

## Original Articles

Decoupling of CO<sub>2</sub> emissions and GDP: A time-varying cointegration approachJeyhun I. Mikayilov<sup>a,b,c,\*</sup>, Fakhri J. Hasanov<sup>a,d,e</sup>, Marzio Galeotti<sup>f,a,g</sup><sup>a</sup> King Abdullah Petroleum Studies and Research Center, PO Box 88550, Riyadh 11672, Saudi Arabia<sup>b</sup> Department of Statistics and Econometrics, Azerbaijan State University of Economics (UNEC), Istiqlaliyyat Str., 6, Baku, Azerbaijan<sup>c</sup> Institute for Scientific Research on Economic Reforms, 88a, Hasan Bey Zardabi Avenue, Baku AZ1011, Azerbaijan<sup>d</sup> Research Program on Forecasting, Economics Department, The George Washington University, 2115 G Street, NW, Washington, DC 20052, USA<sup>e</sup> Institute of Control Systems, Azerbaijan National Academy of Sciences, B. Vahabzade Street 9, Baku AZ1141, Azerbaijan<sup>f</sup> Department of Environmental Science and Policy, University of Milan, Via Celoria 2, 20122 Milano, Italy<sup>g</sup> IEF-Boconi, Via Roentgen, 1, 20136 Milano, Italy

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## ABSTRACT

The relationship between CO<sub>2</sub> emissions, the main gas responsible for global warming, and economic growth is among the most studied themes of environmental economics. Reducing overall emissions while keeping a high pace of economic development is at the heart of the sustainable development concept. When emissions grow less rapidly than GDP environmental economists speak of relative decoupling; if emissions even decrease relative to the pace of economic growth, then decoupling is absolute. Assessing these options requires an empirical analysis of the emissions-GDP relationship. The study of this nexus has special importance for developed countries, given their historical responsibility towards global warming. At the same time, in the last decades, the same countries have been at the forefront of the fight against climate change in terms of emissions-reduction efforts. By applying cutting-edge econometric techniques, this paper aims to investigate the decoupling options, if any, for a group of European economies which can be considered as pioneers in pursuing the sustainable development goals. This question gains further importance considering that some recent studies have found positive GDP elasticities of emissions for certain developed countries, which may be seen as a cause of concern for the sustainable development path of such countries. Unlike the bulk of the literature, in this paper, we allow the income elasticity of emissions – a critical indicator for the study of decoupling – to vary over time. The reason is that the elasticity might change through the time due to the factors affecting the main drivers of the CO<sub>2</sub> emissions. We use a time-varying coefficients cointegration approach to investigate the CO<sub>2</sub> emissions-GDP relationship for 12 Western European countries over a long time period ranging from 1861 to 2015. Our main finding is that the income elasticity of CO<sub>2</sub> emissions is positive in all investigated countries. In addition, we find evidence in favor of relative decoupling in 8 out of the 12 European countries. This is in line with the fact that the selected European countries have shown more determination in adopting carbon reduction policies before and after the Kyoto protocol period and toward the Paris agreement compared to other leading economies such as China, United States, and Russia. For the remaining 4 cases, the income elasticity of CO<sub>2</sub> emissions is in excess of unity. This can be considered as a call for policymakers to take quick and relevant measures to mitigate emissions level without harming the economic development.

## 1. Introduction

At the COP21 conference on climate held in Paris in December 2015, for the first time in history, almost all countries adopted a universal, legally binding global climate deal. Governments agreed on integrating climate change measures into national policies, strategies and planning on the basis of their Nationally Determined Contributions to

the mitigation of greenhouse gas emissions. The key to that agreement is the ability of countries to reduce their own carbon emissions while maintaining a satisfactory, or without compromising, the pattern of their economic development. Not only this is representing a specific Sustainable Development Goal (SDG), but economic growth is the key to the achievement of all the other SDGs. The relevant question, which this paper addresses, is: have indeed emission levels been decoupling

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from the economic growth at least in advanced economies, which have at the same time been main contributors of global emissions historically and most determined and effective in the adoption of policies aimed to curb carbon emissions? To empirically investigate this issue the present paper makes use of cutting-edge methodologies and considers Western European countries observed over a very long time span as a case study.

In the past three years, global emissions of carbon dioxide from the burning of fossil fuels have leveled after rising for decades (Figueres et al., 2017, inter alia). This is a sign that policies and investments in climate mitigation are starting to pay off and that individual commitments within the Paris agreement are being pursued. While there is almost unanimous international agreement that the risks of climate change are too great to ignore, it remains critical to aggressively reduce emissions to reach a zero level before the planet dangerously warms.

As countries embark on the transition to a new climate economy, there's a debate about whether growth can drive, or even coexist with, climate stabilization. On the other hand, there is also a discussion as to whether climate stabilization may negatively affect growth. While the relationship is a complex one, we can say that if the patterns of emissions and GDP growth start to diverge, then these two variables are delinked. More precisely, if emissions grow less rapidly than economic growth, we have a situation of relative decoupling. When they instead decline while the economy grows, we speak of absolute decoupling. This is ultimately the goal of any climate agreement.

The environmental and energy economics literature has long been interested in the empirical study of decoupling of emissions from GDP and in the strictly related concept of the Environmental Kuznets Curve (EKC), according to which decoupling of emissions turns from relative to absolute as income grows after some turning point.<sup>1</sup> Decoupling can be simply computed from actual data as the ratio between growth in emissions relative to growth in GDP, so that year-by-year patterns can be observed.<sup>2</sup> Most contributions in the literature, however, prefer to rely on econometric analysis which allows summarizing the relationship between emissions and GDP by means of a few statistical parameters on which the evidence on decoupling and EKCs is based. In this paper, we study decoupling between carbon dioxide emissions and GDP for 12 Western European countries over a very long time period.

A useful metrics to evaluate decoupling is the income elasticity of CO<sub>2</sub> emissions to GDP. By econometrically estimating an emissions-GDP relationship for each country, in this paper, we compute the income elasticity and therefore obtain inference on the decoupling issue. Unlike the bulk of the literature, we adopt a time-varying coefficient specification for our regression model and implement a recently developed time-varying cointegration method. This approach has a few distinct advantages over the “standard” fixed coefficients approach.

The current study contributes to the existing literature in different ways: first, it employs a new methodology (proposed by Park and Hahn, 1999), which takes explicitly into account certain weaknesses of the previous studies (such as Apergis, 2016; Liddle and Messinis, 2016; Moosa, 2017), to examine the relationship between CO<sub>2</sub> emissions and economic growth in the case of a group of European economies, which can be considered as pioneers in pursuing the sustainable development goals. The time-varying coefficient cointegration approach has some advantages over the conventional cointegration methods (Park and Hahn, 1999; Chang et al., 2014) such as addressing and testing the long-run co-movements under the time-varying coefficients framework,

<sup>1</sup> The EKC, therefore, consists of an inverted-U shaped graphical relationship between (per capita) emissions and (per capita) GDP. The literature on EKCs is vast and several surveys are available that summarize the evidence: see, for instance, Panayotou (1993), Dinda (2004) and more recently Carson (2010).

<sup>2</sup> One recent example of this approach is Naqvi and Zwickl (2017) which examines the decoupling of six pollutants (including CO<sub>2</sub> emissions) from economic activity in six economic sectors of 18 EU over the period 1995–2008. Note that decoupling is not an exclusive concept of CO<sub>2</sub> emissions; it also refers to energy consumption and to several other pollutants (OECD, 2002).

as well as addressing the omitted variable bias problem by employing time-varying coefficients. Furthermore, it is much more important in cointegrated regressions, to allow for TVC, compared to the usual stationary regressions. That is, if you have TVC and disregard it, then you would still expect to have its average value possibly with some bias in a stationary regression. Nevertheless, this is not true in a cointegrated regression. It is very important to model TVC appropriately in a cointegrated regression. If not, the regression becomes spurious. In other words, if the true model is a cointegrated regression with TVC but it is estimated using a regression with fixed coefficients, then the regression outcomes would be spurious and completely senseless; second, the study allows the income elasticity of emissions to vary over time; third, it addresses certain weaknesses of the conventional polynomial method as it does not limit the emissions-income relationship to be a specific polynomial, such as cubic, quadratic or linear.

The remainder of the paper is organized as follows. Section 2 briefly reviews the relevant literature, Section 3 discusses the notion of decoupling and of income elasticity of CO<sub>2</sub> emissions. Section 4 presents the data used to implement the methodology outlined in Section 5. Section 6 discusses the findings and the concluding section closes the paper.

## 2. Literature review

The present paper looks at decoupling on an individual country basis. Most of the literature takes advantage of the availability of statistical information both over time and across countries. Panel econometric methods are the norm. When the model is correctly specified estimated coefficients are more efficient as more information is exploited. However, panel methods typically rest on some cross-sectional homogeneity assumption, which may not be warranted and in principle should be tested for. On a more conceptual level, since countries show significant differences in political, social, economic and biophysics factors, one should expect that different countries exhibit different patterns for their relationships between environment and income. Therefore, the assumption that the EKC slope coefficients are constant across countries would be misleading most of the time. Generally speaking, the standard econometric model in the literature has per capita emissions that are a linear function of powers of per capita GDP, typically either quadratic or cubic.

To keep things short, we limit our attention to recent papers which have investigated the emissions-income relationship for European countries.

Friedl and Getzner (2003) focus on Austria over the period 1960–1999 and find an N-shaped EKC. Lindmark (2004) examines the long-run relationship between CO<sub>2</sub> emissions and economic growth for the most high-income countries over the period 1870–1992, employing the Kalman filter type structural time series method and concluding in favor of the EKC in these cases. Zanin and Marra (2012) investigate the EKC using additive mixed models. The following countries are considered: Australia, Austria, Canada, Denmark, Finland, France, Italy, Spain and Switzerland during the period 1960–2008. Their results show the existence of a classic EKC for France and Switzerland, an increasing relationship for Australia, Italy and Spain, a weak N-shaped relationship for Austria, while new nonlinear shapes are found for Finland (inverted-L-shape relationship), Canada (a special case of the inverted-L-shape relationship), and Denmark (M-shape relationship)<sup>3</sup>. Esteve

<sup>3</sup> Consider a specification where the log of per capita CO<sub>2</sub> emissions is a polynomial function of the log of per capita GDP:  $\ln co_2 = a_0 + a_1 \cdot \ln gdp + a_2 \cdot \ln gdp^2 + a_3 \cdot \ln gdp^3 + a_4 \cdot \ln gdp^4 + e$  where,  $a_i$ 's are the coefficients to be estimated econometrically and  $e$  is an error term. We have the following possibilities: 1. If  $a_1 > 0$ ,  $a_2 < 0$ ,  $a_3 = 0$ ,  $a_4 = 0$ , then the relationship has an inverted U-shape, i.e. an Environmental Kuznets Curve; 2. If,  $a_1 > 0$ ,  $a_2 < 0$ ,  $a_3 > 0$ ,  $a_4 = 0$ , then there is an N-shaped relationship between CO<sub>2</sub> and GDP; 3. If,  $a_1 > 0$ ,  $a_2 < 0$ ,  $a_3 > 0$ ,  $a_4 > 0$ ,

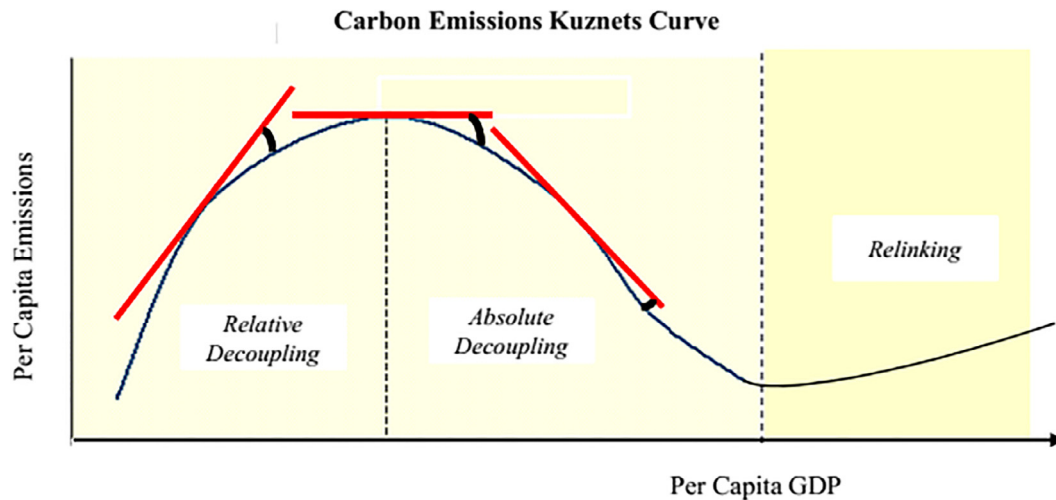


Fig. 1. Decoupling of emissions from GDP.

and Tamarit (2012) study the EKC for the Spanish economy over the period 1857–2007. Their approach accounts for a possible non-linear relationship by making use of threshold cointegration techniques. The non-linearity is confirmed and the results point to the existence of an EKC for the Spanish case. Fosten et al. (2012) study the EKC for the United Kingdom (UK) utilizing a cubic functional form and finding that such specification best fits the UK data and concluding in favor of an EKC. The study makes use of different methods from those used in conventional EKC analyses, such as a threshold autoregressive model and a momentum-threshold autoregressive model. Bella et al. (2014) use a quadratic specification as a starting point and investigate the CO2 emissions-income relationship in 22 OECD countries for 1965–2006, reaching different results for three different country clusters. Baek (2015) studied the impact of income on CO2 emissions for the Arctic countries using the usual polynomial approach. Norway shows an EKC pattern; an N-shape characterizes Sweden, whereas a linear relationship is consistent with the cases of Finland and Denmark. Apergis (2016) applies a Quantile Cointegration Regression method on data for 15 OECD countries for 1960–2013 and concludes that there is strong evidence in favor of time-varying parameters, finding an EKC for 12 countries out of 15. Liddle and Messinis (2016) using the linear cointegration method with endogenous breaks investigate the CO2 emissions-GDP relationship for 21 OECD countries over a very long period 1870–2010 utilizing panel FMOLS and DOLS methods. An inverted-U pattern is found for Denmark, France, Switzerland, and UK; a positive, less than unity income elasticity for Italy and Norway (termed “saturation”), a near zero elasticity for Belgium, and a unitary elasticity (“no transition”) for Spain. Finally, Jaforullah and King (2017) consider OECD countries over 1960–2010 and either quadratic or cubic income polynomial models. Calculated income elasticities of CO2 emissions are in the range (1.2, –2.3) for Denmark, (4.6, 1.2) for Finland, (2.6, 2.2) for Norway, and (5.6, 1.9) for Sweden.

### 3. Decoupling

Our starting point is the standard specification of aggregate (country level) carbon dioxide emissions (CO<sub>2</sub>) which are taken to depend on income/GDP (Y) and population (P). It is customary to express

(footnote continued)

$a_4 < 0$ , then there is a M-shaped relationship between CO<sub>2</sub> and GDP; 4. The relationship is L-shaped (resp. inverted L-shaped) if emissions decrease (resp. increase) sharply first, with an increase of income, and after some point become steady. For a detailed explanation see Dinda (2004), Yang et al. (2015), Zanin and Marra (2012) and Wen et al. (2018).

the relevant variables in per capita terms, to control for the size of the economy. Thus:

$$CO_2/P = g(Y/P) \tag{1}$$

The Environmental Kuznets Curve (EKC) literature has been typically interested in the curvature of the environment-income relationship, in particular, its possible inverted-U shape, and in the location of the income turning point where the curve starts declining. This is equivalent to assume that  $g(\cdot)$  in (1) possesses certain analytical properties. In the literature decoupling, the income elasticity of emissions, and Kuznets curve behavior are closely interrelated aspects of the emissions-income relationship. Thus,  $g(\cdot)$  in (1) should also be able to address both elasticity and decoupling issues. To show these concepts, let  $co_2 = CO_2/P$  and  $y = Y/P$  so that  $co_2 = g(y)$ .

The decoupling of emissions from GDP is evidenced by the sign of the second derivative of  $g(\cdot)$ . That is:

$$\frac{\partial^2 co_2}{\partial^2 y} = g''(y) < 0 \tag{2}$$

Thus, we have decoupling if the function is concave as in an indicated region of Fig. 1.

This is not enough for a Kuznets curve, though. Indeed, condition (2) is necessary and sufficient for “relative” decoupling: emissions rise less than proportionally with income. However, the condition is only necessary for “absolute” decoupling. Indeed, we need to consider also the first derivative of  $g(\cdot)$ . In other words, we have the following:

$$\text{Relative decoupling: } \frac{\partial^2 co_2}{\partial^2 y} = g''(y) < 0; \frac{\partial co_2}{\partial y} = g'(y) > 0 \tag{3}$$

$$\text{Absolute decoupling: } \frac{\partial^2 co_2}{\partial^2 y} = g''(y) < 0; \frac{\partial co_2}{\partial y} = g'(y) < 0$$

The role of the first two derivatives is clearly illustrated in Fig. 1. Absolute decoupling is thus what is needed for a Kuznets inverted-U behavior. Fig. 1 shows that in principle we can have a third possibility: relinking. This occurs when:

$$\frac{\partial^2 co_2}{\partial^2 y} = f''(y) > 0 \tag{4}$$

regardless of the sign of the first derivative. If the second derivative of the function is negative over some range of value of  $y$  and then turns positive over the subsequent range, then an N-shaped relationship would occur. This is what is portrayed in Fig. 1.

The decoupling notion can be easily expressed in terms of income elasticity of emissions. If CO<sub>2</sub> emissions increase as income goes up,

they are a “normal good”. This implies a positive income elasticity. If such elasticity is positive but less than unity, then emissions increase less rapidly than income, implying relative decoupling. For absolute decoupling, however, we have to have that over a range of GDP values, the income elasticity turns negative: as income increases emissions will decline. This will make them an inferior commodity. All this implies the following:

$$\text{Relative decoupling: } \frac{\partial \ln co_2}{\partial \ln y} = \frac{\partial co_2}{\partial y} \frac{y}{co_2} < 1 \tag{5}$$

$$\text{Absolute decoupling: } \frac{\partial \ln co_2}{\partial \ln y} = \frac{\partial co_2}{\partial y} \frac{y}{co_2} < 0$$

Again, an inverted-U Kuznets curve will entail both possibilities, with a positive less than unitary income elasticity turning negative after the turning point. As a matter of fact, the turning point is precisely where the Kuznets curve stops rising and starts to decline. This is equivalent to state that the first derivative turns from positive to negative, as evidenced by Fig. 1.

To quantify the income elasticity and obtain evidence on the potential existence and type of decoupling between a country emissions and its GDP, it is necessary to select a suitable functional form for  $g(.)$  in (1). The most popular parametrization of the emissions-income relationship is the log-linear polynomial function of income. Thus, (1) takes, for instance, the following form:

$$\ln co_2 = \alpha_0 + \alpha_1 \ln y + \alpha_2 (\ln y)^2 + \alpha_3 (\ln y)^3 \tag{6}$$

where the  $\alpha_i$ s are coefficients to be econometrically estimated. The logarithmic specification represents a natural framework where to investigate the income elasticity of CO<sub>2</sub> emissions. In fact:

$$\eta = \frac{\partial \ln co_2}{\partial \ln y} = \alpha_1 + 2\alpha_2 \ln y + 3\alpha_3 \ln^2 y \tag{7}$$

Note that linear double-log specifications of the emissions-income relationship entail a constant income elasticity equal to  $\alpha_1$ : as such neither relative nor absolute decoupling can be modeled. We, therefore, need polynomials of income to be added to the relationship. According to (7) the sign and size of the elasticity depends on the sign and relative size of the estimated coefficients  $\alpha_i$  ( $i = 1, 2, 3$ ) but also on the evolution of per capita GDP. In this sense, the income elasticity is varying over time, driven by per capita GDP.

The typical parametrization of the CO<sub>2</sub> emissions – income relationship in (7) is characterized by fixed  $\alpha_i$ s coefficients. The income elasticity is therefore also based on fixed coefficients. While the most popular, the log-linear parametrization is not the only functional form that has been proposed in the literature. An obvious alternative is the linear-in-variables expression corresponding to (7), other flexible parametrizations include spline functions (Schmalensee et al., 1998) or non-linear-in-parameters specifications (Galeotti et al., 2006). One additional possibility, which has received some attention, is non-parametric specifications. Unfortunately, the calculation of parameter-based indicators such as income or population elasticities is not feasible in that context, besides the very large sample sizes that nonparametric methods typically necessitate.

One important result that relevant for the present purposes is the theorem established by Swamy and Mehta (1975) and confirmed by Granger (2008) which states that any non-linear functional form can be exactly represented by a model that is linear in variables, but that has time-varying coefficients. This is an attractive perspective, as the emissions-income relationship, and therefore the income elasticity of emissions needs not depend only on the evolution of GDP, but maybe in principle affected by several other variables. As noted by Moosa (2017), these additional controls need not be identified explicitly.

There are some studies which employed a time-varying coefficient approach to the emissions-income relationship. Apergis (2016) applies a Quantile Cointegration Regression method on data for 15 countries

and concludes that there is strong evidence in favor of time-varying parameters. Moosa (2017) employs a Kalman filter approach to Australian data to assess the time-varying properties of the coefficients and finds the evidence in favor of time-varying coefficients. Esteve and Tamarit (2012) employ a linear cointegration model which allows structural breaks on Spanish data and find declining but always positive income elasticities. Similarly, Liddle and Messinis (2016) study the CO<sub>2</sub> emissions-income relationship for 21 OECD countries utilizing a reduced form, linear modeling approach which takes into account endogenous breaks. The limitation of employing a reduced form model with an endogenous break is that it requires the choice of regimes, which might limit the results. Studies (Apergis (2016) and Moosa (2017)) employing Kalman filter limited themselves only to the quadratic functional form and tested if the coefficients of the functional form vary over time. In addition, Chang and Martinez-Chombo (2003) and Salisu and Ayinde (2016) note that an income elasticity based on time-varying parameters may be more appropriate in light of the changes an economy may undergo over long periods of time, when structural breaks and parameter instability are likely to occur.

#### 4. Data

This study uses long annual data for CO<sub>2</sub> emissions, GDP and population for the period 1861 to 2015 for 12 Western European countries. These are: Austria, Belgium, Denmark, Finland, France, Germany, Italy, Netherlands, Norway, Sweden, Switzerland, and the United Kingdom. Carbon dioxide emissions from fossil fuel burning are expressed in MtCO<sub>2</sub>, Gross Domestic Product (GDP) is in millions of 1990 International Geary-Khamis U.S. dollars, and population is in thousand at a mid-year. CO<sub>2</sub> emissions data are taken from Boden et al. (2016), the data on GDP and population are taken from the Maddison Project (2013 version) presented in Bolt and van Zanden (2014).<sup>4</sup> CO<sub>2</sub> emissions and GDP are converted to per capita terms after dividing by population.

Long time series are especially suited for a time-varying parameter analysis. On the other hand, since we do not have available data for other relevant explanatory variables for such a long period, in our specification we can only use GDP and population data. However, considering that our main focus is the income elasticity of CO<sub>2</sub> emissions and that, as mentioned above, our time-varying coefficient approach takes into account the omitted variable problem, the use of per capita income as the only explanatory variable likely not causes a significant problem.

The time evolution of per capita emissions and GDP both in terms of levels (logarithms) and growth rates is shown in Fig. A.1 in the Appendix. Table 1 below presents some descriptive statistics. It can be seen that over the sample period CO<sub>2</sub> emissions displayed a high volatility in many countries reaching the highest values in Italy and Finland. It was low for United Kingdom, Belgium, Germany (coefficient of variation smaller than 33%), whereas for France, the Netherlands the volatility of emissions was within somewhat acceptable ranges (coefficient of variation smaller than 66%). Regarding GDP, the volatility is almost the same in many countries of the sample, except for the United Kingdom, Belgium, and the Netherlands. The level of volatility of income is relatively higher in Italy, Finland, Norway, and Sweden.

From the joint consideration of the information in the table and in the figure, two facts stand out. First, is the impact of the World Wars which affected all the countries considered, determining recessionary effects or slumps in the economic activity and consequent falls in emissions. Second, is the sensitivity of emissions to economic activity, evidenced by the higher volatility of the former relative to the latter,

<sup>4</sup> The emissions data from Boden et al. (2016) stop at 2013 and the GDP and population data from Maddison arrive at 2008: we update the data to 2015 using the Enerdata database.

**Table 1**  
Descriptive statistics.

| Country        | CO <sub>2</sub> emissions per capita |       |      |        |         | GDP per capita |      |       |        |         |
|----------------|--------------------------------------|-------|------|--------|---------|----------------|------|-------|--------|---------|
|                | Min                                  | Mean  | Max  | St Dev | CoV (%) | Min            | Mean | Max   | St Dev | CoV (%) |
| Austria        | -1.78                                | 0.74  | 1.97 | 0.97   | 131     | 7.45           | 8.54 | 10.10 | 0.87   | 10      |
| Denmark        | -1.01                                | 1.28  | 2.62 | 1.00   | 78      | 7.47           | 8.74 | 10.13 | 0.85   | 10      |
| France         | 0.10                                 | 1.39  | 2.27 | 0.56   | 40      | 7.48           | 8.62 | 10.01 | 0.85   | 10      |
| Italy          | -3.67                                | 0.06  | 2.10 | 1.56   | 2600    | 7.26           | 8.38 | 9.91  | 0.94   | 11      |
| United Kingdom | 1.70                                 | 2.23  | 2.47 | 0.16   | 7       | 7.97           | 8.88 | 10.11 | 0.64   | 7       |
| Belgium        | 1.22                                 | 2.10  | 2.66 | 0.36   | 17      | 7.75           | 8.75 | 10.07 | 0.73   | 8       |
| Finland        | -3.75                                | -0.13 | 2.59 | 2.12   | 1631    | 6.79           | 8.30 | 10.10 | 1.06   | 13      |
| Germany        | 0.13                                 | 1.91  | 2.66 | 0.62   | 33      | 7.37           | 8.59 | 10.01 | 0.84   | 10      |
| Netherlands    | -0.01                                | 1.52  | 2.59 | 0.73   | 48      | 7.78           | 8.78 | 10.11 | 0.75   | 9       |
| Norway         | -1.51                                | 1.00  | 2.59 | 1.06   | 106     | 7.00           | 8.50 | 10.26 | 1.04   | 12      |
| Sweden         | -1.40                                | 0.96  | 2.44 | 1.06   | 110     | 7.00           | 8.58 | 10.15 | 0.99   | 12      |
| Switzerland    | -1.78                                | 0.74  | 1.97 | 0.97   | 131     | 7.46           | 8.90 | 10.15 | 0.85   | 10      |

Notes: Variables in logarithmic form; St Dev = standard deviation; CoV = Coefficient of Variation.

suggesting a positive elasticity. This is the issue we now want to examine with the help of rigorous statistical tools.

### 5. Econometric methodology and empirical results

#### 5.1. Unit root tests

Since we make use of time series data, the first step is to test for the unit root properties of our variables. Considering that our sample spans the entire 20th century and the trends seen above, we suspect the presence of structural breaks in the series corresponding to the years of WW1 and WW2. To take this fact into account we employed the Zivot-Andrews unit root test which allows for a structural break (ZA) (Zivot and Andrews, 1992).<sup>5</sup>

The results of the unit root tests are presented in Table 2. It reports the results for the ZA test only for the first-differenced variables to conserve space. The years were selected based on graphical inspection and considering the two world wars as mentioned in previous section. All variables appear to be stationary at the first-differenced form; we thus conclude that the logged variables are I(1).

#### 5.2. Time-varying coefficient cointegration approach: Methodological aspects

In the previous section, we noted that a time-varying parametric approach provides a convenient methodological approach to the study of decoupling possibilities between emissions and GDP. In this regard, the time-varying coefficient cointegration (TVC) method proposed by Park and Hahn (1999) allows for the possibility of a time-varying long-run elasticity that is a smooth function of time. In this sense, one can use time as a proxy for unobserved variables that affect the coefficients of the model explanatory variables.<sup>6</sup> As noted by Park and Hahn (1999), and Chang et al. (2014), the TVC method has a few crucial advantages in the study of cointegration. First, it is shown that if the true long-run model is a cointegrated regression with time-varying coefficients but it is estimated using a regression with fixed coefficients, then the econometric results will be spurious and meaningless. Second, the TVC is especially relevant in cases where long dataset is employed,

<sup>5</sup> We performed also standard Augmented Dickey-Fuller tests obtaining the same results. Since ADF and ZA tests are widely employed and described in the literature, we do not describe them here.

<sup>6</sup> The TVC approach has been applied to electricity demand (Chang and Martinez-Chombo, 2003; Chang et al., 2014; Chang et al., 2016; Mikayilov et al., 2017), to gasoline demand (Zuo and Park, 2011), and to money demand (Park and Park, 2013), inter alia.

since the likelihood of having structural changes is higher. In this regard, the dataset employed here includes two World wars, a fact that increases the possibility of different responses of CO<sub>2</sub> emissions to economic development paths. Hence, the use of TVC is justified here both on theoretical and empirical grounds. Within this framework, we can simply specify (6) as follows:

$$lnco_{2t} = \alpha_0 + \alpha_t lny_t + u_t \tag{8}$$

where  $u_t$  is a latent disequilibrium error sequence assumed to be weakly dependent. Note that the GDP elasticity of CO<sub>2</sub> emissions is simply equal to  $\alpha_t$  but it is varying over time and can, therefore, be used to study the decoupling issue.

Coefficient  $\alpha_t$  is assumed to be a smooth function of time and is approximated semi-parametrically by means of a Fourier flexible form (an FFF) functional, which decomposes the function into a linear combination of a polynomial and pairs of periodic functions. Letting  $\alpha_t = \alpha(t/T)$ , where  $\alpha$  is a function defined over the unit interval which admits an FFF, we can write:

$$\alpha_{pq}(r) = \lambda_0 + \sum_{j=1}^p \lambda_j r^j + \sum_{j=1}^q (\lambda_{p+2j-1}, \lambda_{p+2j}) \phi_j(r) \tag{9}$$

where  $\phi_j(r) = (\cos 2\pi jr, \sin 2\pi jr)'$  for  $r \in [0, 1]$ , which approximates a FFF as  $p$  and  $q$  increase. By defining  $\lambda_{pq} \equiv (\lambda_0, \dots, \lambda_{p+2q})'$  and  $\varphi_{pq}(r) \equiv (1, r, \dots, r^p, \varphi_1'(r), \dots, \varphi_q'(r))'$ , we may write  $\alpha_{pq}(t/T) lny_t$  as  $\lambda_{pq}' \varphi_{pq}(t/T) lny_t$  or further as  $\lambda'_{pq} lny_{pqt}$  with  $lny_{pqt} \equiv \varphi_{pq}(t/T) lny_t$ . In other words, the non-linear function may be approximated by a linear function of a new regressor vector  $lny_{pqt}$ . Using this specification, the TVC model we estimate is given by:

$$lnco_{2t} = \tau + z'_{pqt} \theta + u_{pqt} \tag{10}$$

where  $z_{pqt} \equiv (lny'_{pqt})'$ ,  $\theta \equiv (\lambda'_{pq})'$ , and  $u_{pqt} \equiv u_t + (\alpha(t/T) - \alpha_{pq}(t/T)) lny_t$  includes the original disequilibrium error as well as an approximation error due to fixing  $p$  and  $q$ . The new regressor vector  $z_{pqt} \equiv (lny'_{pqt})'$  contains the original regressor(s) and the elements of  $\varphi_{pq}(t/T) lny_t$ , besides simply  $lny_t$ . Note that the TVC model in (10) nests the linear fixed coefficients (FC) model. That is, the TVC model reduces to the FC case when  $p = q = 0$ , or equivalently when  $\lambda_1 = \dots = \lambda_{p+2q} = 0$  for non-zero values of  $p$  and  $q$ . Thus, the null hypothesis of a fixed coefficient specification is equivalent to a joint null hypothesis that all these coefficients are zero, while the TVC alternative is that at least one of them is non-zero. The number of polynomials ( $p$ ) and trigonometric pairs ( $q$ ) in (9) should be chosen based on Bayesian Information Criteria (BIC) (Chang et al., 2014). Eq. (10) can be estimated by Ordinary Least Squares (OLS) method, but to avoid the problems caused by nonstationary data the use of the Canonical Cointegration Regression (CCR) method proposed by Park (1992) is

**Table 2**  
Unit root test results.

| variable<br>country | <i>lnco<sub>2</sub></i>       |                               | <i>lry</i>                    |                               |
|---------------------|-------------------------------|-------------------------------|-------------------------------|-------------------------------|
| Austria             | -4.782 <sup>**</sup> (1914)   | -11.980 <sup>***</sup> (1938) | -11.964 <sup>***</sup> (1914) | -7.489 <sup>***</sup> (1945)  |
| Denmark             | -12.439 <sup>***</sup> (1917) | -17.921 <sup>***</sup> (1945) | -11.879 <sup>***</sup> (1915) | -11.178 <sup>***</sup> (1940) |
| France              | -11.872 <sup>***</sup> (1914) | -11.292 <sup>***</sup> (1939) | -5.344 <sup>***</sup> (1914)  | -6.496 <sup>***</sup> (1940)  |
| Italy               | -10.158 <sup>***</sup> (1916) | -7.833 <sup>***</sup> (1943)  | -10.240 <sup>***</sup> (1919) | -9.669 <sup>***</sup> (1940)  |
| UK                  | -11.242 <sup>***</sup> (1919) | -11.492 <sup>***</sup> (1926) | -9.434 <sup>***</sup> (1919)  | -8.008 <sup>***</sup> (1940)  |
| Belgium             | -11.383 <sup>***</sup> (1914) | -10.494 <sup>***</sup> (1939) | -9.926 <sup>***</sup> (1914)  | -9.741 <sup>***</sup> (1939)  |
| Finland             | -16.036 <sup>***</sup> (1915) | -12.999 <sup>***</sup> (1939) | -6.790 <sup>***</sup> (1914)  | -6.972 <sup>***</sup> (1939)  |
| Germany             | -15.827 <sup>***</sup> (1919) | -10.227 <sup>***</sup> (1945) | -8.838 <sup>***</sup> (1914)  | -4.649 <sup>**</sup> (1945)   |
| Netherlands         | -11.292 <sup>***</sup> (1915) | -11.296 <sup>***</sup> (1939) | -10.009 <sup>***</sup> (1916) | -9.964 <sup>***</sup> (1939)  |
| Norway              | -11.731 <sup>***</sup> (1916) | -14.513 <sup>***</sup> (1940) | -11.931 <sup>***</sup> (1917) | -12.036 <sup>***</sup> (1940) |
|                     |                               | -14.282 <sup>***</sup> (1990) |                               |                               |
| Sweden              | -16.457 <sup>***</sup> (1917) | -15.357 <sup>***</sup> (1940) | -12.662 <sup>***</sup> (1916) | -12.786 <sup>***</sup> (1938) |
| Switzerland         | -11.347 <sup>***</sup> (1917) | -11.291 <sup>***</sup> (1940) | -11.379 <sup>***</sup> (1916) | -11.630 <sup>***</sup> (1938) |

Notes: \* and \*\*\* stand for rejection of null hypothesis at 10% and 1% significance level, respectively. The numbers in parentheses are the years tested for structural breaks. Optimal lag number chosen based on Swartz criteria.

**Table 3**  
Tests for cointegration and for joint significance of coefficients.

| Country        | Test statistics       | Variable Addition Test (VAT) |       |       |        | Test for joint significance of time-varying coefficients |       |       |        |
|----------------|-----------------------|------------------------------|-------|-------|--------|--|-------|-------|--------|
|                |                       | 0.5% CV                      | 1% CV | 5% CV | 10% CV | Test statistics  | 1% CV | 5% CV | 10% CV |
| Austria        | 10.20 <sup>***</sup>  | 14.86                        | 13.28 | 9.49  | 7.78   | 1.95   | 15.09 | 11.07 | 9.24   |
| Denmark        | 4.65 <sup>†</sup>     | 14.86                        | 13.28 | 9.49  | 7.78   | 3.64   | 16.81 | 12.59 | 10.65  |
| France         | 9.58 <sup>†</sup>     | 14.86                        | 13.28 | 9.49  | 7.78   | 1.46   | 16.81 | 12.59 | 10.65  |
| Italy          | 13.95 <sup>****</sup> | 14.86                        | 13.28 | 9.49  | 7.78   | 6.42   | 16.81 | 12.59 | 10.65  |
| United Kingdom | 14.64 <sup>****</sup> | 14.86                        | 13.28 | 9.49  | 7.78   | 2.91   | 16.81 | 12.59 | 10.65  |
| Belgium        | 10.07 <sup>***</sup>  | 14.86                        | 13.28 | 9.49  | 7.78   | 1.95   | 16.81 | 12.59 | 10.65  |
| Finland        | 16.87                 | 14.86                        | 13.28 | 9.49  | 7.78   | 391.37 <sup>***</sup>                                    | 13.28 | 9.49  | 7.78   |
| Germany        | 16.42                 | 14.86                        | 13.28 | 9.49  | 7.78   | 24.17 <sup>***</sup>                                     | 16.81 | 12.59 | 10.65  |
| Netherlands    | 2.59 <sup>†</sup>     | 14.86                        | 13.28 | 9.49  | 7.78   | 4.64 <sup>†</sup>  | 9.21  | 5.99  | 4.61   |
| Norway         | 13.47 <sup>****</sup> | 14.86                        | 13.28 | 9.49  | 7.78   | 0.95   | 15.09 | 11.07 | 9.24   |
| Sweden         | 8.57 <sup>**</sup>    | 14.86                        | 13.28 | 9.49  | 7.78   | 212.63 <sup>***</sup>                                    | 15.09 | 11.07 | 9.24   |
| Switzerland    | 4.66 <sup>†</sup>     | 14.86                        | 13.28 | 9.49  | 7.78   | 94.20 <sup>***</sup>                                     | 15.09 | 11.07 | 9.24   |

Notes: The left-hand side of the table demonstrates the results of the VAT cointegration test. The right-hand side of the table shows the results of joint significance test of time-varying coefficients, namely  $\lambda_1 = \lambda_2 = \lambda_3 = \lambda_4 = \lambda_5 = \dots \lambda_k = 0$  in order to test whether or not the income elasticity is fixed or time-varying. †, \*\*, \*\*\* and \*\*\*\* stand for acceptance of null hypothesis in the case of VAT, and rejection of null hypothesis in the case of TVC at 10%, 5%, 1% and 0.5% significance level, respectively.

preferable (Park and Hahn, 1999). The CCR method transforms the non-stationary data, keeping the same cointegration vector, so that the conventional least squares procedures become valid, if we apply OLS to the transformed data.

In order to test the existence of a long-run relationship between the variables Park and Hahn (1999) suggest the use of a Variable Addition Test (VAT) for cointegration, proposed by Park (1990), which requires adding extra trend variables and testing the joint significance of the appropriate trend coefficients.

5.3. Time-varying coefficient cointegration approach: Results

The first step is to determine the number of the polynomials (p) and trigonometric pairs (q) of (9) which minimizes the BIC value. In Appendix A we report the findings. The next step is to estimate the equations based on the chosen specifications using the CCR approach to the transformed data.<sup>7</sup>

The second step requires testing for cointegration, i.e. if variables move together in the long-run. As mentioned above we use the VAT test, which simply looks at the joint statistical significance of the

coefficients of the added polynomial trend variables. Accepting the null hypothesis implies that the variables are cointegrated. In the testing procedure, whose results are reported in Table 3 we employed four trend polynomials and tested their joint significance.

As can be seen from the Table, for ten countries out of twelve, the test indicates that there is a cointegration relationship with at least a 0.5% significance level. For two countries, namely Finland and Germany, the VAT test suggests cointegration only at 0.2% significance level.<sup>8</sup> Park and Hahn (1999) suggest that the failure to find cointegration relationships in many studies based on fixed-coefficients parametrizations might be the result of parameter instability. In this respect, our findings lend support to Park and Hahn (1999) argument as we found a long-run relationship in all country cases using the VAT test they propose.<sup>9</sup>

We proceed on the assumption that there is a cointegrating relationship for every country considered. The next step involves testing the significance of the time-varying coefficients. As described in Chang

<sup>7</sup> The TVC estimation has been performed using Eviews 9.5 programming features.

<sup>8</sup> The critical value for the 0.2% significance level is 16.92.

<sup>9</sup> Evidence not reported here for brevity shows that using the conventional fixed-coefficients polynomial specification, the standard Engle-Granger cointegration test supports the existence of 7 long-run relationships out of 12. Results available upon request.

**Table 4**  
Estimated time-varying coefficients.

|                | $\tau$     | Parameters of the Time varying Income Coefficient |                         |  |   |   |   |   |
|----------------|------------|---|-------------------------|--|---|---|---|---|
|                |            | $\lambda_0$                                       | $\lambda_1 \frac{t}{T}$ | $\lambda_2 \left(\frac{t}{T}\right)^2$ | $\lambda_3 \cos\left(2\pi \frac{t}{T}\right)$ | $\lambda_4 \sin\left(2\pi \frac{t}{T}\right)$ | $\lambda_5 \cos\left(4\pi \frac{t}{T}\right)$ | $\lambda_6 \sin\left(4\pi \frac{t}{T}\right)$ |
| Austria        | −6.320***  | 1.254***  | −0.067                  |  | −0.003  | −0.010  | 0.013   | 0.004   |
| Denmark        | −8.846***  | 1.455***  | −0.464                  | 0.314                                  | −0.010  | −0.004  | 0.005   | 0.003   |
| France         | −7.680***  | 0.930   | 0.030                   | −0.021                                 | 0.001   | −0.001  | −0.001  | −0.001  |
| Italy          | −15.343*** | 0.746***  | 0.142                   | −0.084                                 | 0.007   | 0.002   | −0.004  | −0.001  |
| United Kingdom | −0.858     | 0.596**   | 0.188                   | −0.176                                 | 0.008   | 0.001   | −0.005  | 0.002   |
| Belgium        | −7.220***  | 0.845***  | 0.054                   | −0.043                                 | 0.002   | 0.001   | 0.001   | −0.001  |
| Finland        | −33.661*** | 0.860***  | −0.020                  | 0.053                                  | −0.025***                                     | 0.001   |   |   |
| Germany        | −0.489***  | 0.235***  | 0.648**                 | −0.402                                 | 0.001   | 0.024***                                      | −0.024***                                     | −0.001  |
| Netherlands    | −10.534*** | 1.141***  | −0.044                  | 0.017                                  |   |   |   |   |
| Norway         | −10.530*** | 0.901***  | 0.119                   | −0.087                                 | 0.008**                                       | 0.004   | 0.001**                                       | −0.0001                                       |
| Sweden         | −15.365*** | 0.724***  | 0.039**                 |  | −0.006  | 0.0001  | −0.005  | 0.011   |
| Switzerland    | −26.493*** | 2.442***  | −0.364***               | 0.034***                               | −0.024***                                     | 0.047***                                      | 0.008***                                      |   |

Notes:  $\tau$  is constant term,  $\lambda_i$ 's are the coefficients of income variable. \*, \*\* and \*\*\* stand for rejection of null hypothesis at 10%, 5% and 1% significance level, respectively.

et al. (2014), the test in the present context has a Chi-square distribution with  $p + 2q$  degree of freedom. To test for the significance of TVC we thus equate all the TVC coefficients ( $\lambda_i$ 's) to zero and check their joint significance.

The results are given on the right side of Table 3. In five countries the TVC coefficients are found to be significant: that is, we have enough evidence to conclude that the income coefficient in Finland, Germany, Netherlands, Sweden, and Switzerland, is time-varying. For the remaining countries the insignificance of TVCs should be interpreted as follow: the coefficient itself is positive and time-changing, but the change is very small, so that the average behavior of the coefficient appears to be constant over time, i.e., the change is insignificant. Hence, the finding of insignificant TVCs does not invalidate the positive relationship between emissions and income. The coefficient of GDP (without the varying part:  $\lambda_0$ ) is significant in all country cases with insignificant TVCs, thus supporting the finding of a positive income elasticity.

5.4. Time-varying coefficients and income elasticity of CO<sub>2</sub> emissions

The estimated parameters of time-varying coefficients for income are reported in Table 4. The results support the significance of the time-varying coefficients for the above mentioned five countries.

For the remaining countries, only the coefficient  $\lambda_0$  is statistically significant. This implies that the income elasticity of CO<sub>2</sub> emissions is based on a single fixed coefficient. In other words, one advantage of the TVC method is that it encompasses the standard fixed coefficient approach.

The time-varying income elasticity of CO<sub>2</sub> emissions we calculate is the following:

$$\eta_t = \frac{\partial \ln CO_2}{\partial \ln y} = \alpha_t = \lambda_0 + \lambda_1 \left(\frac{t}{T}\right) + \lambda_2 \left(\frac{t}{T}\right)^2 + \lambda_3 \cos\left(2\pi \frac{t}{T}\right) + \lambda_4 \sin\left(2\pi \frac{t}{T}\right) + \lambda_5 \cos\left(4\pi \frac{t}{T}\right) + \lambda_6 \sin\left(4\pi \frac{t}{T}\right) \quad (11)$$

Table 5 reports the estimated income elasticities of CO<sub>2</sub> emissions. In the table, we distinguish between countries for which the TVC coefficients  $\lambda_i$  ( $i = 1, \dots, 4$ ) are statistically significant so that the elasticity is time-varying and countries where the elasticity is fixed and constant.

**Table 5**  
Estimated income elasticities of CO<sub>2</sub> emissions.

| Significant TVC coefficients |                 | Insignificant TVC coefficients |                     |              |
|------------------------------|-----------------|--------------------------------|---------------------|--------------|
| Countries                    | TVC interval    | Countries                      | Central coefficient | TVC interval |
| Finland                      | [0.83, 0.89]*** | Austria                        | 1.254               | [1.20, 1.26] |
| Germany                      | [0.22, 0.50]*** | Denmark                        | 1.455               | [1.28, 1.45] |
| Netherlands                  | [1.11, 1.14]*   | France                         | 0.93                | [0.93, 0.94] |
| Sweden                       | [0.72, 0.77]*** | Italy                          | 0.746               | [0.75, 0.81] |
| Switzerland                  | [2.14, 2.52]*** | UK                             | 0.596               | [0.60, 0.64] |
|                              |                 | Belgium                        | 0.845               | [0.85, 0.86] |
|                              |                 | Norway                         | 0.901               | [0.91, 0.94] |

Notes: TVC interval = the interval defined by the minimum and maximum values of TVC coefficients. The central coefficient is the estimated value of  $\lambda_0$ . \* and \*\*\* stand for the significance of TVC coefficients at 10% and 1% significance level respectively.

6. Discussion

The possibility of decoupling the behavior of CO<sub>2</sub> emissions from economic growth is an important feature of countries engaged in fighting climate change and in energy/ecological transitions toward a greener economy. As discussed in Section 3, we can distinguish between a weaker form of decoupling which entails a slower growth in emissions relative to GDP and a stronger form which leads to a reduction in emission levels as the economy keeps growing. Decoupling is strictly related to the income elasticity of CO<sub>2</sub> emissions. Indeed, no decoupling implies an elasticity larger than one, relative decoupling a positive less than unitary elasticity, and absolute decoupling a negative income elasticity.

The standard approach is to evaluate the income elasticity on the basis of parametrized models of the CO<sub>2</sub> emissions – GDP relationship. The typical features of these models are twofold: (i) emissions are a linear function of powers of GDP (typically second or third order), and (ii) the coefficients to be estimated are fixed. The resulting income elasticity depends on GDP, as shown in (7), so that its variability is driven by income.

In the previous section, we have argued that a fixed coefficient framework is restrictive. Indeed, it has been argued that any non-linear functional form can be exactly represented by a model that is linear in

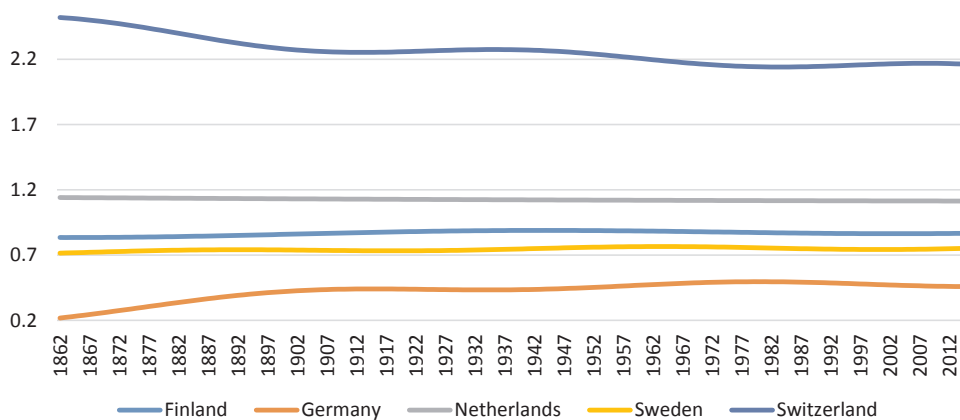


Fig. 2. Time-varying income elasticities of CO<sub>2</sub> emissions (I).

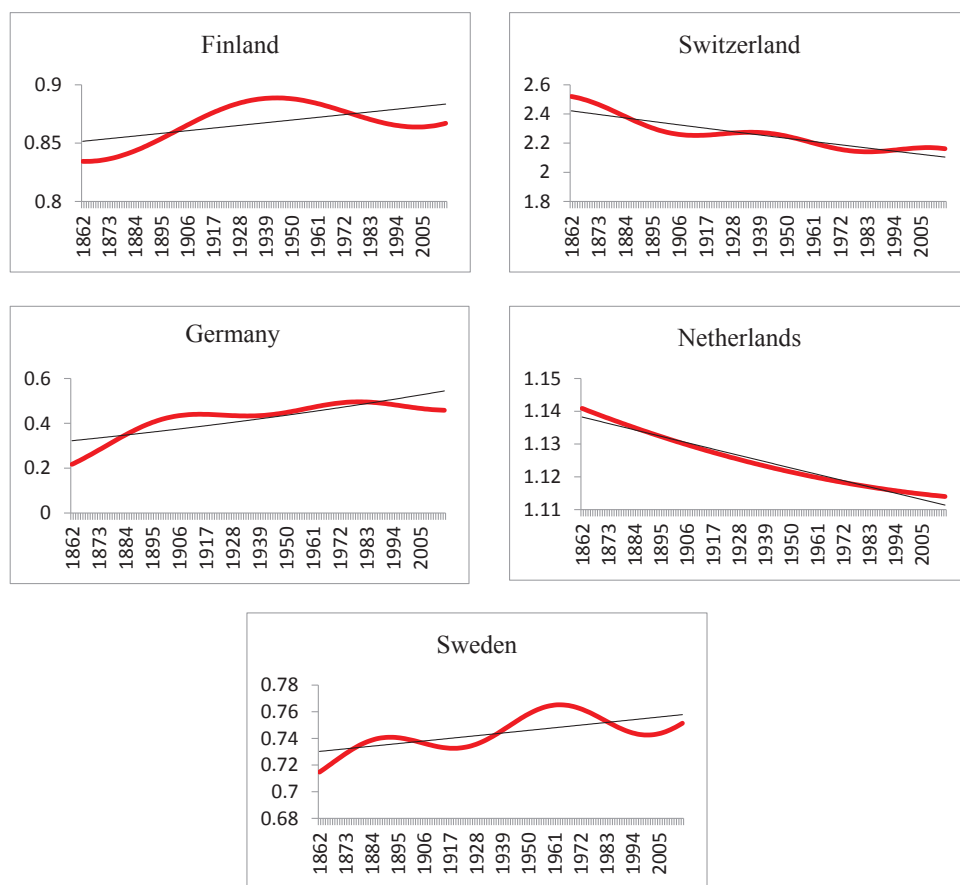


Fig. 3. Time-varying income elasticity of CO<sub>2</sub> emissions.

variables, but that has time-varying coefficients. An income elasticity based on time-varying parameters may be more appropriate in light of the changes an economy may undergo over long periods of time when structural breaks and parameter instability are likely to occur. Fig. 2 shows the pattern of our time-varying income elasticities over time.

The first thing to note, also from Table 5, is that all elasticities are positive. Our analysis conducted for a set of Western European countries over a very long period of time does not provide evidence in favor of negative income elasticities or absolute decoupling based on historical records. The second remark is that there are four countries –

Austria, Denmark, Netherlands, Switzerland – where the income elasticity is in excess of unity, pointing to no decoupling behavior, with emissions excessively sensitive to GDP. The third remark is that income elasticities are time-varying over time. This emerges more clearly in Fig. 3.<sup>10</sup> We see that there is a tendency for income elasticities in Switzerland and Netherlands to decline: these are also the two cases

<sup>10</sup> For completeness we report in Appendix B the time-varying behavior of the income elasticities of the remaining countries.



where the elasticity is highest. In the other three countries, the pattern is less clear: the elasticity appears to be hump-shaped over time, although it seems to be on the rise in the latest years. The variability of these elasticities is however very small.

To summarize, we find evidence in favor of relative decoupling – emissions increasing more slowly than GDP – in 8 out of the 12 European countries for which we have very long time series data. In nearly half of them, the analysis confirms a time-varying pattern for the income elasticities. Finally, no negative income elasticity results from our time-varying cointegration approach. This last result requires two remarks. The first one is that econometric evidence is based on historical data and experience: technological progress and changes in the structure of the economies have not been strong enough as to foster absolute emissions reductions. But this does not imply that policy intervention, which is therefore called for, may permanently reverse the trend in emissions. The second remark is that the usual EKC pattern, whether inverted-U shaped or not, portrays emissions vis-à-vis income, not against time as in Figs. 2–3. The income elasticities that are sometimes reported in the EKC literature are based on fixed coefficients regression models and their behavior is driven by that of GDP. Our income elasticities of emissions instead are based on a time-varying model specification. Comparisons between these two representations and corresponding empirical evidence are therefore not appropriate.

## 7. Conclusions and policy implications

The relationship between carbon dioxide emissions, the main gas responsible for global warming, and economic growth is among the most studied themes of environmental economics. The possibility of reducing overall emissions while keeping a high pace of economic development is at the heart of the notion of sustainable development.

Economists refer to the case when emissions increase (resp. decrease) less rapidly than the pace of economic growth as relative (resp. absolute) decoupling. This issue requires the empirical analysis of the emissions-GDP relationship. The study of this relationship has special importance for developed countries since they have been historically the main contributors of the global warming. The response of the emissions to the economic growth, that is the income elasticity of CO<sub>2</sub> emissions, is an alternative way to consider the decoupling issue. In this regard, the question to be addressed was whether the European economies, which can be considered as pioneers in the attainment of the sustainable development goals. This paper has studied this issue by employing recently developed econometric methodologies. The issue gains further importance if one considers that some recent studies have found always positive income elasticities for developed country cases,

which can be seen as an alarm regarding the sustainable development path of such countries.

The literature on the CO<sub>2</sub> emissions-income relationship is vast: it has used a variety of econometric methods, has been based on a panel of individual country analyses, has regarded developed and developing countries, among other features. In this paper, unlike the bulk of the literature, we have allowed the income elasticity of emissions – a critical metrics for the study of decoupling – to vary over time. The reason is that the elasticity might change through the time due to the factors affecting the drivers of the CO<sub>2</sub> emissions. Since the drivers of emissions evolve over time, the responses of emissions to the changing factors might be time-varying. We have used a time-varying coefficient cointegration approach to investigate the CO<sub>2</sub> emissions-GDP relationship for 12 Western European countries over a long period 1861–2015.

The main finding of the present study is that the income elasticities of CO<sub>2</sub> emissions are found to be positive in all investigated country cases. This does not obviously imply that active climate policy may induce a reduction in absolute emissions levels, as the very recent global trends seem to evidence. Our second main finding is that we find evidence in favor of relative decoupling – emissions increasing more slowly than GDP – in 8 out of the 12 European countries. The explanation for the finding of decoupling is that the investigated European countries pursued stricter carbon mitigation policies following the Kyoto Protocol and toward the Paris Agreement compared to other leading economies such as China, United States, and Russia. The remaining 4 cases the income elasticity of CO<sub>2</sub> emissions are in excess of unity. In nearly half of cases, the analysis confirms a statistically significant time-varying pattern for the income elasticities. In the remaining cases, some time-varying cointegration coefficients are not statistically significant which implies that income elasticities are positive and time-changing, but the change is very small, so that the average behavior of the coefficients seem to be constant over time. This confirms the usefulness of our time-varying coefficient cointegration analysis. The positive impact of income on CO<sub>2</sub> emissions for advanced economies can be considered by decision-makers as a call to take quick and relevant measures to mitigate emissions level without harming the economic development. The finding of relative decoupling allows us to conclude that, although the investigated developed countries pursue the policies to mitigate the environmental degradation and gained noteworthy results, there is still some way to go. That is, even though, the CO<sub>2</sub> emissions grow less rapidly than economic development, the rise in income level still increases emissions. In this regard, the countries should continue to follow proper policies, such as carbon taxation, carbon pricing, promoting the use of less carbon intensive technologies, to mitigate the emissions level.

Appendix

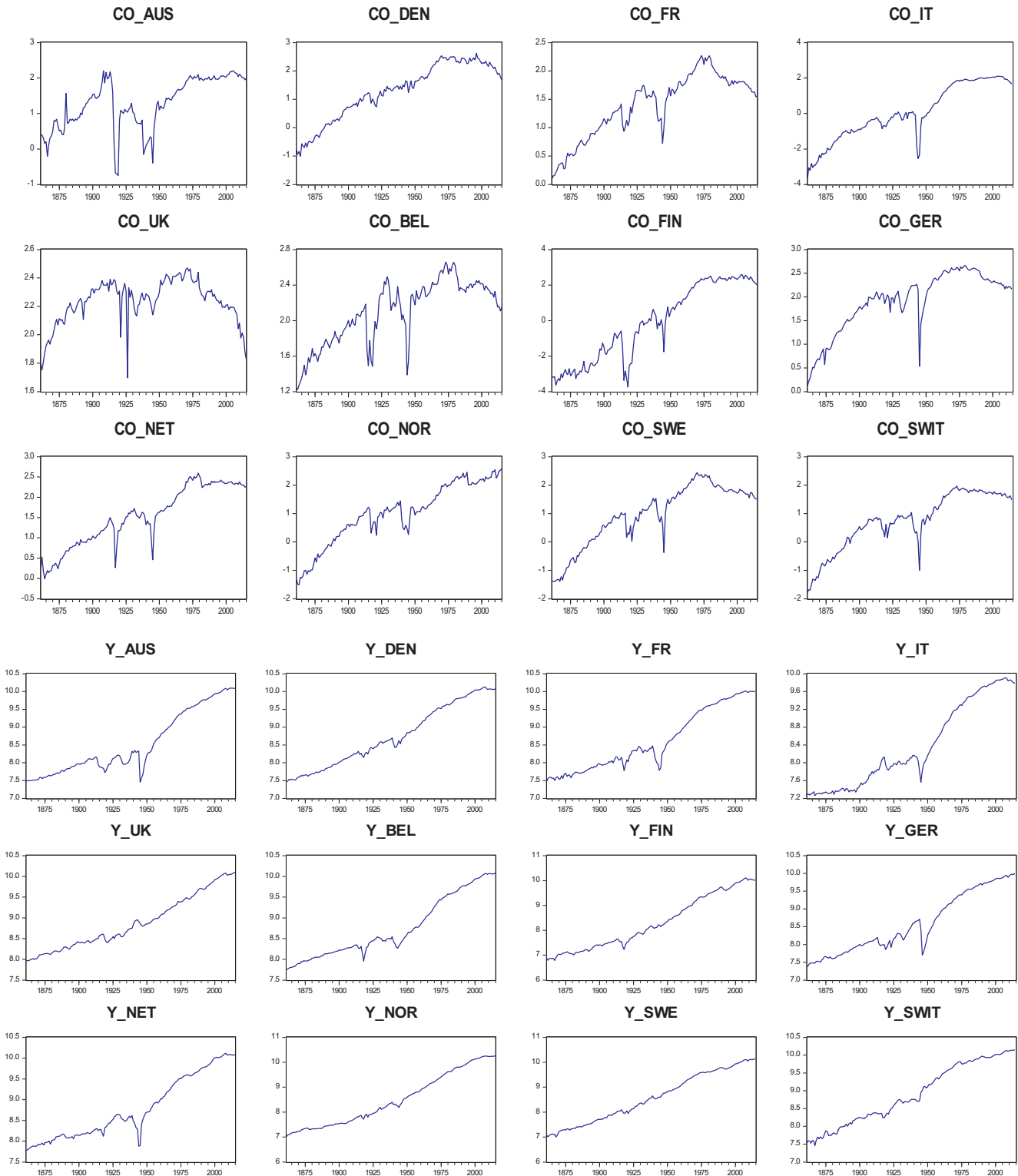


Fig. A.1. Time evolution of the variable levels (Panel A) and growth rates (Panel B). Panel A: Graphs of the levels of variables. Panel B: Graphs of the growth rates of variables.

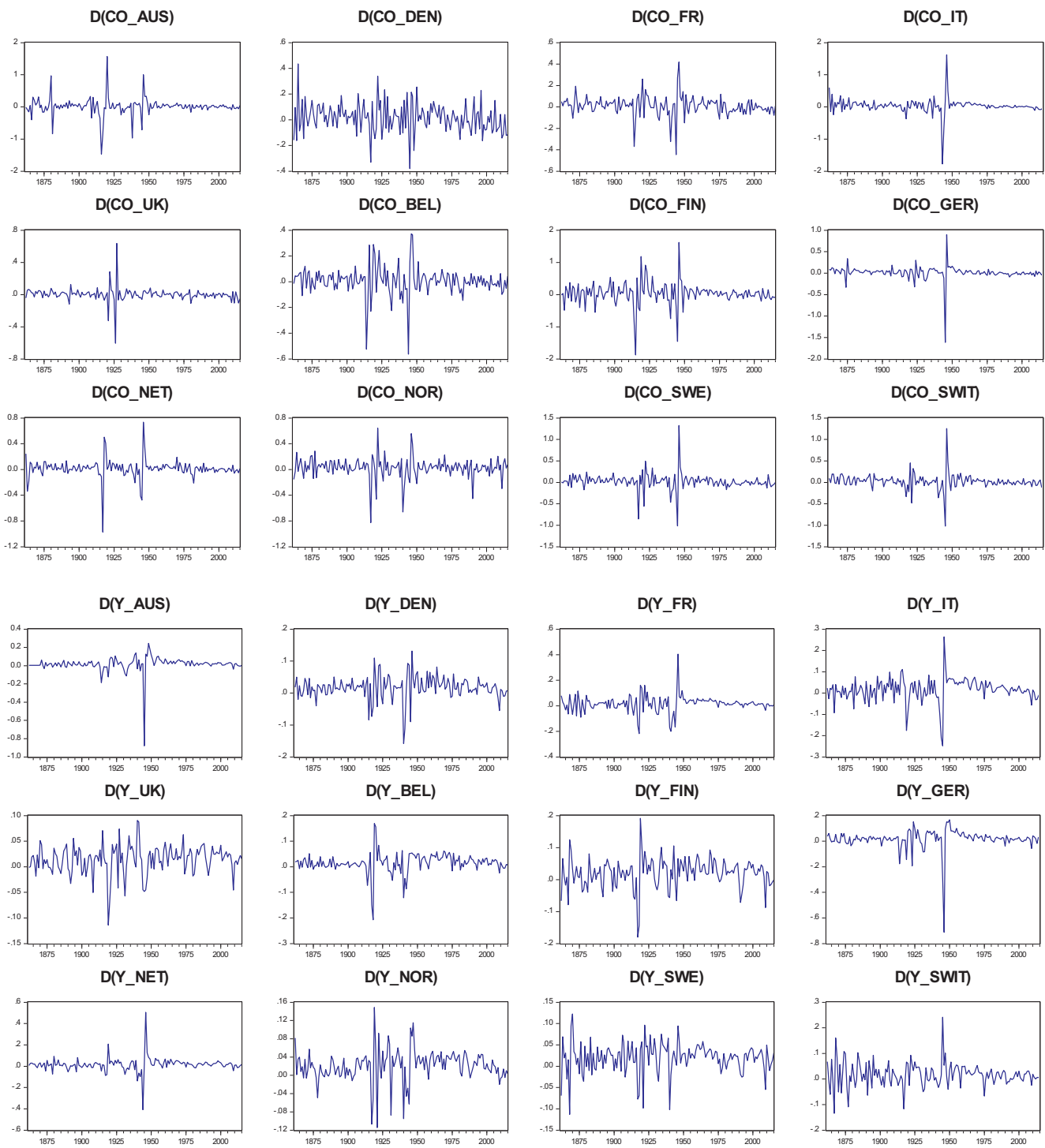


Fig. A.1. (continued)

**B. Determination of the number of the polynomials (p) and trigonometric pairs (q)**

As described in the methodology section the number of polynomials (*p*) and trigonometric pairs (*q*) in (9) should be chosen based on Bayesian Information Criteria (BIC). Based on the Ordinary Least Squares Method (OLS) estimation results the optimal number of *p* and *q* which minimizes the BIC value should be chosen as an optimal value. The selected values are reported in [Table B.1](#).

**Table B1**  
Optimal number of polynomials (*p*) and trigonometric pairs (*q*) in TVC specifications.

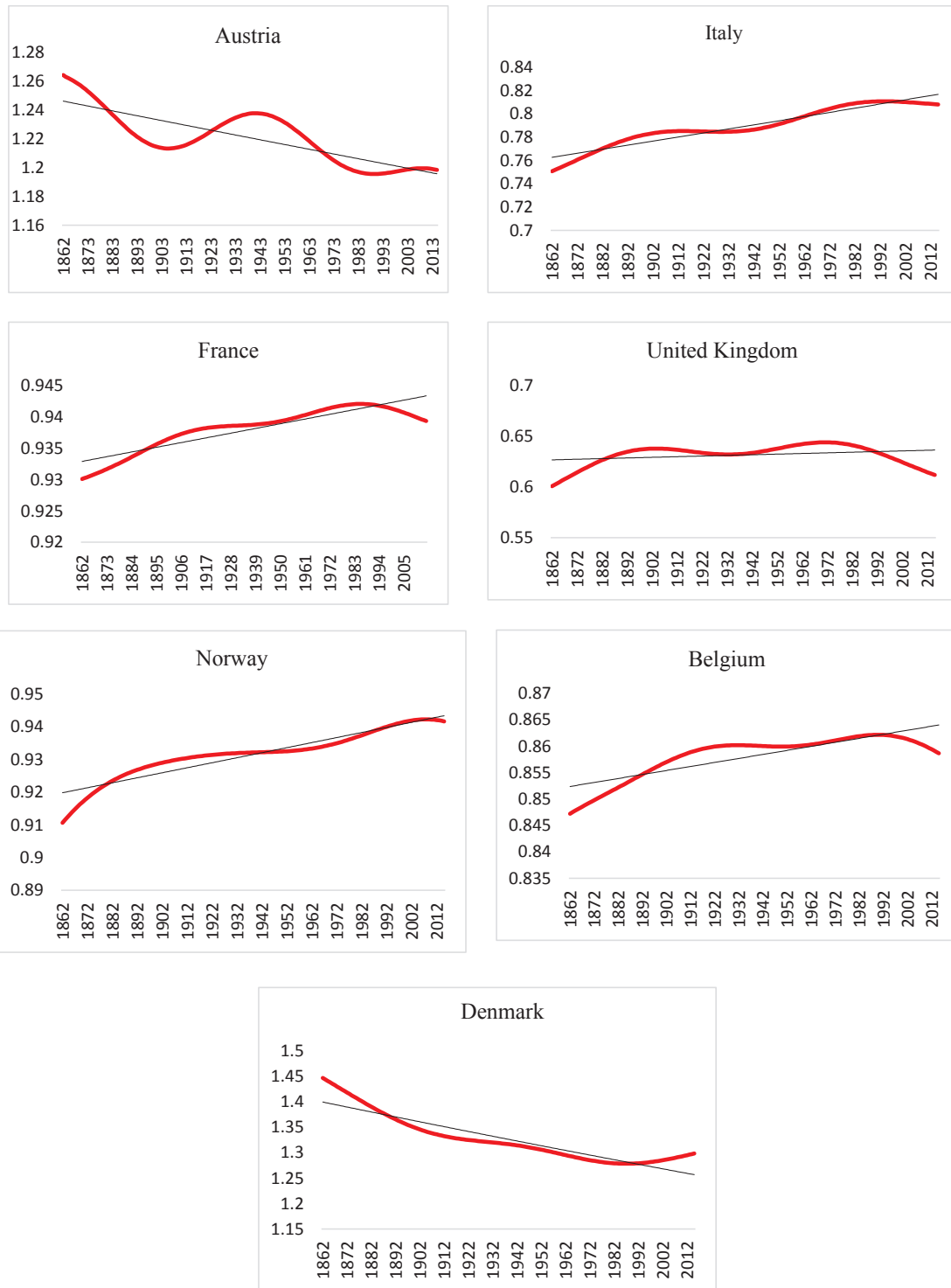
|  | Aus | Den | Fr | It | UK | Bel | Fin | Ger | Net | Nor | Swe | Swi |
|--|-----|-----|----|----|----|-----|-----|-----|-----|-----|-----|-----|
| Number of polynomials ( <i>p</i> )         | 1   | 2   | 2  | 2  | 2  | 2   | 1   | 2   | 2   | 2   | 1   | 1   |
| Number of trigonometric pairs ( <i>q</i> ) | 2   | 2   | 2  | 2  | 2  | 2   | 1   | 2   | 0   | 2   | 2   | 2   |

Notes: Aus = Austria, Den = Denmark, Fr = France, It = Italy, Bel = Beldium, Fin = Finland, Ger = Germany, Net = Netherland, Nor = Norway, Swe = Sweden, Swi = Switherland.

**C. List of countries**

- Austria
- Denmark
- France
- Italy
- United Kingdom
- Belgium
- Finland
- Germany
- Netherlands
- Norway
- Sweden
- Switzerland

**D. Countries with insignificant time-varying income elasticities of CO<sub>2</sub> emissions**



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