$$

The model used in this research to estimate the effect of renewable energy and GDP on FFMF and DMF is based on the STIRPAT model in equation (3). The consumption of primary energy from renewable sources is a good proxy for technological developments in the field of renewable energy, so it incorporates the T variable. All other technology-related effects are retained as part of the error term. The growth in the consumption of energy from renewable sources is expected to displace fossil fuels in the energy mix and to facilitate a reduction in the consumption of these resources. At the same time, the generation of energy from renewable sources also requires the consumption of certain materials, so the effect of these on the DMF is analysed [19–21]. The combination of both analyses provides an approximation of the relationship between renewable energy and dematerialization.

Regarding the GDP, despite its limitations in terms of representing living conditions and even certain aspects of economic developments [49–51], is the most widely used variable in studies on the evolution of environmental impact. Countless research studies have found that GDP is one of the main drivers of environmental impact in general and of material consumption in particular, in one sense or another [4,16,29,45–48,52–54]. It is also the most widely used variable in studies on dematerialization, as it provides context to the evolution of material consumption[1] [10,40,43,55].

While, in pre-industrial societies, population is the most influential factor on environmental impact or resource consumption, the development of industry causes the growth of economic activity to become the main driver of environmental impact [47,52,56,57]. In more developed territories, the effect of population in terms of its composition is more significant, so that the use of total population as an indicator may have more disadvantages than advantages in the model [58,59,81,82]. For this reason, in this work it has been decided to eliminate the population from the set of independent variables.

The model coefficients indicate the proportional change on the environmental impact generated by a variation in one of the components, which is called the ecological elasticity of the dependent variable on the environmental impact [45,55]. Ecological elasticity allows us to quantify the strength of the relationship between the explanatory variable and the explained variable [55]. There is a widely used classification that allows the relationship between variables to be ranked according to the value obtained, providing an indicator of the degree of decoupling between the environmental impact and the variable analysed [40–42,58], listed in Table 1.

Table 1
Interpretation of the value of Ecological Elasticity.

EE value	Interpretation	
0 < EE < 1	Relative or weak decoupling.	ΔT > ΔI > 0
EE < 1	Absolute or strong decoupling or dematerialization.	ΔT > ΔI (ΔI < 0)
EE > 1	Coupling or rematerialisation.	ΔI > ΔT (ΔT > 0)

Source: own elaboration from (Song et al., 2020 [42,60].

2.3. Environmental Kuznets curve and model specification

The STIRPAT specification defined in equations (3) and (4) assumes that the variables are linearly related, but this need not be the case necessarily [61]. were the first to explore a non-linear relationship between economic development and environmental impact. Subsequently [16], studied this issue and proposed that environmental impact and development are related in terms of an inverted U-shaped curve which he called the Environmental Kuznets Curve (EKC), based on the original Kuznets curve relating per capita income growth to inequality reduction [62].

The logic behind this relationship is that a territory or country goes through two phases: first it develops its economic structure, which allows the population to improve their living conditions, but requires high resource use, so development is positively related to environmental impact. Subsequently, technological improvements allow higher standards of efficiency to be achieved and the high standard of living introduces ecological concerns, leading to a reduction in environmental impact [5,16,46,53].

Since then, many studies have been conducted on the interaction between development and economic growth and environmental impact, with different results [5,8,53,54,63]. Furthermore, following the EKC hypothesis regarding the non-monotonicity of the relation between economic development and environmental impact, other work has investigated the possibility that EKC follows the form of a third-degree polynomial. In this way, the EKC would follow an N or inverted N form, something that has been found in multiple studies in recent decades [4,24,52,64]. The shape of N is due to the fact that the effect of technological progress diminishes and efficiency growth stagnates [4,65]. In the case of inverted N, the reasoning is similar, but the phases in the relationship are slightly modified. In a brief first phase, there would be major technical progress resulting in lower environmental impact. Subsequently, the generalisation of progress would lead to a significant growth in the scale of production, leading to an increase in environmental impact. The impact would start to decline in the medium to long term when technical progress would allow significant efficiency improvements.

The freedom to introduce new variables in the STIRPAT model allows the introduction of exponential terms to test for the existence of a non-linear relationship between GDP and environmental impact. To assess the possibility that the EKC theories of non-monotonicity in the relationship between environmental impact and economic growth are fulfilled, a quadratic and a cubic term for GDP are included in the model. The aim is to test whether the polynomial specification is more appropriate, with the aim of achieving the best possible fit without detracting too much from the simplicity of the model. The proposed model is set out in equation 7.

$$\log I = a + b(\log A) + c((logA^{)}) + d((logA^{)}) + f(\log T) + e \tag{5}$$

where I equals MF, A equals GDP and T equals primary energy con-

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[1] For example, when material consumption falls, it is useful to check whether there is also a fall in GDP, which would indicate that this is due to a recessionary cycle and not to a process of dematerialization per se.

sumption from renewable sources.

Following the logic of the non-monotonic relationship between GDP and environmental impact, it is of interest to study this possibility for the case of technology. Therefore, a quadratic and a cubic term are also introduced for the renewable energy consumption, leaving the model expressed by equation 8.

$$\log I = a + b(\log A) + c\left((logA)^2\right) + d\left((logA)^2\right) + e(\log T) + f(logT)^2 + g\left((\log T)^3\right) + h \tag{6}$$

In this way, it is hoped to approximate as closely as possible the relation between environmental impact and GDP and the consumption of primary energy from renewables, considering the possible variations derived from the different phases of social and technological development. The model is estimated for both FFMF and MF discounting FF, which allows the effect on fossil fuels to be analysed, but also on the rest of the material categories. Table 2 lists all the content variables used in the models.

One of the main objectives of the estimation of the models is to obtain the sign of each of the coefficients to interpret the direction of the effect of the variables. Therefore, it is considered important to present all possibilities, as shown in Table 3.

2.4. *Limitations*

One of the main limitations of this work is that the development of renewable energies is still very recent, which makes it difficult to identify relationships and trends. Furthermore, its development coincides in time with the 2008 crisis, which introduces significant distortions in the analysis.

Although it is not the aim of this paper, the model proposed could incorporate different variables to improve the fit and provide accurate estimates. n addition, one of the problems of polynomial models, multicollinearity, worsens the quality of the estimates made.

In the material consumption data for Germany, it should be considered that the reunification of the country implies the introduction of some distortions in the first years of the analysis, which may influence the results.

Portugal's fossil fuels imports in raw materials equivalents suffer a very significant drop in 2018, affecting its RTB and its FFMF. Although the original source, the Global Material Flows Database, shows it as such, it is considered that the figure should be interpreted with caution.

Table 2
Summary of variables included in the models.

Variable	Letter	Type	Definition
Fossil Fuels Material Footprint (FFMF)	I	Dependent	It covers the consumption of fossil fuels within a territory and the consumption of fossil fuels to produce the goods imported into that territory, irrespective of where it occurs.
Discounted Material Footprint (DMF)	I	Dependent	Variable resulting from discounting the FFMF to the whole of all Footprint Material.
Gross Domestic Production (GDP)	A	Independent	It allows to test the effect of economic growth on the dependent variable.
Consumption of primary energy from renewable sources.	T	Independent	It approximates technological progress. It shows the effect of renewable energy development on the dependent variable.

Source: own elaboration.

Table 3
Interpretation of the sign of the coefficients of the polynomial model of degree 3.

Sing of the coefficient	Interpretation
$E > 0$, $E^2 = 0$, $E^3 = 0$	Positive linear relation.
$E < 0$, $E^2 = 0$, $E^3 = 0$	Negative linear relation.
$E > 0$, $E^2 < 0$, $E^3 = 0$	U-shaped quadratic relation.
$E < 0$, $E^2 > 0$, $E^3 = 0$	Inverted U-shaped quadratic relation.
$E > 0$, $E^2 < 0$, $E^3 > 0$	N-shaped cubic relation.
$E < 0$, $E^2 > 0$, $E^3 < 0$	Inverted N-shaped cubic relation.

Source: own elaboration based on [24]; Gyamfi et al., 2021; [16].

3. Results and discussion

3.1. *Descriptive analysis of data*

This section presents the main results of the descriptive analysis of the data. Fig. 1 shows primary energy consumption by source in each of the countries analysed for the period 1990–2018.

There are notable differences in energy consumption per capita, with Finland and Sweden in the lead and Spain and Portugal with considerably lower values than the other countries. In general terms, until the 2008 Crisis, primary energy consumption grew or remained stable in all countries. The effect of the Crisis can be clearly identified in all cases, but it is more pronounced in Spain and Portugal, economies where it was particularly severe. At the same time, 2008 marks a turning point from which the trend in energy consumption starts to decline in most countries, although growth recovers in Spain and Portugal.

In all cases, a process of substitution of coal by gas can be seen, with the exceptions of Finland and Germany, where it is not so evident. The case of Sweden is noteworthy, where most of the primary energy consumption from fossil fuels is linked to oil. This is because Sweden relies heavily on hydropower for electricity generation. In the case of Finland, where there is also a significant share of primary energy consumption that cannot be linked to fossil or renewable energies, it is due to the use of nuclear energy.

In the 2000s renewable energy began to gain ground, never ceasing to grow at any time, even in those countries that reduced their total primary energy consumption more markedly. In any case, the sum of the different fossil energy sources maintains a considerable importance in all countries. The contribution of renewable energies is still moderate, as can be seen in Fig. 2.

It should be noted that oil is the most consumed fossil energy source in all countries and the one that suffers the least disruption, as it is still practically irreplaceable in the transport sector [66,67], of both goods and persons.

In up to five of the countries analysed, energy from fossil fuels accounts for more than 70%. Dependence is somewhat lower in the case of Finland because nuclear energy has a certain weight in electricity generation, and in Sweden, due to the significant development of hydroelectric power, as mentioned above. At the same time, the share of energy from renewable sources is quite low, ranging from 12% to 15%. The exception to this is Denmark, where renewable energy is almost 30%, but far behind fossil energy sources in any case.

The primary energy consumed provides a territorial consumption figure, so it can be smoothed by consumption elsewhere in the world to produce goods that are ultimately consumed in the countries analysed [12,32,40]. To study the consumption of fossil fuels in the rest of the world on which the countries studied depend, the RTB can be used, depicted in Fig. 3.

In all countries the RTB is positive, which implies that they import more resources than they export. It is worth remembering that, as explained in the methodology, the RTB of fossil fuels includes both the trade flows of these resources and the amount of these resources used in the production processes of other goods. Therefore, the energy consumption of the examined countries is smoothed by the material consumption of these resources outside their territory. This is a normal

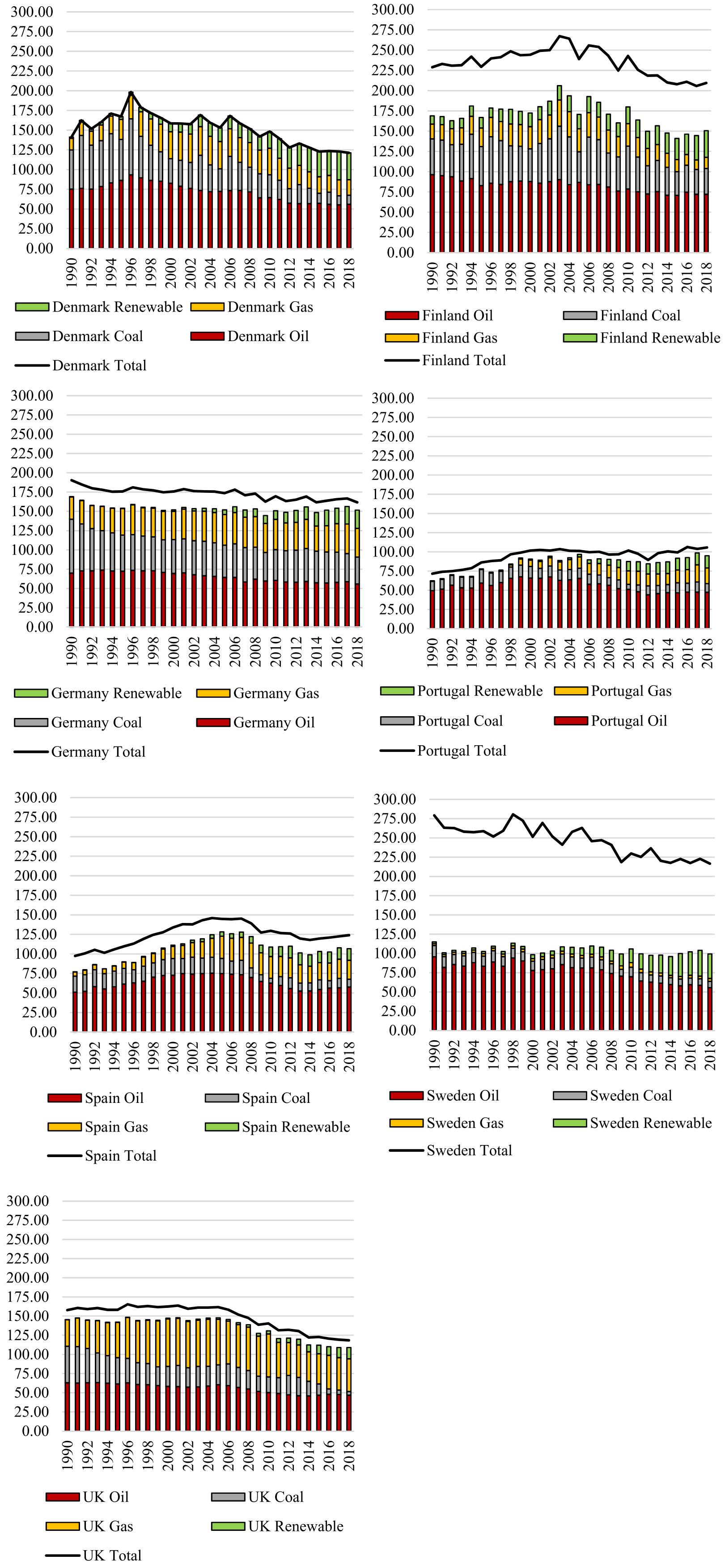

Fig. 1. Evolution of primary energy consumption by source, gigajoules per capita, 1990–2018. Source: own elaboration based on data from BP Statistical Review of World Energy.

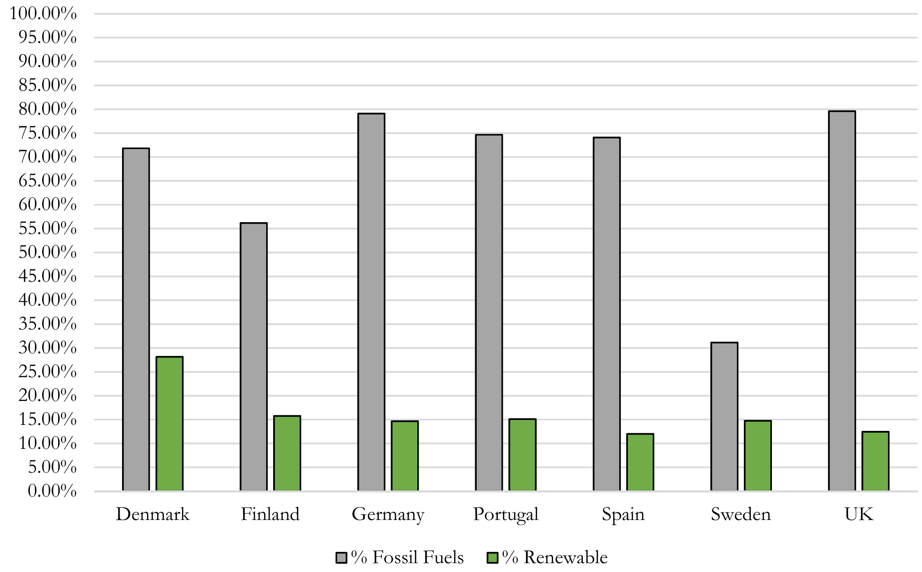

Fig. 2. Share of renewable and fossil energy in total primary energy consumption by countries, 2018. Source: own elaboration based on data from BP Statistical Review of World Energy.

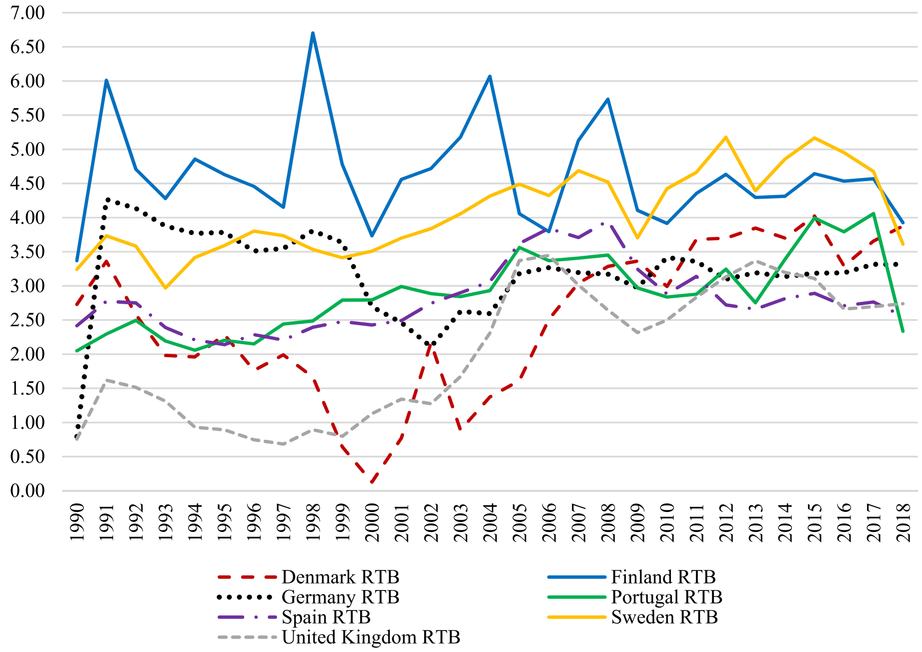

Fig. 3. RTB of fossil fuels by country, tonnes per capita, 1990–2018. Source: own elaboration based on data from Global Materialflows Database [33].

result, considering the processes of delocalization of production that, as in most developed countries, have taken place in recent decades [32,68]. Physical trade flows fluctuate to a greater extent than monetary trade flows because small differences in the composition of physical trade flows can imply large amounts in terms of weight, even if they are hardly noticeable in monetary terms [27,30,32].

Regarding the evolution of the RTB, the effects of the 2008 crisis can again be seen. However, for this indicator there are not so many cases of decrease and, in most countries, growth recovers after the Crisis. This implies that the environmental impact externalised to the rest of the world is growing, averaging around 4 tonnes per capita, which is quite high considering that only fossil fuel consumption is considered. Fig. 4 shows the Material Footprint of fossil fuels.

In general terms, an upward trend can be seen until the 2008 crisis, which was a turning point for all countries. In most of them, FFMF growth does not recover, except in Sweden and Portugal, while Germany suffers a more moderate fall and has remained practically stable in recent years. It is noteworthy that the RTB of fossil fuels represents in all cases a very important part of the FFMF, indicating that a significant amount of fossil fuel consumption linked to final demand in these countries takes place in third countries. This situation is closely related to the relocation of production in most developed countries in recent decades [12,69].

Fig. 5 shows the evolution of the DMF by country.

The high values reached in all countries are noteworthy, with Finland standing out, because of increased resource extraction activity. Furthermore, despite the fall caused by the 2008 crisis, all countries maintain a notable FMD, in many cases above 20 tonnes. Spain and Portugal have the lowest values in recent years. This is a consequence of the effect of the crisis on sectors such as construction, which are highly

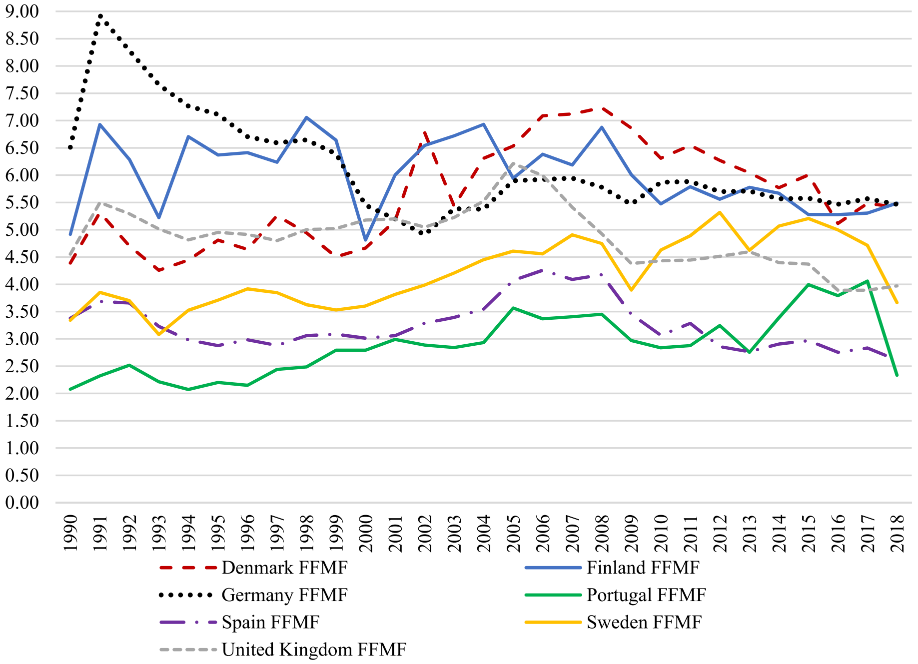

Fig. 4. Material Footprint of fossil fuels, tonnes per capita, 1990–2018. Source: own elaboration based on data from Global Materialflows Database [33].

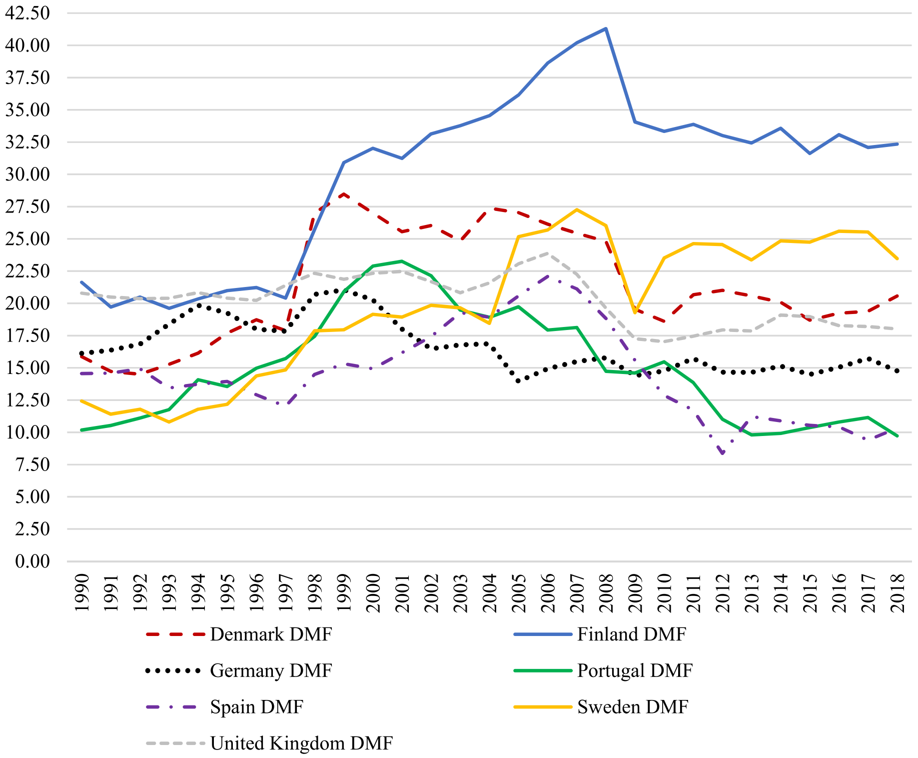

Fig. 5. Discounted Material Footrprint, tonnes per capita, 1990–2018. Source: own elaboration based on data from Global Materialflows Database [33].

materially intensive and much more dynamic in these countries than in the others analysed [29,30].

To analyse in more detail the growth trend of FFMF, DMF, energy consumption and GDP, it is interesting to study their cumulative rates of change, as shown in Fig. 6.

Although trends diverge across countries, the 2008 crisis leads to a sharp fall in all countries for all indicators. Before this point, there was remarkable growth in all countries except Germany. Subsequently, the decline in the FMD is particularly pronounced for Spain and Portugal, probably due to the weight of the construction sector in both countries, as well as a longer recessionary period than in other cases [10]. At the same time, they are the only countries that recover an increasing level of Primary Energy Consumption, which may be related to the fact that they started from a lower level of development than the rest. Countries such as Denmark, Finland, Sweden, and the United Kingdom seem to recover part or all their growth a few years later, showing no signs of dematerialization beyond the recessionary period [43].

On the other hand, Germany and Spain do show dematerialization

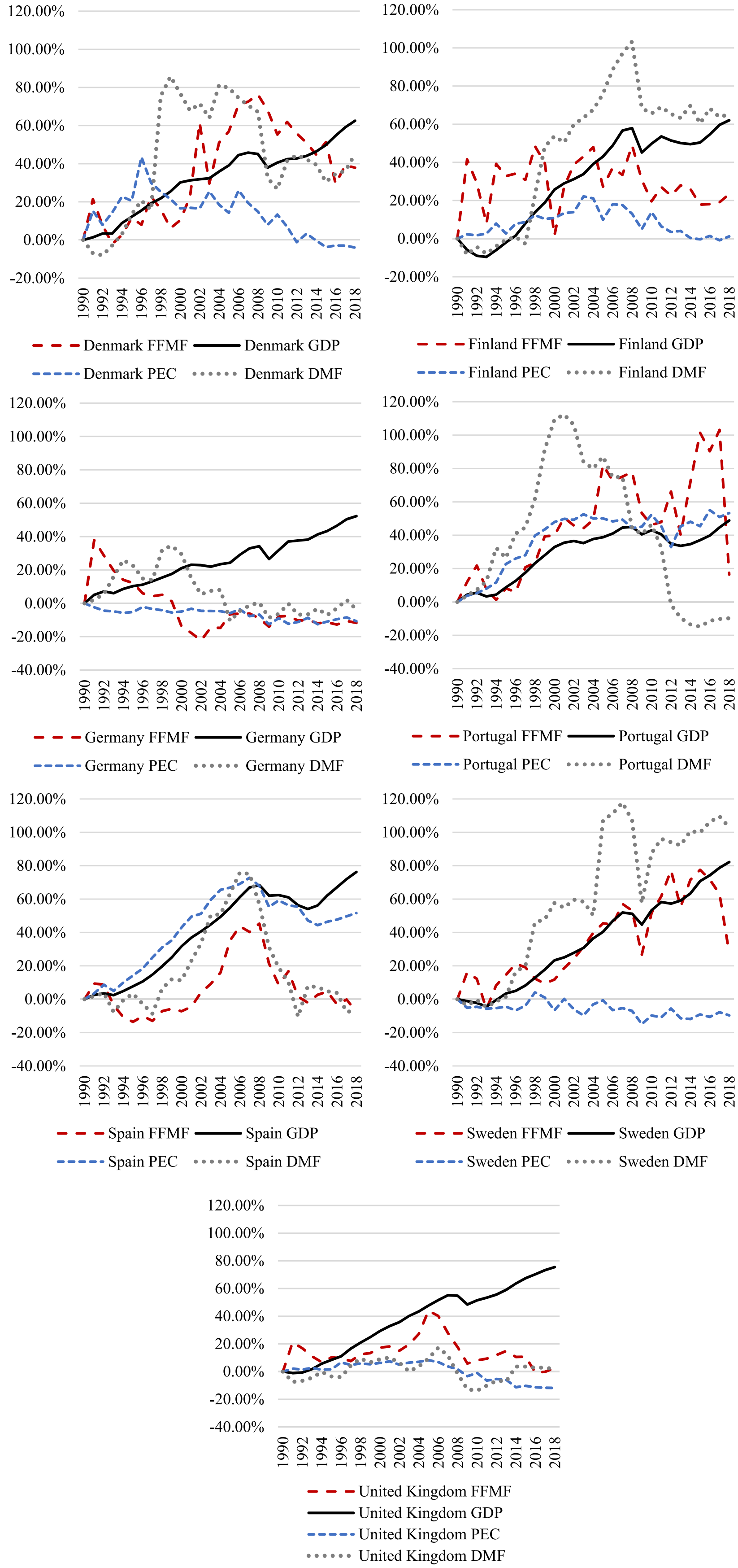

Fig. 6. Cumulative rate of change of FFMF, primary energy consumption, DMF and GDP, 1990–2018. Source: own elaboration based on data from Global Materialflows Database [33].

trends. In Germany, it is clearer in the case of fossil fuels, while in Spain, part of the explanation may lie in a longer recessionary period. In any case, it is the country where growth in energy consumption and a decrease in FFMF coexist most clearly, which may reveal a certain substitution of fossil energy by renewable energy.

3.2. Model results and assessment

This section presents the results for the model described in the methodological section. The variables of the model are stationary of first order (stationary in first differences) and the residuals of the model are stationary, so it can be assumed that the variables are cointegrated and the estimators are consistent.

To select the most appropriate way to estimate the model, the Breusch-Pagan Lagrange multiplier test has been performed to select between OLS and random effects, and the Hausman test to select between fixed and random effects. The results are shown in Table 4.

The results indicate that estimation by random effects is the most appropriate. On the other hand, considering that models based on STIRPAT may present multicollinearity problems, the degree of multicollinearity between the independent variables of the model has been checked. For this purpose, the Variance Inflation Factors (VIFs) of the regressors are examined. Usually, it is considered that there is a significant problem of multicollinearity when the VIFs take values greater than 10, the ideal being that they take the smallest possible values. The results of the VIFs are shown in Table 5

In no case is a significant VIF observed that would indicate any multicollinearity problem between A and T. It is important to note that the incorporation of the quadratic and cubic term of each variable implies introducing new variables inevitably correlated with A and T, respectively. Obviously, the use of quadratic and cubic terms implies increasing the variance of the estimators and worsens their properties. With the full model, the VIFs are considerably higher, as can be seen in Table 6. However, for polynomial models which, due to their characteristics, tend to present multicollinearity problems, higher values for the VIFs can be tolerated, as in this case [70]. Since the aim of this model is not to make predictions, but to determine the direction of the effect of each variable in the estimated period. The absence of collinearity problems between A and T is considered sufficient to achieve this purpose satisfactorily. Tables 7 and 8 show the results of the model estimation for the FFMF and for the DMF.

The coefficient of determination is not very high, so the influence of GDP and renewable energy consumption on FFMF would be moderate. The sign of the coefficients of GDP indicates that the inverted N structure found in other studies is verified [4,24,52,64]. Although all the analysed countries were already highly developed at the beginning of the period under study, the evolution of the relation of the FFMF and the GDP could fit into the phases usually described. The first phase would correspond to a turbulent economic cycle, which would give way to a very important expansion during the first years of the 21st century. The last phase would be marked by the development of renewable energy sources and by the effect of the 2008 crisis.

The descriptive analysis shows that, in most cases, dematerialization appears after the 2008 crisis. It is true that in all countries GDP recovers rapidly, which can be understood as a recovery in the pace of development. However, although it is commonly used as a proxy for development, GDP is an indicator with important limitations when it comes to representing social conditions [49–51]. In the social sphere, the 2008 Crisis had deeper and more lasting effects than on GDP, especially in countries such as Spain and Portugal. Overall, the recession led to higher levels of unemployment, poverty and inequality in most of the countries analysed [71–74]. This is most obviously reflected in material consumption, as both the population and companies reduce their overall consumption capacity. The evolution of primary energy consumption in the years following the crisis is a good approximation of its effect on domestic demand. It should also be noted that the sectors most affected by the recession were construction and certain industries [18,23,75]. Although these sectors do not have a very high weight in GDP, they are very important in terms of material intensity. Therefore, although there is a reduction in material consumption and GDP growth, it may not be appropriate to talk about dematerialization, as lower material consumption may be more linked to worsening living conditions than to improvements in resource efficiency [10,40].

Table 4
Results of the estimation method selection tests.

Test	Chi-Square	p-value
Breusch-Pagan	439.39	<2.2e-16***
Hausman	5.4639	0.4858

Source: own elaboration based on data from Global Materialflows Database [33]. Indicate that *, ** and *** mean respectively significance at 10%, 5% and 1%.

Table 5
VIFs for A y T.

Variables	VIF
A and T	1.222
A^2 and T^2	1.093
A^3 and T^3	1.051

Source: own elaboration based on data from Global Materialflows Database [33].

Table 6
VIF for the whole model.

	T	T^2	T^3	A	A^2	A^3
VIF	8.7	67.3	43.4	11.9	27.9	86.0

Source: own elaboration based on data from Global Materialflows Database [33].

Table 7
Results for model (6) with FFMF as dependent variable.

Variable	Coefficient	Error	z-value	R^2
Intercept	1644.3	523.28	3.142**	0.401
T	−0.109	0.050	−2.006*	
T^2	−0.026	0.023	−1.152	
T^3	−0.001	0.003	−0.355	
A	−183.30	57.901	−3.166**	
A^2	6.863	2.133	−3.217**	
A^3	−0.085	0.026	−3.263**	

Source: own elaboration based on data from Global Materialflows Database [33]. Indicate that *, ** and *** mean respectively significance at 10%, 5% and 1%.

For renewable primary energy consumption (T), only the linear coefficient of T, which is negative, is significant. Therefore, a negative effect of renewable energy consumption on the FFMF is deduced, in line with the ecological elasticity coefficients. The development of renewable energy has positive effects on the reduction of energy consumption from fossil resources, as well as on the reduction of material consumption related to these energy sources, following the line of previous studies with similar characteristics [14,15,17,18,52,54]. It is important to highlight the importance of this result, considering that it is the effect of the consumption of renewable energy within the countries analysed on their total FFMF. This cancels out the effect of the offshoring of high material intensity activities, because the material consumption carried out in other parts of the world to satisfy the demand of the countries analysed is taken into account [12,29].

However, the results should be interpreted with caution. The share of renewable energy in total primary energy consumption is still very small in these countries, even though they are the countries with the highest share of renewable energy consumption. Moreover, fossil fuels are still fundamental in all of them, representing in many more cases more than 70% of the primary energy consumed. In the field of transport, the situation is even more complex, as oil remains virtually irreplaceable in this sector [67]. Thus, despite rapid growth in recent years, renewables can be still in the early stages of development even in countries that consume a higher proportion of renewable energy. In this sense, some research questions whether the speed and capacity of renewable energy development is sufficient to move away from fossil fuels at the rate currently being pursued [76–78].

It is also not surprising that the increase in primary energy consumption is related to the decrease in FFMF. However, the development of the necessary infrastructure for the production of renewable energy requires a certain consumption of material resources [19–21]. It is therefore of interest to analyse the results presented in Table 8 below.

In the model for the DMF, the coefficient of determination improves significantly. In the GDP, the inverted N-form is again fulfilled for the EKC. This implies that a point is reached at which there is dematerialization. However, the sign of the coefficients for renewable energy consumption is only negative for the linear term. Both the quadratic and the cubic are positive and significant, so that renewable energy consumption cannot be related to a decrease in the other components of the Material Footprint. Part of the explanation can be found in the fact that the use of material resources requires the consumption of material resources for the construction of infrastructures, generators, and production centres [19–21]. This material consumption is not reflected in the FFMF, as renewable energy consumption directly replaces fossil energy consumption, which explains the differences. The existence of a significant positive effect of renewable energy consumption on the DMF is even more striking if one considers that only energy from wind and solar power is considered, leaving aside hydroelectric power, whose installation requires large resource consumption.

The sign of the consumption of renewable energy contributes to raise doubts regarding the interpretation of the inverted N-shape found in both models for GDP. The effect of the 2008 Crisis is of great importance and is very likely to be a key factor in explaining the shape of the EKC. Considering that, as mentioned above, there are multiple effects on quality of life that are not reflected in GDP, it becomes clear that there is a need to analyse dematerialization with alternative indicators to GDP [10,49–51].

In sum, the results confounded the capacity of renewable energy to contribute to the dematerialization of the economy. The material requirements of these energy sources are a constraint when considering energetic or ecological transition scenarios. Furthermore, their implementation is still reduced even in the most advanced countries in terms of their use, maintaining a high dependence on fossil resources. In addition, there are doubts about the ability of renewable energy to fully replace fossil energy, due to problems such as the lack of storage solutions or alternatives in the field of transport [76–80]. This means that reducing energy consumption must now be seen as a key measure in any dematerialization and ecological transition plan.

Table 8
Results for model (6) with DMF as dependent variable.

Variable	Coefficient	Error	z-value	R^2
Intercept	1718.6	549.92	3.125**	0.673
T	−0.155	0.053	−2.951**	
T^2	0.043	0.024	1.802*	
T^3	0.008	0.003	2.395*	
A	−191.61	60.839	−3.150**	
A^2	7.117	2.241	3.176**	
A^3	−0.0871	0.027	−3.170**	

Source: own elaboration based on data from Global Materialflows Database [33]. Indicate that *, ** and *** mean respectively significance at 10%, 5% and 1%.

4. Conclusions

This research has analysed the interaction between the Material Footprint and the consumption of primary energy from renewable sources, distinguishing between the Material Footprint of fossil fuels and the Material Footprint of the other material categories. The objective is to determine whether renewable energies favour the reduction of material consumption. Additionally, the relationship between the Material Footprint of fossil fuels and GDP has been analysed, considering the hypotheses of the Environmental Kuznets Curve, which makes it possible to study the existence of dematerialization. To develop the analysis, a model derived from STIRPAT has been used, specified in equation (6), which relates the Material Footprint, renewable energy consumption, GDP, and population. A quadratic and a cubic term for GDP are included in the model to test the assumptions of the Environmental Kuznets Curve.

The results of the model indicate that the FFMF and GDP maintain an inverted N-shaped relationship, thus validating the Environmental Kuznets Curve. Therefore, a process of dematerialization of fossil fuels is taking place after a certain level of economic growth. The analysed countries would go through a first phase in which GDP growth would be related to the decrease in FFMF, a second phase in which the relation would be positive, and a third phase in which they would return to the inverse relation. In the long run, these countries would achieve dematerialization. In the area of renewable energy, the model indicates that its effect on FFMF, only the linear coefficient is significant, with negative sign. It can be assumed that the development of renewable energy favours the reduction of material consumption of fossil fuels.

In the case of the model estimated for the rest of the material categories, the results are very similar for GDP, once again validating the inverted N-shaped relationship and, therefore, the existence of dematerialization from a certain level of GDP onwards. However, these data should be interpreted cautiously, as these phases could correspond to an unstable period in the 1990s, the years of high growth prior to the 2008 Crisis and the unstable years after the Crisis. Several studies indicate that social conditions have worsened since 2008, so it would be a dematerialization conditioned by these effects.

There is a positive effect in the case of renewable energy consumption for the quadratic and cubic terms. Therefore, renewable energy consumption cannot be related to dematerialization in the material categories beyond fossil fuels. This can be related to the material requirements of these technologies, related to the development of infrastructures and of the energy generators themselves. The consumption of these materials is not reflected in the fossil fuel category but is reflected in the others. But it is necessary to mention the effects of the 2008 Crisis, as this coincides in time with the development of renewable energy sources. Moreover, in some countries there is a decrease in primary energy consumption, so primary energy consumption may not be the main factor in the reduction of FFMF.

Finally, it is important to note that the share of renewable energy in total primary energy consumption is still moderate in these countries, even though they are the ones with the highest values. Fossil fuels represent a higher share of primary energy in all cases, exceeding 70% in most of them. Energy transition targets will be very difficult to achieve, but new targets should be set to reduce energy and material consumption.

Contributions

Rosa María Regueiro-Ferreira: Conceptualization, Methodology, Writing-Review & Editing, Resources, Visualization, Supervision. **Pablo Alonso-Fernández:** Conceptualization, Methodology, Software, Validation, Formal Analysis, Investigation, Resources, Writing – Original Draft.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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