Bocconi

WORKING PAPER SERIES
ISSN 1973-0381

WORKING PAPER
N. 101
FEBRUARY 2018

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Decoupling of CO_2 emissions and GDP: A time-varying cointegration approach

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Abstract

The relationship between CO_2 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 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 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.

Unlike the bulk of the literature, in this paper we allow 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_2 emissions. We use a time-varying coefficients cointegration approach to investigate the CO_2 emissions-GDP relationship for 12 Western European countries over a long period ranging from 1861 to 2015.

The main finding is that the income elasticities of CO_2 emissions are found to be positive in all investigated countries. In addition, we find evidence in favor of relative decoupling – emissions increasing more slowly than GDP – in 8 out of the 12 European countries. The remaining 4 cases the income elasticity of CO_2 emissions are in excess of unity. In nearly half of cases the analysis confirms a statistically significant time-varying pattern for the income elasticities.

Keywords: CO_2 emissions, time-varying coefficient cointegration, economic growth, EKC hypothesis, decoupling

JEL classifications: C14; C32; Q01; Q43; Q52; Q53; Q56

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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.

In the past three years, global emissions of carbon dioxide from the burning of fossil fuels have levelled after rising for decades. 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 abandoning the planet to 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 side of the coin, it’s also a discussion of whether climate stabilization can drive growth. While the relationship between growth and resources is a complex one, recent developments show that CO_2 emissions stayed flat in the three-year period 2014-2016 while GDP continued to grow.

When emissions cease to increase or even decline while the economy grows we have what is referred to as decoupling. 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), whereby as income grows relative decoupling turns into absolute after some income turning point.[1] 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

[1] Decoupling is not an exclusive concept of CO2 emissions. It also refers to energy consumption and to several other pollutants (OECD, 2002).

can be observed.[2] Most contributions in the literature, however, prefer to rely on econometric analysis which allow to summarize 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 observed over a very long time period.

A useful metrics to evaluate decoupling is the income elasticity of CO_2 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 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_2 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 warrantied 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

[2] One recent example of this approach is Naqvi and Zwickl (2017) which examines the decoupling of six pollutants (including CO2 emissions) from economic activity in six economic sectors of 18 EU over the period 1995-2008. The literature on EKCs is vast and several surveys are available that summarize the evidence: one critical review is, for instance, Carson (2010).

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 CO2 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. The limitation of this method is that it requires having regimes for the used time period. Zanin and Marra (2012) investigate the EKC hypothesis 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). Esteve 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 Artic countries using the usual polynomial approach. Norway shows an EKC pattern; a 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 CO_2 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_2) which are taken to depend on income/GDP (Y) and population (P). It is customary to express the relevant variables in per capita terms, to control for the size of the economy. Thus:

(1) $$CO_2/P = g(Y/P)$$

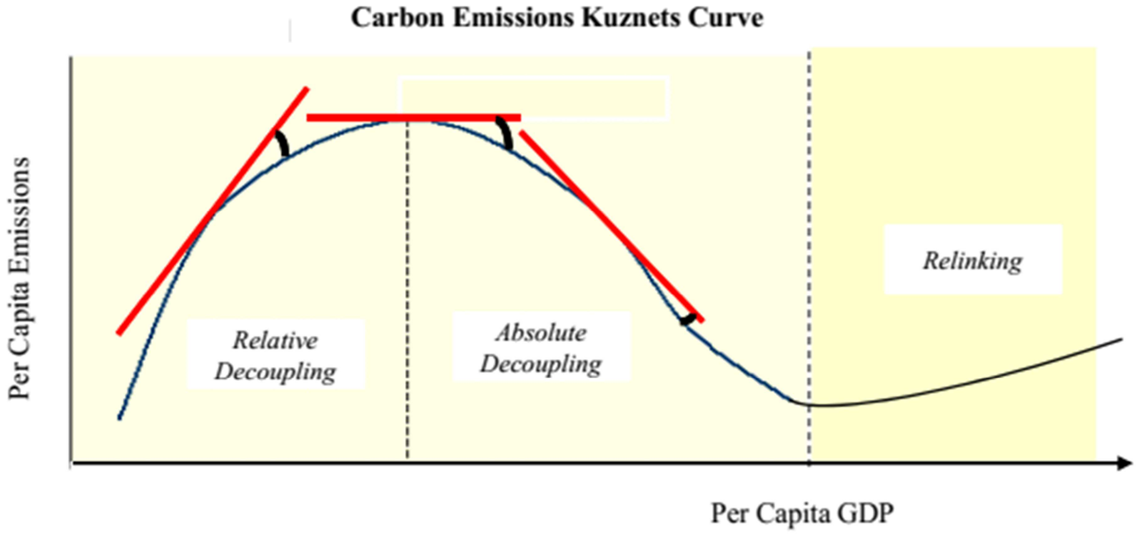
The Environmental Kuznets Curve (EKC) literature has been typically interested in the curvature of the environment-income relationship, in particular its possible inverted-U shape, and in the location of the income turning point where the curve starts declining. This is equivalent to assume that $g(.)$ in (1) possesses certain analytical properties. In the literature decoupling, income elasticity of emissions, and Kuznets curve behavior are closely interrelated aspects of the emissions-income relationship. Thus, $g(.)$ 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 $g(.)$. That is:

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

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

Figure 1: Decoupling of emissions from GDP



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*(.). In other words, we have the following:

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

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 Figure 1. Absolute decoupling is thus what is needed for a Kuznets inverted-U behavior. Figure 1 shows that in principle we can have a third possibility: relinking. This occurs when:

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

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 a N-shaped relationship would occur. This is what is portrayed in Figure 1.

The decoupling notion can be easily expressed in terms of income elasticity of emissions. If CO_2 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:

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

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 t ary 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 Figure 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:

(6) $$lnco_2 = \alpha_0 + \alpha_1 lny + \alpha_2 (lny)^2 + \alpha_3 (lny)^3$$

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_2 emissions. In fact:

(7) $$\eta = \frac{\partial lnco_2}{\partial lny} = \alpha_1 + 2\alpha_2 lny + 3\alpha_3 ln^2 y$$

Note that linear double-log specifications of the emissions-income relationship entail a constant income elasticity equal to α_1: as such neither relative nor absolute decoupling can be modelled. 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 α_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_2 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, Stoker, and Judson, 1998) or non-linear-in-parameters specifications (Galeotti, Lanza, and Pauli, 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 may be 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) employes 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_2 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 Kalman filter approach and a reduced form model with endogenous break is that they require the choice of regimes, which might limit the results. 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_2 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 United Kingdom. Carbon dioxide emissions from fossil fuel burning are expressed in $MtCO_2$, 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_2 emissions data are taken from Boden at al. (2016), the data on GDP and population are taken from the Maddison Project (2013 version) presented in Bolt and van Zanden (2014).[3] CO_2 emissions and GDP are converted to per capita terms after dividing by population.

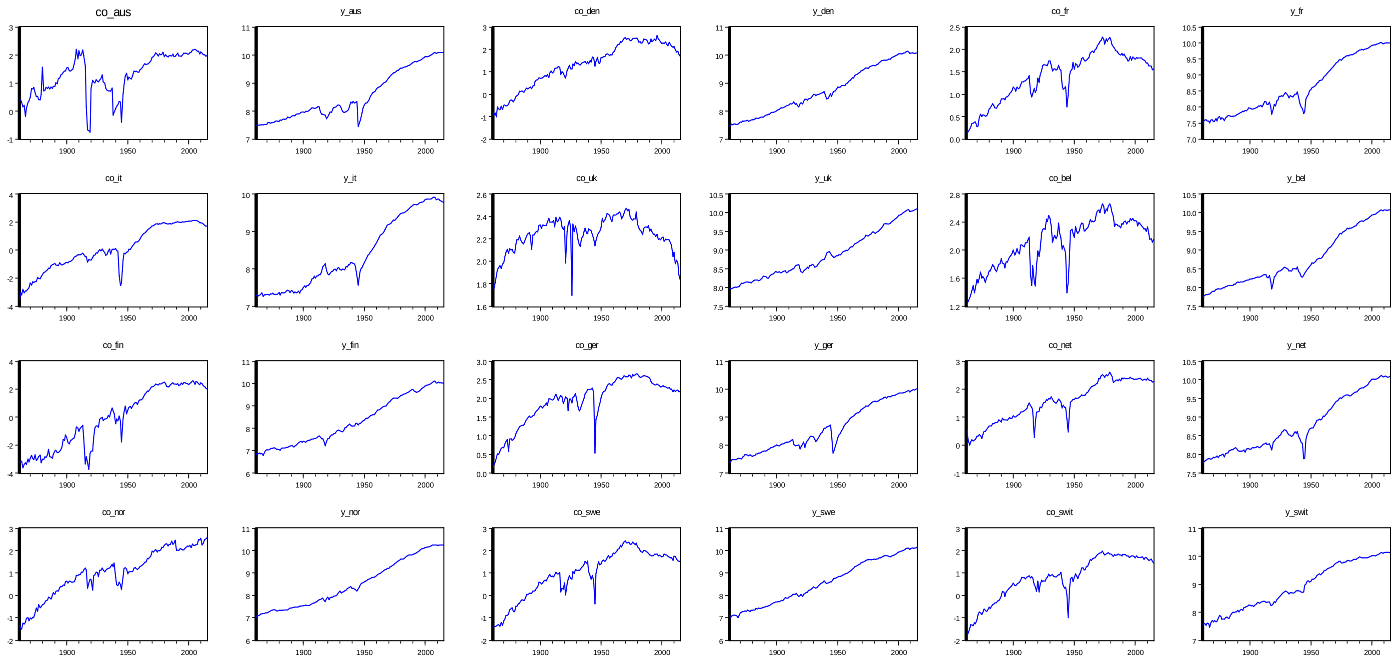
Long time series are especially suited for a time-varying parameter analysis. On the other hand, since we do not have available data for other relevant explanatory variables for such a long period, in our specification we can only use GDP and population data. However, considering that our main focus is the income elasticity of CO_2 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 is likely not cause a significant problem.

Figure 2 shows the time evolution of per capita emissions and GDP both in terms of levels (logarithms) and growth rates.

[3] The emissions data from Boden at 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.

Figure 2: Time evolution of the variable levels (Panel A) and growth rates (Panel B)

<u>Panel A: Graphs of the levels of variables</u>



<u>Panel B: Graphs of the growth rates of variables</u>

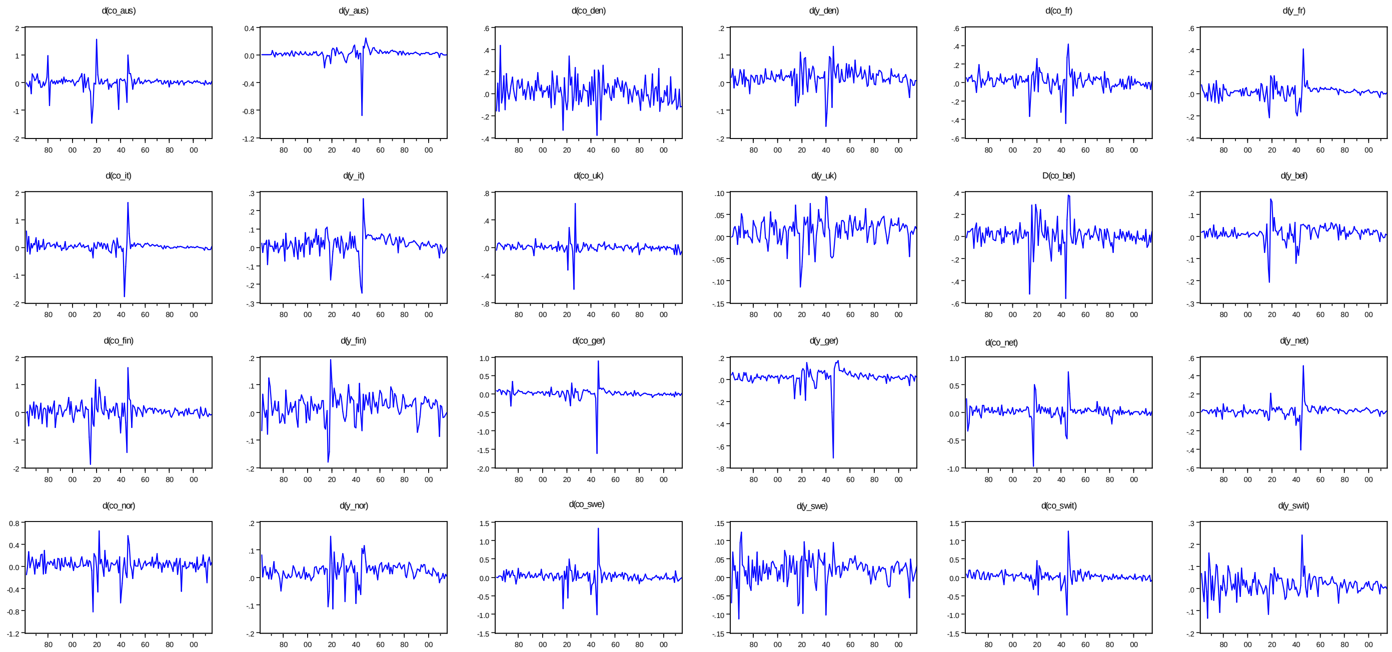


Table 1 presents some descriptive statistics. It can be seen that over the sample period CO_2 emissions displayed a high volatility in many countries reaching the highest values in Italy and Finland. It was low for United Kingdom, Belgium, Germany (coefficient of variation smaller than 33%), whereas for France, 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 United Kingdom, Belgium and Netherlands. The level of volatility of income is relatively higher in Italy, Finland, Norway and Sweden.

Table 1: Descriptive statistics

	CO_2 emissions per capita					GDP per capita				
Country	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.

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, 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 structural break (ZA) (Zivot and Andrews, 1992).[4]

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 prevoius section. All variables appear to be stationary at the first differenced form; we thus conclude that the logged variables are I(1).

[4] 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.

Table 2: Unit root test results

variable / country	$lnco_2$		lny	
Austria	-4.782**(1914)	-11.980***(1938)	-11.964***(1914)	-7.489***(1945)
Denmark	-12.439***(1917)	-17.921***(1945)	-11.879***(1915)	-11.178***(1940)
France	-11.872***(1914)	-11.292***(1939)	-5.344***(1914)	-6.496***(1940)
Italy	-10.158***(1916)	-7.833***(1943)	-10.240***(1919)	-9.669***(1940)
UK	-11.242***(1919)	-11.492***(1926)	-9.434***(1919)	-8.008***(1940)
Belgium	-11.383***(1914)	-10.494***(1939)	-9.926***(1914)	-9.741***(1939)
Finland	-16.036***(1915)	-12.999***(1939)	-6.790***(1914)	-6.972***(1939)
Germany	-15.827***(1919)	-10.227***(1945)	-8.838***(1914)	-4.649**(1945)
Netherlands	-11.292***(1915)	-11.296***(1939)	-10.009***(1916)	-9.964***(1939)
Norway	-11.731***(1916)	-14.513***(1940) -14.282***(1990)	-11.931***(1917)	-12.036***(1940)
Sweden	-16.457***(1917)	-15.357***(1940)	-12.662***(1916)	-12.786***(1938)
Switzerland	-11.347***(1917)	-11.291***(1940)	-11.379***(1916)	-11.630***(1938)

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

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.[5] Within this framework, we can simply specify (6) as follows:

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

where u_t is a latent disequilibrium error sequence assumed to be weakly dependent. Note that the GDP elasticity of CO_2 emissions is simply equal to α_t but it is varying over time and can therefore be used to study the decoupling issue.

[5] 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.

Coefficient α_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 α is a function defined over the unit interval which admits a FFF, we can write:

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

where $\phi_j(\mathrm{r})$=$(cos2\pi jr,\ sin2\pi jr)'$ 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:

(10) $$lnco_{2t} = \tau + z_{pqt}'\theta + u_{pqt}$$

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 $\lambda_1 = \cdots = \lambda_{p+2q} = 0$ 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). Equation (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 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.[6]

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.

Table 3: Tests for cointegration and for joint significance of coefficients

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

[6] The TVC estimation has been performed using Eviews 9.5 programming features.

Switzerland	4.66*	14.86	13.28	9.49	7.78	94.20***	15.09	11.07	9.24

Notes: The left hand side of the table demonstrates 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 $\lambda_1 = \lambda_2 = \lambda_3 = \lambda_4 = \lambda_5 = \ldots \lambda_k = 0$ 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.

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 at 0.5% significance level. For two countries, namely Finland and Germany, the VAT test suggests cointegration only at 0.2% significance level.[7] Park and Hahn (1999) suggest that the failure to find cointegration relationships in many studies based of 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.[8]

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 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 (λ_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: λ_0) is significant in all country cases with insignificant TVCs, thus supporting the finding of a positive income elasticity.

[7] The critical value for the 0.2% significance level is 16.92.

[8] 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.

5.4 Time-varying coefficients and income elasticity of CO_2 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.

Table 4: Estimated time-varying coefficients

			Parameters of the Time varying Income Coefficient					
	τ	λ_0	$\lambda_1: \frac{t}{T}$	$\lambda_2: (\frac{t}{T})^2$	$\lambda_3: cos(2\pi \frac{t}{T})$	$\lambda_4: sin(2\pi \frac{t}{T})$	$\lambda_3: cos(4\pi \frac{t}{T})$	$\lambda_4: sin(4\pi \frac{t}{T})$
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: τ is constant term, λi's are the coefficients of income variable. *, ** and *** stand for rejection of null hypothesis at 10% , 5% and 1% significance level, respectively.

For the remaining countries only the coefficient λ_0 is statistically significant. This implies that the income elasticity of CO_2 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 CO2 emissions we calculate is the following:

(8)
$$\eta_t = \frac{\partial lnco_2}{\partial lny} = \alpha_t = \lambda_0 + \lambda_1 \left(\frac{t}{T}\right) + \lambda_2 \left(\frac{t}{T}\right)^2 + \lambda_3 cos\left(2\pi \frac{t}{T}\right) + \lambda_4 sin\left(2\pi \frac{t}{T}\right) + \lambda_3 cos\left(4\pi \frac{t}{T}\right) + \lambda_4 sin\left(4\pi \frac{t}{T}\right)$$

Table 5 reports the estimated income elasticites of CO_2 emissions. In the table we distinguisgh between countries for which the TVC coefficients λ_i (i = 1,...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_2 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 minimum and maximum values of TVC coefficients. Central coefficient is the estimated value of λ_0 . * and *** stand for significance of TVC coefficients at 10% and 1% significance level respectively.

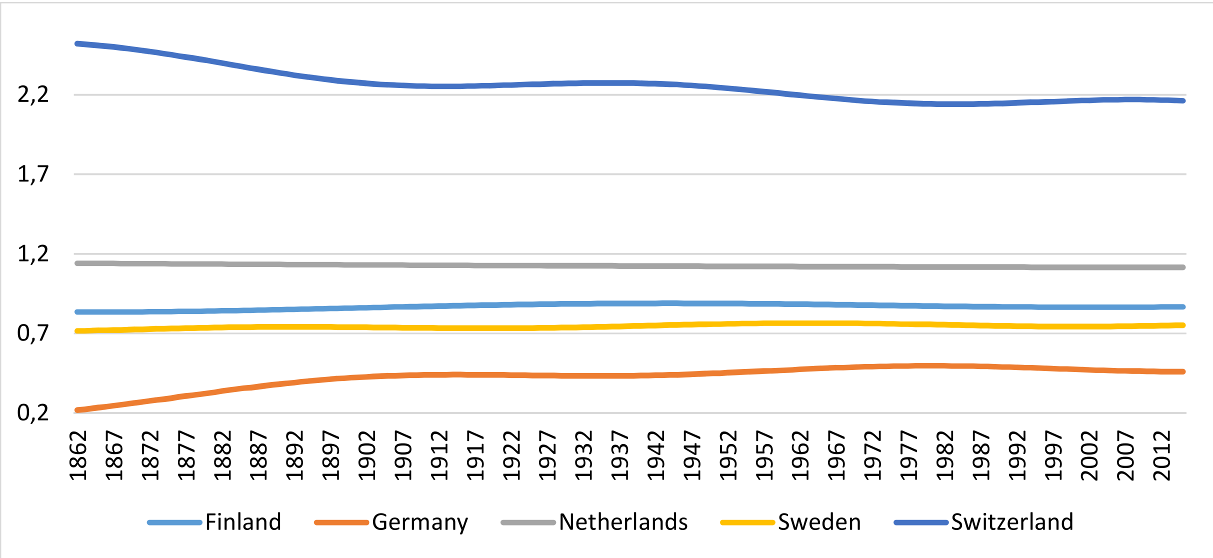
6. Discussion

The possibility of decoupling the behavior of CO_2 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 bewteen 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_2 emissions. Indeed, no decoupling implies an elasticity larger than one, relative decoupling a positive less then 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_2 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 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. Figure 3 shows the pattern of our time-varying income elasticities over time.

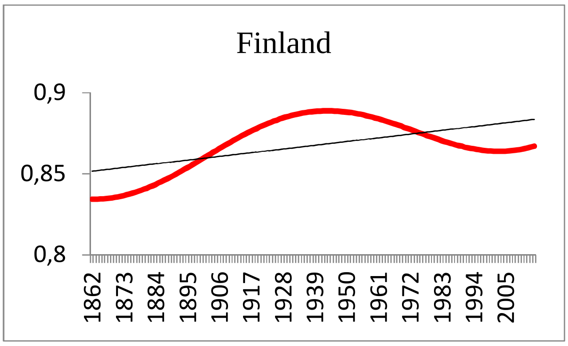
Figure 3: Time-varying income elasticities of CO_2 emissions (I)

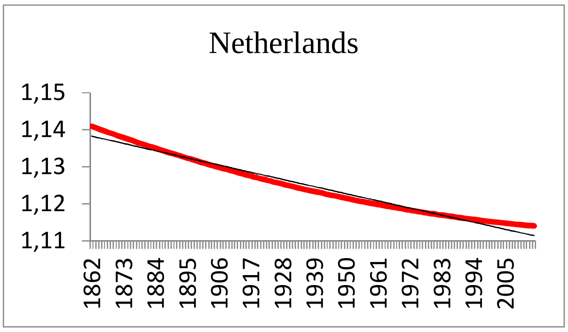


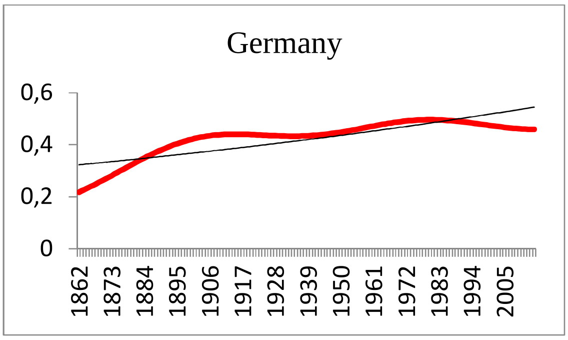
The first thing to note, also from Table 5, is that all elasticities are positive. Our analysis conducted for a set of Western European countries over a very long period of time does not provide evidence in favor of negative income elasticties or absolute decoupling based on historical records. The second 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 elasticties are time-varying over time. This emerges more clearly in Figure 4.[9] We see that there is tendency for income elasticities in Switzerland and Netherlands to decline: these are also the two cases 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.

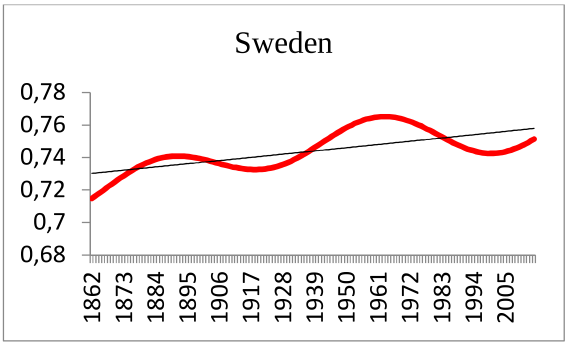
Figure 4. Time-varying income elasticity of CO_2 emissions

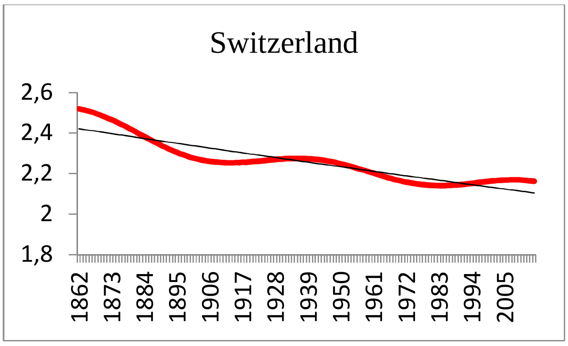
[9] For completeness we report in appendix B the time-varying behavior of the income elasticties of the remaining countries.











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 Figures 3-4. 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_2 emissions is an alternative way to consider the decoupling issue.

The literature on the CO_2 emissions-income relationship is vast: it has used a variety of econometric methods, has been based on 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_2 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_2 emissions-

GDP relationship for 12 Western European countries over a long period ranging from 1861 to 2015.

The main finding of the present study is that the income elasticities of CO_2 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 remaining 4 cases the income elasticity of CO_2 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 coefficient seem to be constant over time. This confirms the usefulness of our time-varying coefficient cointegration analysis.

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Appendix

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

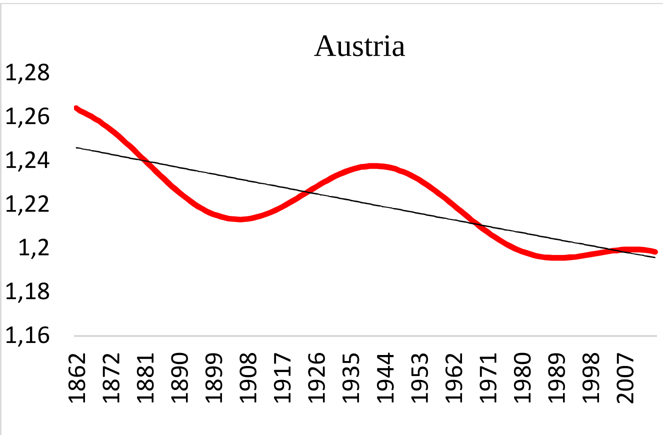
As described in the methodology section the number of polynomials (*p*) and trigonometric pairs (*q*) in (9) should be chosen based on Bayesian Information Criteria (BIC). Based on the Ordinary Least Squares Method (OLS) estimation results the optimal number of *p* and *q* which minimizes the BIC value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

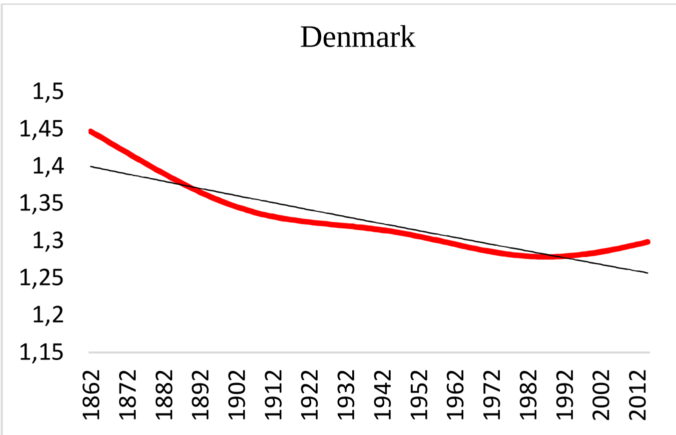
Table A.1: Optimal number of polynomials (*p*) and trigonometric pairs (*q*) in TVC specifications

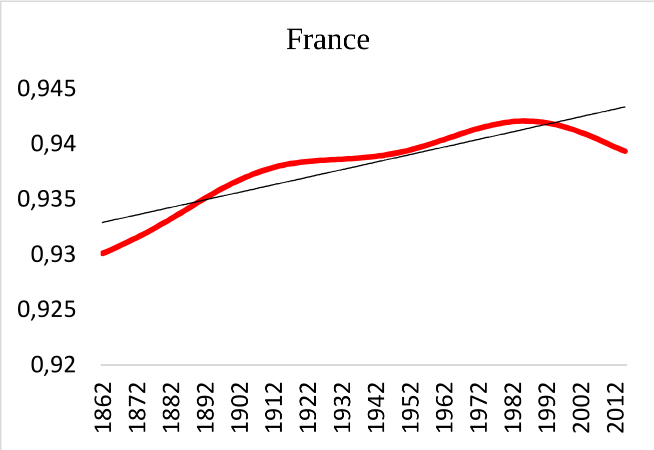
	Aus	Den	Fr	It	UK	Bel	Fin	Ger	Net	Nor	Swe	Swi
Number of polynomials (*p*)	1	2	2	2	2	2	1	2	2	2	1	1
Number of trigonometric pairs (*q*)	2	2	2	2	2	2	1	2	0	2	2	2

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

B. Countries with insignificant time-varying income elasticities of CO_2 emissions



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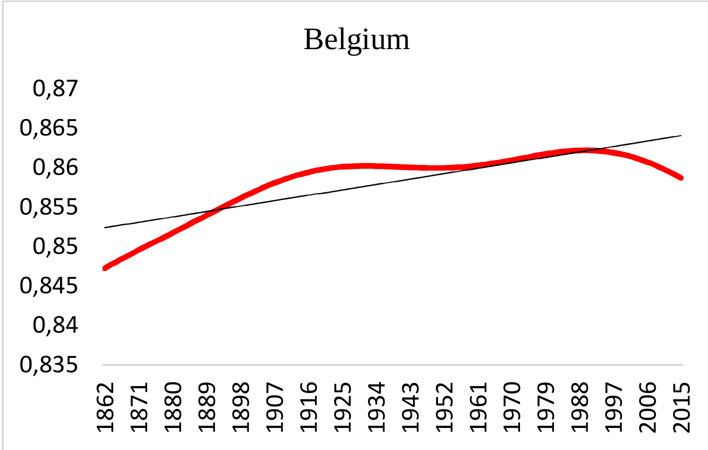
1862 1872 1882 1892 1902 1912 1922 1932 1942 1952 1962 1972 1982 1992 2002 2012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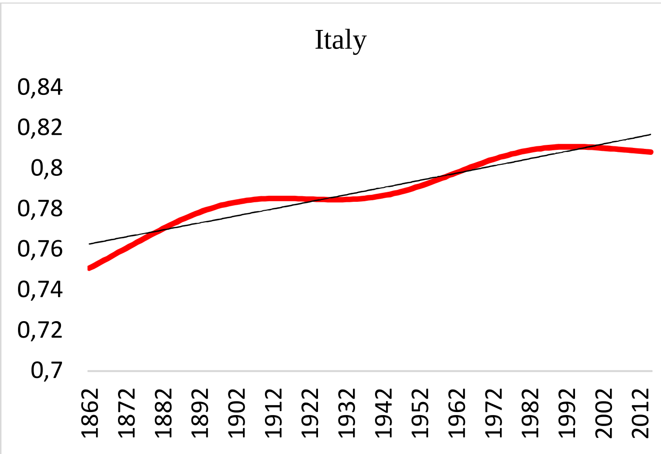
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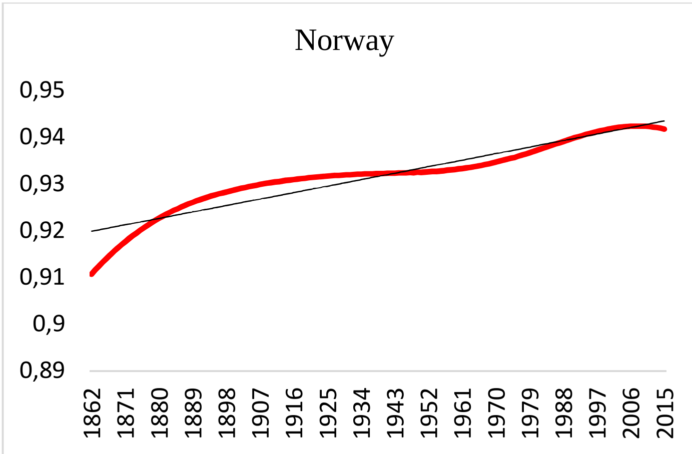
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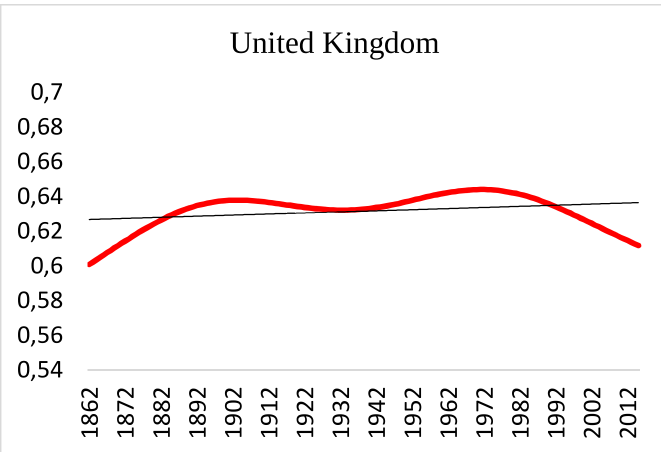
United Kingdom
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1862 1872 1882 1892 1902 1912 1922 1932 1942 1952 1962 1972 1982 1992 2002 2012