“Relationships between economic growth, CO2 emissions, and innovation for nations with the highest patent applications”

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Relationships between economic growth, CO_2 emissions, and innovation for nations with the highest patent applications

Abstract

This study aims to provide insight on the nexus between innovation, economic growth and CO_2 emissions. In order to achieve this, data on potential factors such as innovation, environmental taxes, research and development (R&D) spending, electricity production, population size, high-technology exports and prices of photovoltaic systems are collected for the sample of the leading innovative countries over the period from 1990 to 2014. Based on a cointegrated panel methodology and a vector error correction model, the long-run, as well as the short-run dynamics of all possible combinations between the variables under study, are estimated. The results reveal that except for China, economic growth is mainly driven by electricity production, population size, CO_2 emissions and R&D spending. However, innovation was found to have lesser effect on economic growth. In addition to that, the authors found evidence in favor of CO_2 emissions being affected positively by population size and prices of photovoltaic systems and negatively by environmental taxes, high-technology exports, R&D spending and innovation. Moreover, on the contrary to population size, well-being is positively affected by CO_2 emission and R&D spending.

Keywords: economic growth, CO_2 emissions, innovation, population, electricity generation, vector error correction.
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Introduction

During the past two decades, many countries took actions to mitigate climate change, undergoing a structural shift from fossil fuel-based economy towards a green economy. To achieve this goal, a massive deployment of green technologies has been pursued, and policy efforts have been undertaken in order to allow for less carbon emissions to produce the electricity needed by the whole residential, commercial and industrial markets, target more environmentally-friendly transport options, and help replace energy-intensive products with products that are more environmentally sustainable.

Moreover, many countries have concentrated on acquiring production technologies, skills and talent not only to address climate change, but also to obtain a larger share of the green business. In fact, although the main drivers in mastering a production technology are not easy to identify, particularly when the technology has been initiated and developed by other countries, there is general agreement that innovation is the main driver of economic and social progress, and is an important path to help address climate change. The majority of countries have increased significantly their R&D budgets to spur stronger technology industries and producers towards developing new products or/and improving existing designs. Other parameters, such as the environmentally related taxes (ERT), the domestic spending on research and development (GERD), electricity generat, the size of population, high-tech exports, and the average prices of photovoltaic panel systems are often cited, since all of these parameters are likely to play an important role (Figure 1).

The literature dealing with interrelations between GDP growth, R&D expenditures, energy sector, electrical energy consumption, technology patents, energy technology patents, CO_2 emissions, electricity consumption, fossil fuel prices and costs of PV technology is extensive, and sometimes confusing. However, the reported studies are limited to a particular choice of a country or a group of countries, a particular time period of varying length, and a particular relationship and concern only specific proxy variables.

The objective of this study is to identify and analyze all the long-term relationships between all the relevant economic variables involved over the same time period and on the same country basis. Countries targeted are chosen among the most active in terms of patent applications. Two key variables are targeted: real GDP and CO_2 emissions. Specifically, the analysis presented in

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this paper focuses on the existence of long-term and short-term relationships between these variables and between the innovation, the environmentally related taxes (ERT), the domestic spending on research and development (GERD), the electricity generated, the size of population, the high-technology exports, and the level of price of photovoltaic panel systems.

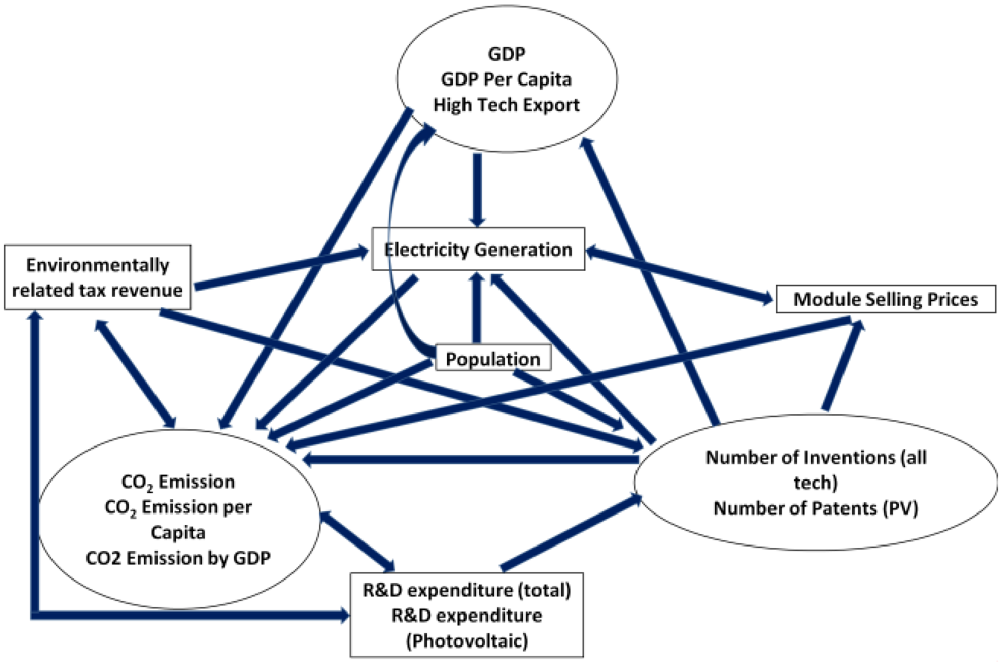


Fig. 1. Interactions between the different variables

For the purpose of empirical analysis, a comprehensive list of proxy variables/indicators is established. Moreover, the analysis is specific to a panel of countries that are the most active in terms of patent applications. The period between 1990 and 2014 is selected for the analysis since it has experienced the most deployment of renewable energy technologies in history so far.

Using a cointegrated panel methodology and the vector error correction model (VECM), the long-term and short-term dynamics are examined through all combinations of variables in order to highlight the most likely relationships that meet the long-term equilibrium conditions.

The remainder of this paper is organized as follows: section 1 presents a select review of the pertinent empirical literature; section 2 describes countries and data selection, research methodology, and data processing; section 3 gives the empirical results and analyses and discussions, and indicates the limitations with some suggestions for further research; The final section draws the main conclusions and policy recommendations resulting from the analysis results.

1. Literature review

The literature examining the relationship between growth, innovation that is driven by R&D and CO_2 emission is abundant. Everett et al. (2010) went over the literature that focused on the environmental policies intended to affect investment in innovation and, hence, growth. They evinced the complexity of the relationship between economic growth and the environment and tried to provide some insight to design effective policies that respect the environment and help the economy achieve sustainable and durable economic growth.

Our main objective is to verify to which extent innovation can generated growth while reducing CO_2 emissions. In particular, we focus on the literature that deals with renewable energies, notably the photovoltaic energy. We intend to provide a brief review of the main studies by presenting the methodologies employed and main results achieved.

The majority of the studies that explored the relationship between energy consumption and GDP treated the case of developing or emerging countries, and rarely that of developed ones. In addition to that, the methodologies that are often employed are mainly the cointegration models or the Granger causality techniques. Among the studies that dealt with developing or emerging countries, we can cite Lee (2005), Wang et al. (2012), Kapusuzoglu and Karan (2012) and Van der Zwaan et al. (2016).

Lee (2005) examined the relationship between energy consumption and GDP for 18 developing economies over the period from 1975 to 2001. Using panel-based cointegration error correction models, he found evidence in favor of the growth hypothesis. That is, energy consumption drives GDP growth both in the long run and in the short run. Hence, for developing economies, restrictive energy policies can hamper growth.

Wang et al. (2012) differentiated between fossil-fueled energy and carbon-free energy technologies and explored the causality running from energy technology to CO_2 emissions for 30 provinces in Mainland China over the period from 1997 to 2008. Based on dynamic panel data, they found that on the contrary to fossil-fueled energy technologies, carbon-free ones helped reduce CO_2 emissions, especially in Eastern China.

Kapusuzoglu and Karan (2012) considered a set of factors including total population, share of rural population, GDP, energy prices and carbon dioxide emissions for a sample of 30 developing countries over the period from 1971 to 2007. They used Granger causality methods to explore the causal relationship between energy consumption and the factors chosen. They found no general causal relationship between energy consumption and the factors chosen for all countries. In fact, they claimed that such a relationship seems to be country-specific. However, they found evidence in favor of the quantity of CO_2 emissions being closely correlated with energy consumption. Nevertheless, due to the difference in the energy efficiency level of each country, its change is not proportional. In addition to that, they detected the existence of a causal relationship between energy consumption and GDP for the countries, where energy is considered as a more important factor of production than capital or labor. They also claimed that for the developing countries, considered energy prices are found not to strongly affect energy consumption.

Van der Zwaan et al. (2016) focused on electricity production in Latin America, which is responsible for significant increases in greenhouse emission, but considered as a part of the efforts deployed to dwindle the climate change effects. They suggested several scenarios and assessed the future quantities of CO_2 emissions in Latin America. They also evaluated the relation between economic growth and the electrification of the energy system in order to reduce CO_2 emissions.

Among the studies that dealt with developed or emerging countries, we can cite Lorde et al (2010), Lanzi et al. (2012), Zheng and Kamman (2014).

Lorde et al. (2010) employed a neo-classical one sector aggregate production model and treated the case of Barbados for the period from 1960 to 2004. They focused on electricity consumption and distinguished between residential and non-residential sectors. They found evidence in favor of a long-run relationship between electricity consumption and economic growth. In particular, electricity consumption by non-residential drives GDP growth in the long run and granger causes real GDP in the short run.

Lanzi et al. (2012) considered the incentives used by 11 OECD countries over the period between 1978 and 2008 to employ electricity production technologies that help to alleviate climate change effects. They found that fossil-fuel prices impact significantly the invention activities within or across the different technologies considered. They suggest that after a certain price level of fossil fuel, the invention activities will move away from fossil fuel based technologies to the renewable energy technologies.

Zheng and Kamman (2014) constructed a dataset for the photovoltaic industries in the United States, China, Japan, and Germany covering the period from 2000 to 2012. They examined the significance of innovation and cost reduction in photovoltaic technology as a potential long-run solution to alleviate climate change effects. They suggested that incentivizing innovation in the photovoltaic sector should be conducted until rendering it cost-competitive relation to the conventional electricity production, after which it can benefit from economies of scale, market growth and cost reduction to enjoy a self-expanding phase.

2. Methodology and data description

2.1. Methodology. The empirical analysis in this study is conducted using a cointegrated panel methodology to overcome the endogeneity and the nonstationarity problems. In particular, the constructed two-dimensional panel data provided us with a large number of observations and helped us increase the degrees of freedom, while reducing collinearity between variables. Our approach consists of the following three steps.

First, for each variable under study, we apply five panel unit root tests that were proposed by Levin, Lin and Chu (2002, henceforth, LLC), Breitung (2000), Im, Pesaran, and Shin (2003, henceforth IPS), Fisher-ADF (Dickey & Fuller, 1981), and Fisher-PP (Phillips & Perron, 1988). These panel unit root tests have higher power than unit root tests based on individual time series (Maddala & Wu, 1999; Choi, 2001). The null and the alternative hypotheses of all these tests are provided in Table 1. According to the results of the panel unit root tests, we can safely conclude that all the variables under study are integrated of order 1, I(1).

Table 1. Null and alternative hypothesis for unit root tests

Test	Null hypothesis (H0)	Alternative Hypothesis (Ha)
LLC	Panels contain unit roots	Panels are stationary
Breitung	Panels contain unit roots	Panels are stationary
IPS	All panels contain unit roots	At least one panel is stationary
Fisher-ADF	All panels contain unit roots	At least one panel is stationary
Fisher-PP	All panels contain unit roots	At least one panel is stationary

Second, we perform the heterogeneous panel cointegration tests developed by Pedroni (1995, 1997) and Kao (1999). These tests are based on an examination of the residuals of a spurious regression performed using I(1) variables. When the variables are cointegrated (the alternative hypothesis), the residuals are expected to be I(0). Otherwise, the residuals will be I(1) (the null hypothesis). Consider the following regression, where y and x are assumed to be I(1), and are heterogeneous intercepts and trend coefficients across cross-sections:

$$y_{i,t} = \alpha_i + \delta_i t + x_{i,t}^1 + x_{i,t}^2 + ... + x_{i,t}^s + e_{i,t} \qquad (1)$$

Under the null hypothesis of no cointegration, the residuals $e_{i,t}$ will be I(1). We test whether the residuals are I(1) by performing the following regression:

$$e_{i,t} = \rho_i \ e_{i,t-1} + u_{i,t} \qquad (2)$$

where $\rho_i = 1$ indicates the non-rejection of the null hypothesis of no cointegration.

Pedroni distinguishes two alternative hypotheses: the homogenous alternative ($\rho_i = \rho > 1,$ for all I), which Pedroni terms the within-dimension test, leading to eight statistics, and the heterogeneous alternative ($\rho_i = \rho < 1,$ for all i) referred to as the between-dimension, leading to three other statistics.

A total of eleven statistics are generated, whose properties depend on the number of periods and the number of cross-sections. The tests for cointegration proposed by Pedroni also allow for three deterministic trend specifications (individual intercept only, individual intercept and individual trend, and neither intercept nor trend). The Kao test is based on the same approach as the Pedroni tests, but specifies cross-section specific intercepts and homogeneous coefficients on the first-stage regressors. It also allows for three types of lag length selection (Akaike Info Criterion, Schwartz Info Criterion, and Hannan-Quinn Criterion).

Third, in order to confirm the existence of cointegration and examine the short-run and long-run causalities, we apply a panel vector error correction model (VECM). More precisely VECM is a restricted VAR designed to be used for non-stationary series that are known to be cointegrated. Engle and Granger (1987) demonstrated that a set of I(1) cointegrated variables can always be represented by a VECM model, meaning that the variations of a dependent variable are explained, on the one hand, by the variations in the other explanatory variables, and, on the other hand, by a function of the level of imbalance occurring in a long-term relationship, called the error correction term. The VECM model can be described by the following equation:

$$\Delta y_{it} = \delta_{1i} + \delta_{2i} t + \alpha_i \left(y_{it-1} - \beta'_i x_{it-1} \right) + \sum_{j=1}^{p_i} \alpha_{ij} \Delta y_{it-j} + \sum_{j=0}^{p_i} \gamma_{ij} \Delta x_{it-j} + e_{it} \qquad (3)$$

where δ_{1i} and δ_{2i} represent the deterministic components. A deterministic component generally includes a constant and a linear time trend. It describes the short-run impact of a change in y_{it-1} , y_{it-2} . . . and x_{it} , x_{it-1} , x_{it-2} . . . on y_{it} . The term in parentheses represents the long-run movement towards the equilibrium relationship between the variables. The error correction model in Eq. (3) can be stable only if all the variables are stationary. Hence, a long-run equilibrium relationship can be defined by the vector only if that the errors are also stationary. Any deviation from this equilibrium relationship leads to a correction by a proportion $\alpha_i < 0$

Our analysis is performed using a panel data set of 12 countries including China and India, spanning the period from 1990 to 2014, as described in section 2.2. Proxies are selected for a set of variables and a vector error-correction model is constructed when cointegration exists. Later, the long-run and short-run dynamics are examined through all possible combinations of the variables considered by the study.

2.1.1. The variables considered. Variables are chosen from the commonly used and accessible data sources. Because time series data have usually the property of being non-stationary, resulting in spurious regression analysis, only variables I (1) are considered. Thus, we first perform a panel unit root test (Kwiatkowski et al., 1992), including five statistics, namely Levin, Lin and Chu (LLC), Breitung, Im, Pesaran, and Shin (IPS), Fisher-ADF, and Fisher-PP (Levine et al., 2002; Breitung, 2000; Im et al. 2003; Dickey & Fuller,1981; Phillips & Perron, 1988). Tests are carried out on the original variables and on their first differences, allowing for individual effects and individual linear trends, and selecting automatically maximum lag length based on Schwarz Information Criterion (SIC). The test results for the retained variables are summarized in Table 7 provided in the Appendix, hence, recording twenty-nine variables I(1). Table 8 in the Appendix defines each variable and specifies the sources and the scope of data. With these 29 variables, eight groups are constituted as indicated in Table 2.

Groups 1, 2 and 3 are, respectively, associated with CO_2 emissions, GDP and innovation. The choice of a dependent variable Y in one of the groups 1 or 2 and four explanatory variables X_1, X_2, X_3, and X_4 each in one of the remaining groups leads to 35,108 possible choices[1].

Table 2. The eight groups (29 variables)

Group	Variables	Number of variables
1	CO_2_EMISSION, CO_2_EMISSION_PC, LOG(CO_2_EMISSION), LOG(CO_2_EMISSION_PC)	4
2	GDP_PC, GDP_2010US, H_TECH_EXP, LOG(GDP_PC), LOG(GDP_2010US), LOG(H_TECH_EXP)	6
3	NB_INVENTIONS_ALL_TECH, NB_PATENT_WB, PCT, TOTAL_WIPO, LOG(NB_INVENTIONS_EPV), LOG(NB_RD_P1000)	6
4	RD_PCNT_GDP, RD_EXP_2010US, GERD_USD_PPP_2005, LOG(RD_EXP_2010US), LOG(GERD_USD_PPP_2005)	5
5	TOT_ELEC_GENERATION, LOG(TOT_ELEC_GENERATION)	2
6	ERT_PCNT_GDP	1
7	MODULE_SELLING_PRICE, LOG(MODULE_SELLING_PRICE), LOG(PRICE_SI_PV_CELLS)	3
8	POP, LOG(POP)	2

2.1.2. Relationships and linkage analysis. In order to analyze all possible forms of relationships that can link CO_2 emissions and GDP, among themselves and with the other variables, the following three steps are considered (Figure A1 in Appendix):

♦ First step: equations pre-selection

Since the adopted modeling strategy is based on the widely used Johansen's co-integration test to determine long-run equilibrium association between a set of several I(1) times series, a series of cointegration tests is undertaken on the 35,108 equations. For that purpose, cointegration is tested using both the Kao test (1999) for the three lag selection choices: Akaike (AIC), Schwarz (SIC), and Hannan-Quinn (HQC), and the Pedroni test (within and between) for the three trend specifications (no deterministic trend, deterministic intercept and trend):

$$\Delta Y_{it} = C\left[Y_{it-1} - \sum A^k X^k_{it-1} - T_{CE}\right] + \left[\alpha \Delta Y_{it-1} + \beta \Delta Y_{it-2}\right] + \sum\left[B^k \Delta X^k_{it-1} + C^k \Delta X^k_{it-2}\right] + T_{VAR} \quad (4)$$

The existence of a long-term relation leads to retain only the equations for which the coefficient C in eq. (4) is negative and significant. Furthermore, in order to facilitate economic interpretation, only limited number of equations is kept including those that are such that if the dependent variable is expressed as a value, the explanatory variables are not expressed in log and vice versa. Finally, and to ensure a minimum quality of regression models, R2 is set to be higher than 0.6 and DW to be higher than 1.65.

Hence, 284 equations are pre-selected, satisfying four conditions: cointegration is confirmed, long-run equilibrium association is proven, R_2 adjusted is greater than 0.6 and DW is greater than 1.65.

♦ Second step: Vector error correction model estimation

For the 284 pre-selected equations, a vector error correction model (VECM) is established to examine for short-run and long-run causalities. Accounting for the trends TCE and TVAR in data, each equation (4) is indeed estimated five times, leading to 1,420 VECM regressions. Estimation results (Table 3) show 998 equations out of 1420 satisfying the conditions that the coefficient C is significant, C<0, R^2adj > 0.6 and DW>1.65, with a majority of them concerning GDP (71%). Among these equations, only four dependent variables Y are involved:

[1] The authors firstly select one group from groups 1 or 2, then four groups (in the disorder) from the remaining seven groups, i.e. 70 choices (2 x C_7^4).Inside each of the five groups, one variable is selected: the variable chosen in the first group is denoted Y, and X_1, X_2, X_3, and X_4 denotes the variables chosen in the following four groups. Hence, 35,108 different choices are made, and as many equations are analyzed: 16,544 are relevant to Y belonging to group 1 and 18,564 are relevant to Y belonging to group 2.

Table 3. Variables obtained and number of equations

Dependent variable (Y)	Number of equations
GDP_2010US	527
LOG(GDP_2010US)	181
CO_2_EMISSION	175
LOG(GDP_PC)	115
TOTAL	998

♦ Third step: results compilation and analysis

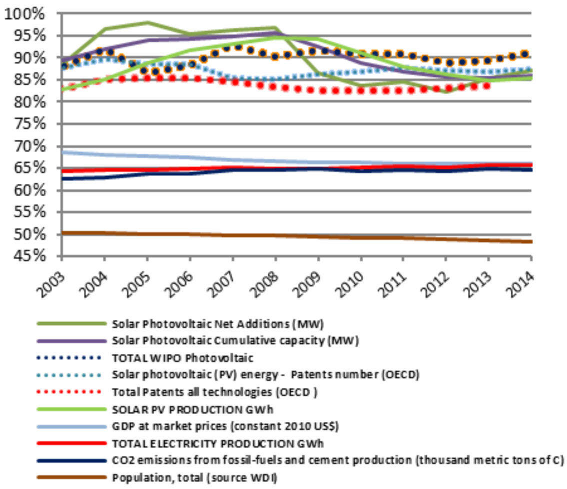
For each dependent variable Y, explanatory variables Xi with significant coefficients Ai, Bi and Ci are identified. The number of apparitions, the sign of the coefficient, and the median value are recorded. For each explanatory variable Xi, this allows for a statistical analysis to be performed, for example, counting the number of significant positive/negative value, calculating average and median value, graphically representing its distribution. The approach reported above is illustrated Figure 11 in the Appendix.

2.2. Panel data countries and period. The choice of the sample countries is based on data availability, especially, information about innovation. Patent statistics and R&D data are widely used in economic studies as innovation proxies, although they are both open to criticism. For the analysis conducted in this study, the total number of patent applications over the period 1995-2015 through the World Intellectual Property Organization (WIPO) is selected as a measure of innovation. Table 4 shows that twelve countries (ten OECD countries plus China and India) heads the ranking, with about 88 percent of total patent applications, (32,295,639 from 36,895,996); these countries are Canada, China, France, Germany, India, Italy, Japan, Republic of Korea, Spain, Switzerland, United Kingdom and United States. Thus, in this study, we will focus our analysis on these specified countries.

Table 4. Total patent application in percentage of global patent applications, during the period 1995-2015

Country	Percent (%)	Country	Percent (%)
China	26.2	United Kingdom	1.1
Japan	22.5	France	0.4
United States	18.2	Switzerland	0.2
Republic of Korea	8.9	India	0.2
Germany	5.8	Italy	0.2
Canada	2.2	Others	12.5
Spain	1.8	Total	100.0

Data published by the World Bank (WDI) also show that these countries account for 77.4 percent of research and development expenditures in the world, for the period between 1996 and 2014, and 86.7 percent for the period between 2010 and 2014. These countries account for about 50 percent of the world's population (Figure 2); approximately 65 percent of the global GDP, and about 65 percent of global CO_2 emissions. Their total electricity production is around 65 percent, while solar photovoltaic electricity production exceeds 85 percent. Moreover, the development of photovoltaic energy really began around 1990, and experienced a significant and continuous growth over the next few years.



Sources: World bank, IRENA, BNEF, IEA, WIPO, CDIAC, OECD, UNdata.

Fig. 2. Worldwide contribution of the 12 countries to solar PV and total electricity and solar PV production, solar photovoltaic capacity, CO_2 emissions, solar PV patents and all technologies patents, population, and GDP

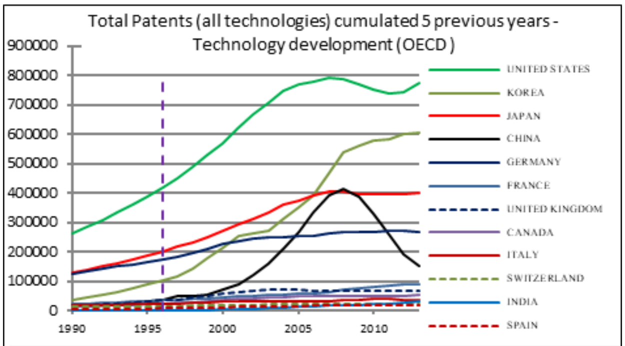
The empirical analysis is carried out using annual data for these 12 countries for the period between 1990 and 2014, namely Canada, China, France, Germany, India, Italy, Japan, Republic of Korea, Spain, Switzerland, United Kingdom and United States.

2.3. Data description.

2.3.1. Technological innovation. Firms spend significant resources on research, depending on the nature of their activity or their products, in order to make discoveries that can help develop new products. Research carried out and efforts undertaken are rewarded and resulted in patents granted, which are generally considered a good indicator of performance in research and development. The number of inventions (simple patent families) developed by country's inventors, have emerged as one of the main indicators suitable for measuring innovation and for tracking developments in technologies in general.

Using the total number of patents, all technologies developed (covered) by the OECD as a proxy to measure technological innovation, Figure 2 shows that since 2003, these countries experienced the largest share of patent applications, exceeding 80 percent of the global total. The same observation holds for the number of patents related to the photovoltaic sector based on OECD statistics, and for the patent applications shown in the most recent World Bank data (worldwide patent applications filed through the Patent Cooperation Treaty procedure or with a national patent office).

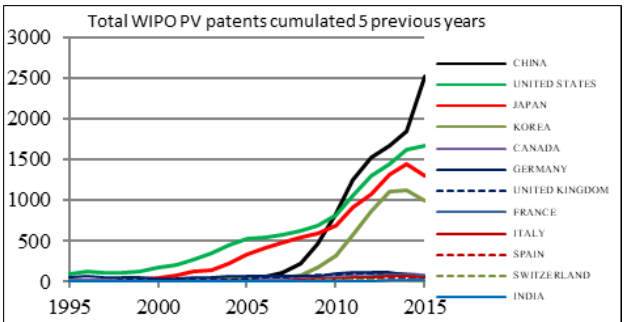
According to the OECD statistics and WIPO data, Figure 3 and Figure 4 indicate that Korea, United States, Japan, Germany and China are the major inventors (all technologies), and are also, with varying degrees, the most active in solar photovoltaic energy technologies.



Source: Own calculations using OECD statistics.

Fig. 3. Cumulated five previous years patents (all technologies)

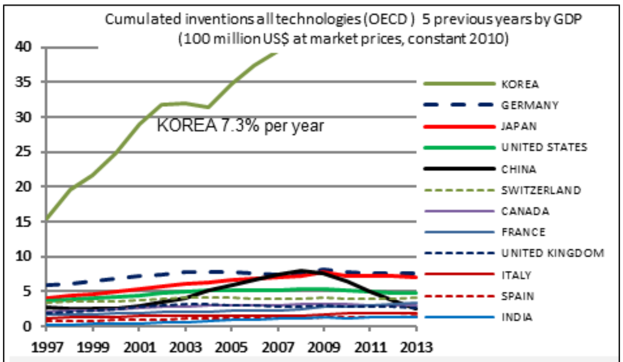
Differences in patent activity among countries reflect the substantial heterogeneity in the size and structure of the economy, the size of the population, and the budget devoted to innovation and dedicated to research and development. Thus, it is more appropriate to consider the number of patent applications relative to GDP, population, R&D budget, environmental taxes, etc.



Source: Own calculations, using the PATENTSCOPE database WIPO

Fig. 4. Number of patents related to photovoltaic sector, and containing one of the keywords "photovoltaic" or "solar cell" or "solar module" or "solar panel" in the title and in the English abstract

For two decades, as reveals the Figure 5, the Republic of Korea held by far the first position in number of patents application per GDP, with an increase of 7.3% annually. Germany stood in second place, followed by Japan and the United States. It is noteworthy that for all the twelve countries, the curves display an increasing ratio.

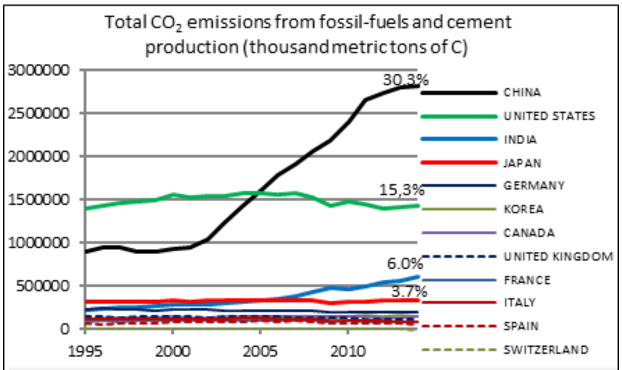


Source: Own calculations, from OECD statistics

Fig. 5. Five previous year cumulated inventions all technologies by 100 million US$ of GDP (at market prices, constant 2010)

For almost all the 12 countries, one can also see (Figure 5) a slight decrease in the patents application-to-GDP ratio from 2008 onwards, with the sharpest decline recorded for China. The Republic of Korea had also the highest applications-to-population ratio, followed by Germany, Japan, Switzerland and the United States.

2.2.2. CO_2 emissions. The top 4 emitting countries in the year 2013, together account for more than half (55.3%) of the total global CO_2 emissions (Figure 6)[2].



Source: CDIAC.

Fig. 6. Total CO_2 emissions from fossil fuels and cement production

China is by far the largest CO_2 emitting country, mainly due to the size of its population and

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[2] CO_2 emissions data are counted as the national emissions coming from domestic production, and do not account for the emissions embodied in international trade and in global production chains.

economy, but also because of the high share of coal in its energy mix (PBL and JRC, 2015).

The evolution of CO_2 emissions between 2005 and 2013 (Table 2) indicates a substantial variation among countries: China, India and the Republic of Korea hold the highest growth rates with, respectively, 7.9, 6.9 and 3.5 percent annually. These growth rates were higher than those recorded from 1995 to 2005. In contrast, the trend for the others countries has reversed with the best results achieved by Spain and Italy. Further, all countries but China, Republic of Korea and India reduced carbon emissions from energy consumption while increasing GDP over the period 2005-2013.

Table 5. Variation in CO_2 emissions between 1995 and 2013

	Percent (%)			Percent (%)	
Country	1995-2005	2005-2013	Country	1995-2005	2005-2013
China	5.2	7.9	United States	1.1	-1.6
India	3.7	6.9	Canada	1.6	-2.0
Republic of Korea	2.4	3.5	France	0.8	-2.0
Japan	0.6	-0.2	United Kingdom	0.0	-2.5
Switzerland	0.2	-0.8	Italy	1.1	-3.9
Germany	-0.8	-1.1	Spain	4.2	-5.2
			World	2.1	2.6

The rate of carbon emissions depends on various factors, such as the changes in the structure of the economy and its size, the growth of the economy itself, the energy intensity (total energy consumption per unit of GDP), the share of fossil fuel consumption in total energy consumption, GDP per capita, and the population size. Policy actions such as public expenditures on energy R&D also play a significant role in mitigating the CO_2 emissions at a country level.

The highest carbon emission intensity (CO_2 emissions by GDP ratio) levels were registered in China, India and Republic of Korea (Figure 7). Noteworthy, the carbon emission intensity has a sustained downward trend for the twelve countries exceeding two percent per year. These changes have several explanations. Among them, the structural changes in the economy, for example, in the relative share of gross domestic product (GDP) produced by the industrial, agricultural, or services sectors. Another factor is about the effects of environmentally related taxes on the spending household income, such as for heating and electricity. R&D expenditures are also likely to spur more research and marketing, leading to inventions in efficiency-enhancing electricity generation technologies as well as energy efficient vehicles, and encourage fuel efficiency investments.

The range of per capita carbon emission levels across countries is very large (Figure 8), reflecting wide divergences in energy end-uses. While the amounts of CO_2 per capita are falling down for the majority of the countries considered in the study panel, India, China and Republic of Korea showed a substantial growth.

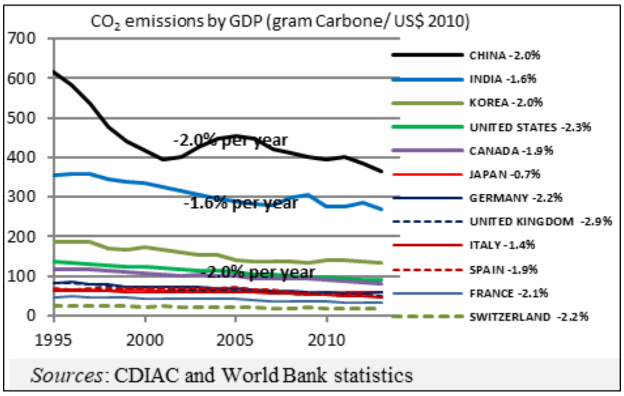

Fig. 7. CO_2 emissions by GDP (gram carbon/US$ 2010)

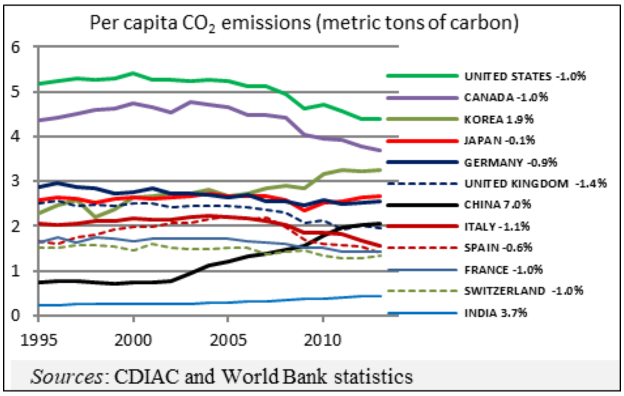

Fig. 8. Per capita CO_2 emissions (metric tons of carbon)

Using the Kaya decomposition analysis (1990), the main macroeconomic drivers of CO_2 emissions trends can be identified. Specifically, the identity expresses, for a given period, CO_2 emissions as the product of population, per capita economic output, energy intensity of the economy (primary energy consumption/GDP) and carbon intensity (CO_2 emission by primary energy consumption).

Figure 9 shows that GDP per capita is manifestly the main driver for the emissions growth, outpacing the growth of population and the decrease of CO_2 emission by GDP ratio. The latter was of significant contribution in mitigating the CO_2 emission growth.

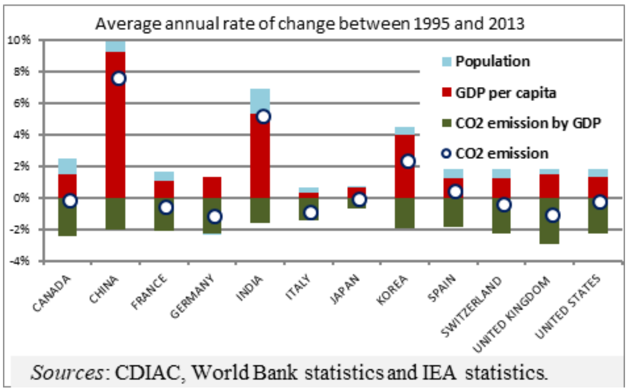

Fig. 9. Annual rate of change for CO_2 emissions and its drivers using Kaya decomposition analysis

Only China, India and the Republic of Korea have an important gap to close, as they contribute around 38 percent of the total world CO_2 emissions in 2013, respectively, 30.3%, 6.0% and 1.7% (see Figure 6).

2.2.3. Environmentally related taxes and R&D budgets. In order to achieve a sustained economic growth while enabling to address environmental challenges, governments implemented policies and designed instruments to shape relative prices of goods and services, and allocated budgets for R&D in innovating technologies.

Environmentally related tax (ERT) revenues, as a market-based instrument, have been designed to meet environmental and economic objectives, and consisted essentially of revenues from taxes on energy use and vehicles. Of course, the ERT has affected the international competitiveness of the countries industry. While these taxes were designed to meet primarily climate change goals, the environmental effectiveness of these measures is questionable and should be integrated as part of the whole market based instruments. Table 3 shows that the ratio ERT to GDP varies between about 1 and 2.5 percent for most countries. The greatest percentages are observed for Italy and the Republic of Korea. Table 3 also shows that for the period from 2005 to 2014, the ratio of ERT to GDP fell slightly for all countries, except for China, Korea and Italy: in fact, ERT increased by 18% per year for China and 4.1% for Italy, while GDP growth was 9.7% for the former and -0.9% for the latter.

Table 6. Average environmentally related tax revenue % of GDP

Country	1995-2005	2005-2014
Canada	1.43	1.17
China	0.75	1.26
France	2.22	1.91
Germany	2.34	2.17
India	1.28	1.05
Italy	2.98	3.19
Japan	1.73	1.63
Korea	2.59	2.69
Spain	2.11	1.78
Switzerland	1.89	1.83
United Kingdom	2.58	2.34
United States	0.95	0.79

Public investment in R&D also plays an important role in fostering innovation and in developing products that are more environmentally sustainable.

Between 1995 and 2014, as shown in Figure 10, China and Korea experienced the most important increases in R&D intensity (defined as GERD as a percent of GDP), and the highest values recorded are again found for the Republic of Korea and China, followed by the United States, Japan, Germany and India.

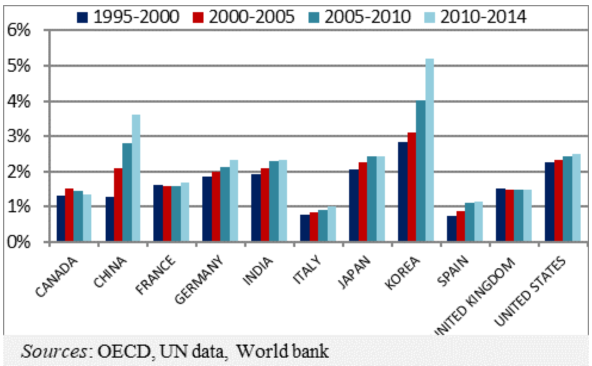

Fig. 10. R&D intensity average (five years periods)

This trend confirms the significant increase effort in R&D in emerging market economies, and its importance in turning these economies into high value-added producers.

3. Empirical results and discussion

As a reminder, the approach, followed in the analysis, examines only the equations that show the existence of a long-term equilibrium relation. Moreover, the analysis considers only significant coefficients to be taken into account. This reasoning led to only four dependent variables as indicated in Table 3. Among the variables listed in Table 3, three variables LOG(CO2_EMISSION), CO2_EMISSION_PC and LOG(CO2_EMISSION_PC) are not concerned by a long-term equilibrium relation linking them to the other variables. Only the variable CO2_EMISSION arises from this group 1. Similarly, among the variables dealing with GDP (group 2), the three variables GDP_PC, H_TECH_EXP and LOG(H_TECH_EXP) are not concerned by a long-term equilibrium relation linking them to the other variables. Table 11 to Table 14 in the Appendix summarize these details for GDP_2010US, LOG(GDP_2010US), LOG(GDP_PC) and CO2_EMISSION. Specifically, These Tables provide values for the long-term coefficients, the short-term coefficients at t-1 and the short-term coefficients at t-2, referring respectively to Ai, Bi and Ci coefficients in the equation (4).

3.1. Real GDP drivers. Focusing on GDP as dependent variable (Table 11 in Appendix), it appears that electricity production has the most direct long-term effect: 1 USD of GDP (at market prices, constant 2010) is associated with a 0.243 kWh increase in electricity generated. A short-term effect is also present with a negative sign at one year and positive sign at two years. The electricity production elasticity of GDP is 0.847 for the long term (Table 12). This indicates that the countries panel's economy is energy-dependent and, hence, electricity generation will result in economic growth. In other words, energy scarcity reduces economic performance. Hence, electrical energy sector acts as a driver of long-term economic growth.

Electricity demand is closely linked to GDP, as industries need energy to operate, electricity consumption increases when business prospers. Nonetheless, the relationship between GDP and electricity demand is rather complex. Indeed, focusing on energy end-uses, the electricity generated is broadly consumed by four segments: industrial, residential, commercial, and transportation. The primary electricity consumers differ between countries (refer to Figure 12 in Appendix). While the energy used by the commercial and public services sector ranges between 28 and 36 percent in 2014, China and India excluded, the greatest country disparities arise concerning the share of the industrial and the residential sectors. In 2014, the industry sector is by far the largest electricity consumer for China, Korea, Germany and India, whereas for the United States, France and the United Kingdom, the residential sector is the most significant consumer. In addition, the panel of evaluated countries is experiencing slower electricity demand due to the effects of the increasing efficiency in domestic appliances, the switching to renewable energy technologies for space heating and cooling and for water heating, and the emergence of efficient machines consuming less electricity.

On the other hand, a country's GDP stems from the industrial, agricultural, and services output. In countries that have high exposure to the industrial sector, the relationship between GDP and electricity generation is high since the industrial sector demands more energy than the service and agricultural sectors. Therefore, the structural changes which affect economic sectors have effects on the electricity demand. Moreover, within the same sector of activity, the development of new processes that is less energy-intensive, lead to higher productivity by having the same output with less energy consumption. Power producers and electricity suppliers are also involved, in particular with the new ongoing green programs.

Overall, the analysis shows that GDP is positively linked to the electricity generated in the long term, with an electricity production elasticity of GDP less than one. Moreover, the structural shifts in the economies of the different countries - which have diverse origins, such as competitions between companies on the domestic and international levels, environmental policies, and electricity prices - have been accompanied by improved energy efficiency. The results of the analysis, carried for this study, agree with those reported by Morimoto and Hope (2004) who found that changes in electricity supply have a significant positive impact on a change in real GDP in Sri Lanka, based on annual data for the period 1960–1998. The analysis findings are also in line with those of Yang (2000) who proved a causality between GDP and energy consumption (the aggregate as well as for coal, oil, natural gas, and electricity) for Taiwan by using data for the period 1954–1997. Fatai et al. (2004) found analogous results when analyzing four Asian economies between 1960 and 1999 (India, Indonesia, Thailand and the Philippines), and demonstrating a causality link running from energy to income. Masih and Masih (1996) also provided evidence of causality running from energy to income for India and Pakistan, over the period 1955–1990.

Population size has the second most relevant long-term impact on real GDP, also positively with a per capita contribution of 27.978 USD. In contrast, population size has no short-term effect. The population elasticity of GDP is 0.708 for the long-term effect (Table 12 in Appendix), indicating that changes in countries' population size lead to increases in output, due to increase in human skills and workforce. Far more important, it is noteworthy that real GDP per capita is negatively related to the population size with an elasticity of -0.569 (Table 13 in the Appendix). The same long-term negative impact is found when a set of analyses is carried out using smaller panels by excluding one country including China, the US, India, Korea, or Canada.

In fact, several internal and external factors underlie the assumptions of the different models of economic growth.

These factor are linked to the marked rise in working-age population, the improvement access to education and training, raising workers' skills levels widely, the labor globalization and the significant expansion of immigration, the rise in trade openness, and the facilitation of relocating manufacturing processes to less costly foreign locations (offshore outsourcing). The analysis approach, considered in the study, does not depend on the assumptions of a particular model. Even if the transmission processes are not explicitly modeled, the considered analysis takes into consideration a broader range of transmission processes from population to real GDP per capita. In this respect, it is worth recalling that the reported literature dealing with the relationship between population and real GDP per capita is extensive including the neo-classical growth theory, and the endogenous growth theory . In the first, economic growth is driven by productivity enhancement, particularly improvement of industrial production and technology, but the linkage between population growth and capital accumulation or technology is not proven. In the second, technological change is driven by population growth, and the transmission mechanism allow for a positive long-run relationship between population and the level of real GDP per capita.

Thus, the findings of the analysis conducted in this study are more consistent with the implications of standard neo-classical growth models, and are seemingly at odds with the implications of endogenous growth models.

Similarly, CO_2 emissions are also positively associated with GDP in the long-term, with 280 gr CO_2 (1÷0.01309 = 76.4 gr Carbon) per USD of GDP (Table 11 in the Appendix). Among the 198 equations in which the variable CO_2 emissions is present, only 5 have a significant short-term coefficient, indicating that the short-term effect is rather weak or non-existent. The CO_2 emissions elasticity of GDP is 0.703 (Table 12 in Appendix), which is close but lesser than the electricity production elasticity of GDP. Regarding GDP per capita, Table 13 in the Appendix shows that CO_2 emissions as well as CO_2 emissions per capita are beneficial to the standard of living. The GDP per capita elasticity to CO_2 emissions is 0.591 (Table 13). However, it must be stressed that such CO_2 emissions are production-based, counted as the national emissions generating from domestic production, and ignore the emissions embodied in international trade and global production chains.

Patent applications relating to photovoltaic sector (WIPO statistics) also appear to have a negative long-term impact on GDP. At the opposite, the analysis results show a presence of a positive effect in the short term. Unlike patent applications related to photovoltaic sector, the number of inventions accounting for all technologies (OECD patents data) shows a positive effect in the long-term, in line with the findings reported by the majority of the studies from literature that used patents as an innovation measure. However, this result is not convincing. Indeed, testing for robustness by repeating the same regressions after removing China from the panel, inventions accounting for all technologies appears to have a negative effect on GDP in the long term (Table 9 in the Appendix), meaning a decreasing role of innovation on economic growth when China is excluded from the panel. Moreover, Table 9 shows a positive impact of patents all technologies on economic growth when the panel considers China, but exclude any other country.

It is sensible to question whether innovation still plays a positive role in driving economic growth as it did in the past. Figure 13 in the Appendix shows that the ratio GDP to the 5-year cumulated patents observed various paths among countries. The ratio indicates a continual decline trend for most of the countries. Only China demonstrated an upward reversal of the trend after year 2008. Among the reasons that can be evoked related to the recent declining in the usefulness of inventions include:

The recent inventions are mostly extensions of the great past inventions, and no longer fundamentally improve the standard of living significantly as they used before.

The time lag is long between the moment of innovation and its effective broad dissemination in the economic landscape: it may well be that their effects to economic growth and living standards are revealed much later.

The impacts of macroeconomic instability, such as oil price movements, as well as the financial crises of 1997 and 2008, have probably contributed to the decline of the role of innovation (Griliches, 1988).

The effects of offshoring due to globalization can be significant. Whereas R&D and patent activities occur domestically, a part of the economic output is increasingly relocated overseas, particularly for less sophisticated production, requiring less highly qualified operating personnel.

The drawback of using patents as a proxy for innovation can be misleading: if patents are used by firms to protect their inventions, some prefer secrecy over patenting, depending on the value of invention. Moreover, only large companies have the means to patent their products, because small businesses cannot afford to pay fees. Similarly, some firms file patents to bar access to competitors.

Table 11 also shows that gross domestic expenditure on research and development (GERD) provides long-term benefits for the economy, as one USD GERD generates 42.7 USD additional GDP. A short-term effect is also present with a negative sign at one year and positive sign at two years. The GERD elasticity of GDP is 0.329 for the long-term. These findings are also valid (Table 9 in Appendix) when the panel excludes countries like Korea, China, and USA, which have the highest R&D intensity levels during the period 2010-2014 (Figure 10). However, the value of the long-term coefficient (0.04267) is the medium value among 91 values, and one should outline the presence of 28 negative values.

In fact, it is worth remembering that R&D expenditures can moderately measure the level of innovation since they capture only commercial innovation conducted by specifically defined R&D departments. The findings of the analysis conducted in this study indicate that R&D expenditures have a positive long-term impact on GDP, in compliance with the endogenous growth theory pioneered by Romer (1986) and Lucas (1988) who stressed the importance of innovation as a driving force of economic growth.

It is worth underlining that real GDP per capita is positively related to R&D expenditures expressed as percent of GDP, as well as to the number of researchers per million people (Table 13 in the Appendix).

3.2. CO_2 emission drivers. It should be stressed that CO_2 emissions are defined as the domestic production-based emissions. This definition has a major drawback in mitigating global climate change. Indeed, it overlooks the fact that the reduction of per capita carbon emissions in countries committed by international treaties to binding targets (especially the rich countries), has been accompanied by a significant increase in emissions in countries which are not falling under these agreements (generally the developing countries). Another negative point in using production-based emissions is that they ignore the emissions embodied in international trade and in global production chains.

Be that as it may, focusing on CO_2 emissions as dependent variable, analysis of long-term effects reveals the following insights (Table 14 in Appendix).

CO_2 emissions are positively impacted by population size in the long term. Although this finding is now well established (Casey & Galor, 2016; Anqing Shi, 2001; Raupach et al., 2007; O'Neill et al., 2010), the relationship is much more complex. It ignores the population composition and its age structure, both factors that can affect directly work productivity and indirectly carbon emissions through economic growth, as well as lifestyle associated with the level of urbanization. Moreover, urbanization can play a significant role in energy efficiency and work productivity (O'Neill et al., 2010). The countries included in the selected panel are very heterogeneous in this respect; USA and Canada on the one hand have the greater per capita emissions, while on the other India and China have the lowest ratio (see Figure 8).

Environmentally related taxes expressed in percent of GDP stands second behind population size and entail a reduction in CO_2 emissions (Table 14 in the Appendix).

As market-based instruments to meet environmental objectives, environmentally related taxes are a part of the policy strategy undertaken to take advantage of the growth and promote jobs opportunities provided by eco-innovation and environmentally-oriented products and services related sector. The effectiveness of environmentally related taxes measures is debatable (Figure 14), and depends on the country's social and economic structure including the share of the manufacturing industry, the share of the service sector, the final energy consumption, the share of fossil fuels in the primary energy supply, the electricity consumption related to the residential and commercial sectors. It also depends on the level of integration among others, market-based instruments, and the policy strategy used.

In our panel countries, China and USA (which together accounted for 45.6% of world carbon emissions in 2013), follow distinct patterns (see Table 10 in Appendix). China has seen a continuing high growth of 9.8% per year between 1995 and 2015. The USA has experienced 2.2% growth over the same period. Chinese ERTs increased by 18% per year between 2005 and 2014, whereas they decreased (-0.5% per year) for the USA. For China, emissions have accelerated sharply from 5.2% per year (1995-2005) to 7.9% per year (2005-2013), while at the same time emissions from the USA decreased (-1.6% per year between 2005 and 2013). Although the carbon emissions to GDP ratio have declined for both China and the US, the decline for China is -13.5%, less than for USA (-18.5%). Moreover, per capita emissions have doubled for China from 0.85 tons to 1.65 tons (2005-2013), but still remain below the US level of about 5 tons.

Thus, for China, carbon emissions have increased significantly due to structural changes in the population. Environmental taxes, although very important, must be continued and well managed in order to cope with the pollution sources caused by growth, as well as those linked to household consumption due to structural changes in the population.

High technology exports come in third place in mitigating CO_2 emissions. High-tech exports, which include aerospace, computing, pharmaceuticals, scientific instruments, and electrical machinery, have generally a low carbon emissions intensity and a high value-added. The analysis results show that increasing high-tech exports improves low-carbon emissions in the long, as well as the short term. Thus, a policy that encourages R&D and promotes investments in advanced technologies can help spur export of high value-added products, and hence induce a beneficial effect for the environment.

As would be expected, the decline in the prices of photovoltaic panels induces a decline in CO_2 emissions in the long-term. Because solar photovoltaic power plants are highly capital intensive and require significant upfront investments, the levelized energy costs of solar-generated electricity automatically drop as prices decline, which result in an increase of the renewable energy share in the overall energy matrix. Investment costs will also benefit from economies of scale and through the learning by doing process.

The three variables related to R&D budgets (GERD_USD_PPP_2005, RD_EXP_2010US and RD_PCNT_GDP) show a negative effect on CO_2 emissions.

This trend also applies to the number of patent applications relating to photovoltaic sector through the PCT variable.

We also note that the total electricity generation contributes to the increase of greenhouse gases.

Interestingly, GDP growth tends to move towards a lower level of CO_2 emissions, indicating that an economic growth policy can comply with the objectives of environment policy.

Regarding short-term effects, all the variables have some impacts. In particular, the variable for the environmental taxes expressed in percent of GDP has the highest effects among all the variables considered in the analysis and is more likely to affect positively CO_2 emissions. On the other hand, the raise of high technology exports entail diminishing CO_2 emissions in the short-term. It is interesting to note that the total electricity generation and the number of inventions for all technologies go in the direction of a slowdown in CO_2 emissions. However, GDP as well as the variables related to R&D budgets all show a positive impact on CO_2 emissions in the short-term.

3.3. Limitations and areas for further research. However, we must admit that our analysis could be improved in several ways. First, our data suffers from the aggregation problem and the results could have been improved if more disaggregated data were available for instance, for the expenditures of the photovoltaic sector on R&D for the case of India and China. However, such data are not available and is not calculated in the same way as it is calculated for the OECD countries.

Second, in our study, data on CO_2 emissions are counted as national emissions from domestic production without taking into account emissions incorporated into international trade, hence, into global production chains. In fact, when deciding on R&D activities, companies do not only consider policies adopted domestically, but usually take into account policies implemented by all other countries including developing ones. Hence, it is more plausible to add other countries to the study sample, especially emerging or developing ones. In the absence of complete data, it would be more interesting to apply the analysis using data on CO_2 emissions that take into account emissions incorporated into international trade and into global production chains.

Third, it is generally accepted that during the last two decades several policies were adopted and undoubtedly affected the innovation activities, CO_2 emissions and GDP growth. Hence, assessing the impact of such policies on other explanatory variables can help to improve our analysis by deciding if possible, on which other variables to include.

Finally, we believe that the model that we have developed on Eviews is very promising and can be extended to deal with other specifications and hence provide analysis of more complex and realistic cases.

Conclusions and policy recommendations

During the past two decades, many countries took actions to mitigate climate change pursuing a massive deployment of green technologies, undertaking policy efforts to shift the energy needed by the residential, commercial and industrial consumers towards less carbon emissions, allowing for more environmentally-friendly products and services, aiming for sovereignty over their energy self-sufficiency, and aspiring to economic and social progress. These measures were accompanied by significant advances in electricity production technologies, as well as high-level skills targeting the leading share of the green business market.

Based on the principle that innovation is the main driver of economic and social progress, this study focuses on the most active countries in terms of patent applications to identify and analyze the long-term drivers of the real GDP and the CO_2 emissions, in their interrelationships between the innovation, environmental taxes, domestic spending on research and development, the electricity generated, the size of population, the high-technology exports, and the price of photovoltaic panel systems.

In this study, a cointegrated panel methodology is considered using the vector error correction model (VECM) to examine the long-run and short-run dynamics through all combinations of variables. For the regression analysis, commonly used variables are selected from readily accessible data sources, satisfying the property of non-stationary. The results are analyzed through regressions that provide convincing outcomes econometrically.

The analysis outlined in this paper demonstrates a certain number of conclusive results:

First, among the explanatory variables considered (four relating to CO_2 emissions and six relating to GDP), four variables out of ten satisfy a long-run equilibrium equation: CO2_EMISSION, GDP_2010US, LOG(GDP_2010US) and LOG(GDP_PC). The other variables appear not to be involved as a dependent variable in a long-term equation.

Secondly, the long-term variation of real GDP is significantly impacted by five factors: electricity production, population size, CO_2 emissions, innovation, and R&D expenditure.

Real GDP is driven primarily by electricity production, meaning that the economy output is energy-dependent and, hence, electricity generation will result in economic growth. While effect is positive, the magnitude of the impact varies depending on the consumption breakdown among industrial, residential, commercial and public services and transportation. Therefore, policy actions taken to increase efficiency in domestic appliances, to lead a sustainable development through the switching to renewable energy technologies for space and water heating and cooling, to boost the emergence of efficient machines, and to spur the development of new processes that are less energy-intensive, especially amongst power producers and electricity suppliers, will inevitably contribute to foster the economic growth while consuming less electricity.

Real GDP is also positively affected by population size, likely due to increase in human skills and workforce. However, the living standard proxied by real GDP per capita is negatively related to the population size with an elasticity of -0.569, at odds with the implications of endogenous growth models. Hence, the population increase was coupled with a decline in the per capita GDP, and a downward pressure on living standards is expected to continue even as output grows.

Similarly to electricity generation, CO_2 emissions are also positively associated with the long-term real GDP, with 280 gr CO_2 (76.4 gr carbon) per USD of GDP. In the same vein, CO_2 emissions as well as CO_2 emissions, per capita are linked to the standard of living, measured via GDP per capita. These findings are valid as long as the CO_2 emissions are those generated from national production, and not those embodied in international trade and global production chains.

The role of innovation has decreased on economic growth during the last decade, particularly when China is excluded from the panel, suggesting that innovation probably no longer plays a net positive driver for economic growth as it did in the past. This raises several issues about the possible decline of the usefulness of inventions, also the time lag between the moment of innovation and its effective broad dissemination in the economic landscape. This diminished impact of innovation is most likely due to rising trade openness and offshoring and more broadly to globalization.

The variables related to R&D expenditure indicate broadly a positive effect on real GDP in the long term, particularly considering the World Bank data. Similarly, R&D expenditure expressed as percent of GDP, as well as the number of researchers per million people provide higher living standards in the long term.

Thirdly, CO_2 production-based emissions are clearly affected by six factors in the long run. Population size and module selling prices have as expected a net positive effect on CO_2 emissions. On the other side, environmentally related taxes (in percent of GDP), high technology exports, the variables related to R&D expenditure and patent applications relating to photovoltaic sector show a negative impact. These findings bring into the forefront the importance of increasing active policy efforts stimulating research and development at global level, especially in renewable energy technologies, as a potential and central pillar to mitigate climate change, while achieving sustainable development.

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Appendix

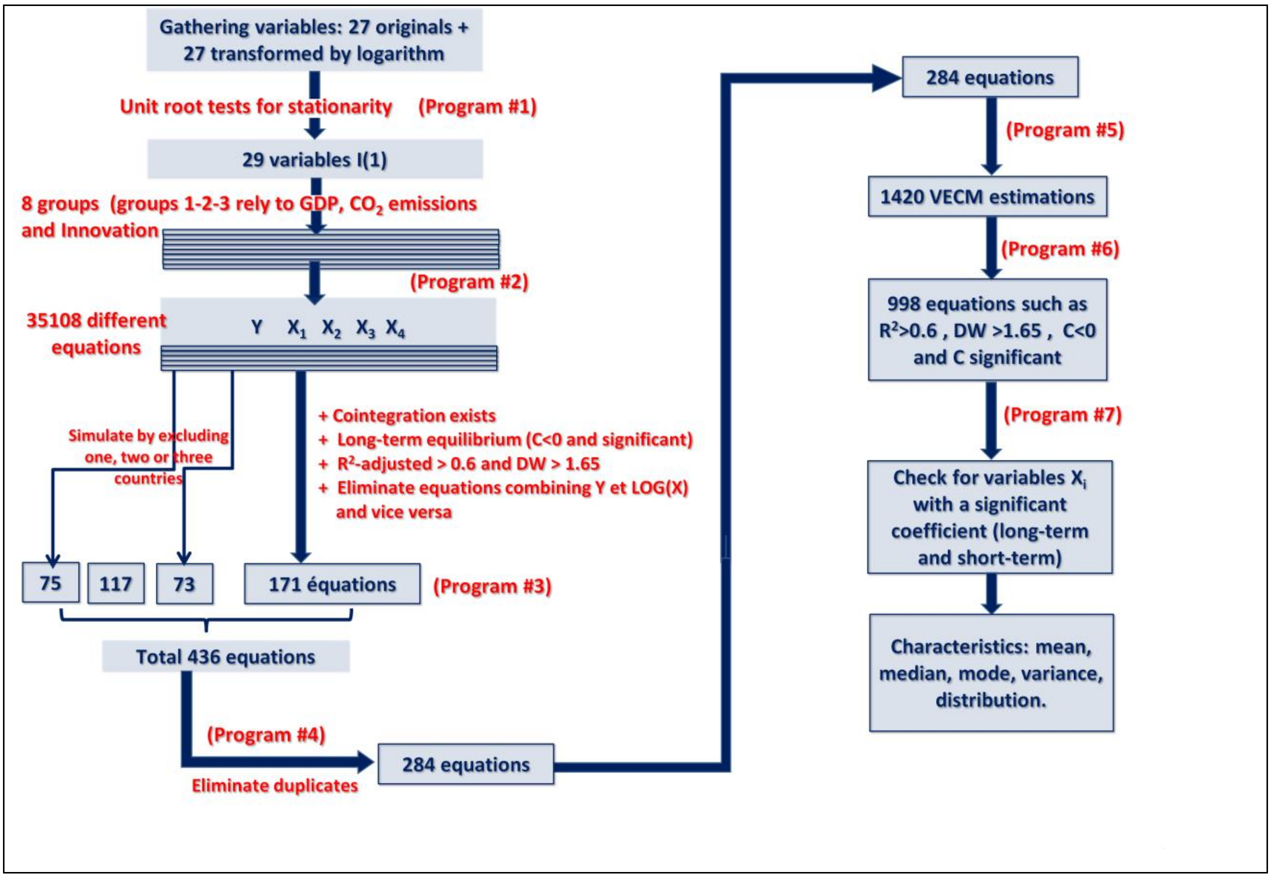
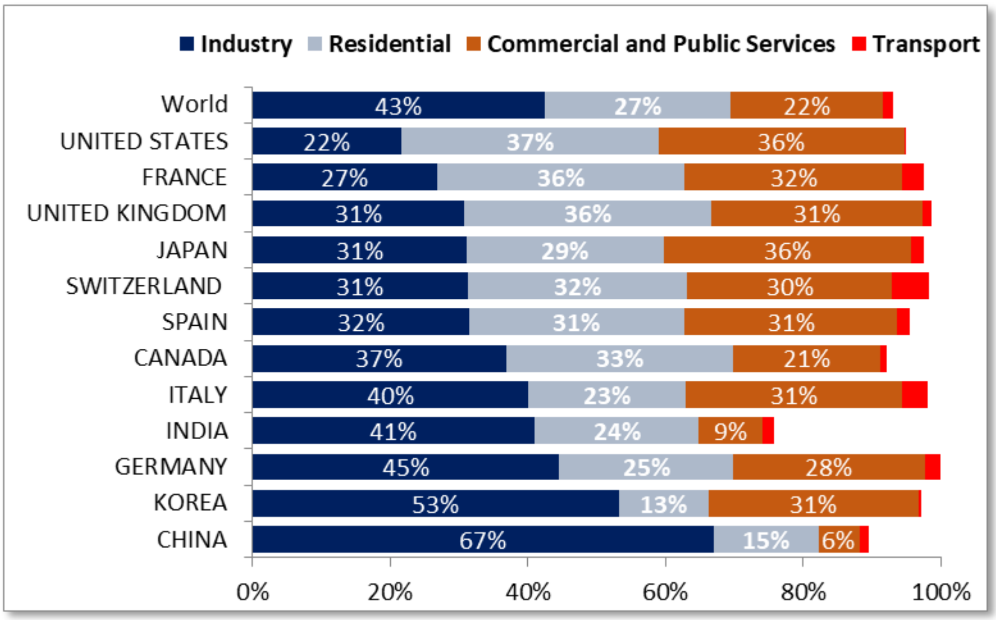
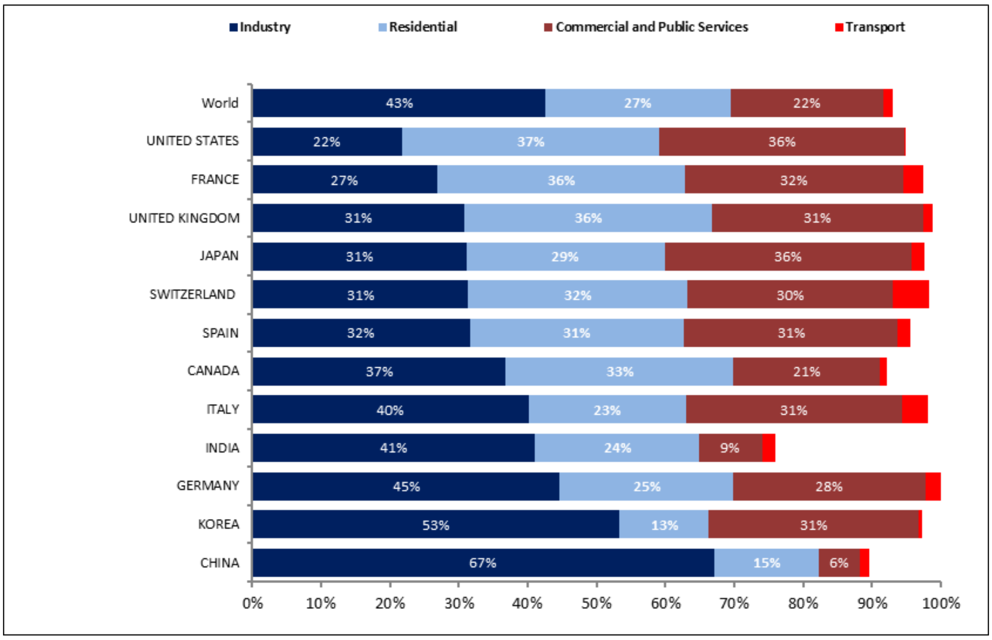


Fig. 11. Synthetic diagram of the approach undertaken



Source: IEA.

Fig. 12. Electricity consumption by sector in year 2014 (as percent of total)



Source: OECD statistics.

Fig. 13. Ratio GDP to 5 years cumulated inventions. (*) Total patents all technologies

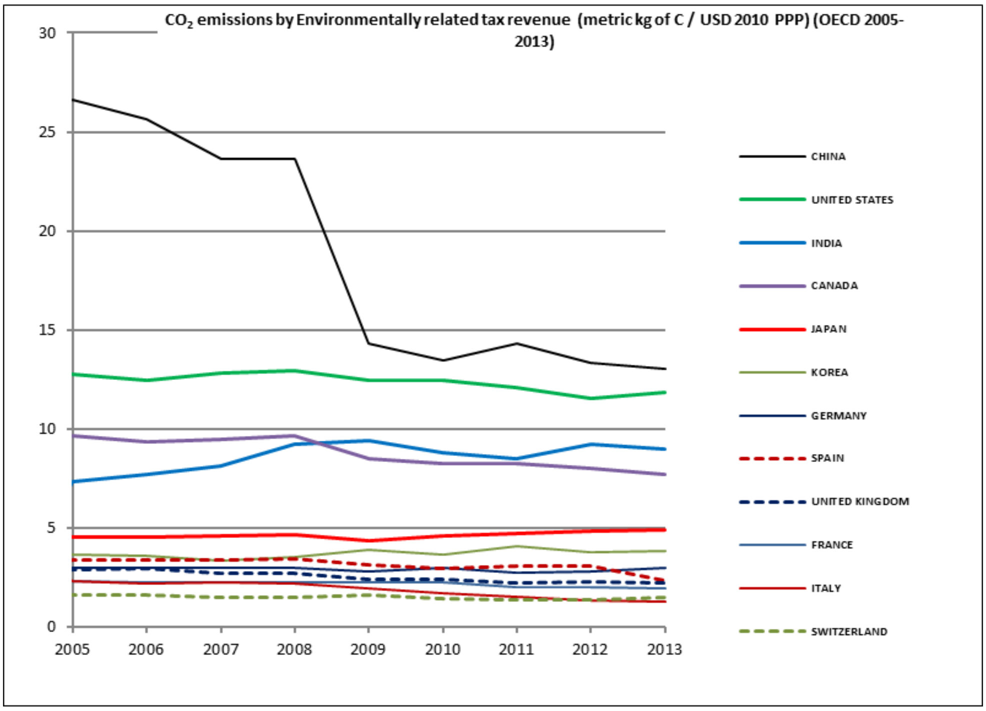


Fig. 14. Ratio of CO_2 emission to environmentally related tax revenue (ERT)

Table 7. Unit root test statistics with individual intercept and trend - automatic lag method SIC and automatic newey-west variable bandwidth selection (1990-2014)

	Original variables					First difference variables				
	Levin, Lin & Chu	Breitung	Im, Pesaran and Shin	ADF	PP - Fisher	Levin, Lin & Chu	Breitung	Im, Pesaran and Shin	ADF	PP - Fisher
CO_2_EMISSION	1,067	3,946	2,797	21,004	18,418	-10,018***	-6,640***	-9,856***	127,970***	234,127***
CO_2_EMISSION_PC	0,729	3,422	3,040	15,951	15,096	-9,560***	-6,693***	-9,458***	122,404***	224,761***
ERT_PCNT_GDP	-1,508*	1,097	-0,298	32,299	29,267	-12,340***	-5,384***	-8,262***	127,091***	137,526***
GDP_2010US	0,568	4,196	1,446	25,069	21,952	-7,248***	-5,564***	-6,601***	85,010***	207,939***
GERD_USD_PPP_2005	2,447	7,672	2,760	18,939	12,306	-5,160***	-3,633***	-3,790***	52,278***	53,203***
H_TECH_EXP	-1,105	3,356	-0,391	30,416	27,429	-12,727***	-8,371***	-12,999***	155,800***	266,143***
MODULE_SELLING_PRICE	0,864	-1,674**	0,474	14,548	16,679	-10,855***	-11,187***	-6,926***	84,014***	84,014***
NB_INVENTIONS_ALL_TECH	0,783	3,448	1,169	21,450	10,848	-4,948***	-1,939**	-5,029***	67,258***	329,018***
NB_PATENT_WB	1,495	2,886	1,223	33,003	17,279	-4,548***	0,944	-3,649***	71,050***	90,570***
PCT	5,877	6,061	1,445	30,850	25,577	-5,758***	0,471	-11,929***	159,524***	281,152***
POP	-0,942	1,862	3,352	18,117	12,701	-0,894	4,052	-3,244***	63,435***	109,201***
RD_EXP_2010US	0,030	6,306	0,545	21,369	8,876	-4,461***	-3,508***	-3,890***	50,490***	60,341***
RD_PCNT_GDP	-3,106***	2,605	-1,538*	30,365	23,393	-7,800***	-5,503***	-6,129***	75,210***	91,686***
TOT_ELEC_GENERATION	3,320	7,820	5,440	19,122	17,766	-11,580***	-5,052***	-12,606***	161,571***	408,543***
TOTAL_WIPO	9,025	4,171	0,729	25,989	25,526	-3,770***	-0,942	-14,957***	208,031***	318,885***
GDP_PC	0,495	2,878	1,666	23,121	20,410	-7,044***	-5,034***	-6,565***	84,377***	175,159***
LOG(CO_2_EMISSION)	1,383	3,552	2,319	23,150	20,415	-10,401***	-7,591***	-10,738***	137,297***	267,763***
LOG(CO_2_EMISSION_PC)	1,296	3,592	2,500	19,303	15,732	-10,683***	-7,900***	-10,775***	136,858***	227,423***
LOG(GDP_2010US)	0,412	1,493	0,762	25,258	18,941	-6,733***	-4,678***	-6,881***	88,045***	197,727***
LOG(GERD_USD_PPP_2005)	0,482	0,887	-2,251**	39,590**	15,728	-3,782***	-3,653***	-2,325**	40,374***	48,827***
LOG(H_TECH_EXP)	-1,116	0,611	-0,699	27,925	27,808	-9,189***	-7,839***	-10,153***	123,693***	287,322***
LOG(MODULE_SELLING_PRICE)	7,305	6,340	8,202	0,233	0,750	-9,371***	-7,861***	-5,338***	65,720***	65,720***
LOG(NB_INVENTIONS_EPV)	-3,085***	1,435	-4,882***	68,813***	83,013***	-14,459***	-3,486***	-12,861***	237,409***	629,702***

Table 7.(cont.) Unit root test statistics with individual intercept and trend - automatic lag method SIC and automatic newey-west variable bandwidth selection (1990-2014)

	Original variables					First dfference dariables				
	Levin, Lin & Chu	Breitung	Im, Pesaran and Shin	ADF	PP - Fisher	Levin, Lin & Chu	Breitung	Im, Pesaran and Shin	ADF	PP - Fisher
LOG(NB_RD_P1000)	-1,389*	-2,270**	0,196	32,461**	28,031	-9,624***	-3,954***	-8,301***	89,310***	111,282***
LOG(POP)	-0,712	5,047	2,604	18,623	20,689	-1,114	4,011	-3,964***	69,995***	109,702***
LOG(PRICE_SI_PV_CELLS)	22,990	17,018	18,946	0,000	0,000	10,185	3,143	4,559	0,654	121,926***
LOG(RD_EXP_2010US)	-3,230***	-3,112***	-1,776**	45,628***	23,655	-8,443***	-5,077***	-5,974***	72,585***	71,945***
LOG(TOT_ELEC_GENERATION)	2,463	3,913	4,332	17,000	18,380	-12,008***	-5,411***	-12,590***	160,582***	538,002***
LOG(GDP_PC)	-0,006	1,263	0,249	30,912	20,599	-6,539***	-4,277***	-6,565***	84,039***	186,788***

Note: *, **, and *** represent significant at 1%, 5% and 10% significance level.

Table 8. Retained variables: definition, scope of the data and sources

Variable name	Scope of data	Brief definition and units	Data sources
CO_2_EMISSION	1990-2014	Carbon dioxide emissions (CO_2) from fossil-fuels and cement production (thousand metric tons of C)	The Carbon Dioxide Information Analysis Center (CDIAC)
CO_2_EMISSION_PC	1990-2014	Per capita CO_2 emissions (metric tons of carbon)	The CDIAC and the World Bank
ERT_PCNT_GDP	1995-2014	Environmentally related tax revenue as % of GDP	The OECD
GDP_2010US	1990-2015	GDP at market prices (constant 2010 billion US$)	The World Bank (WDI)
GERD_USD_PPP_2005	1990-2015	Gross domestic expenditure on research and development (GERD) (million PPP$, constant prices 2005)	The United Nations Statistics Division (UNSD) and the OECD
H_TECH_EXP	1990-2015	High-technology exports (billion current US$)	The World Bank (WDI)
MODULE_SELLING_PRICE	1990-2015	Average selling PV Module prices (US$/W)	Renewable Energy World: http://www.RenewableEnergyWorld.com
NB_INVENTIONS_ALL_TECH	1990-2013	Total patents all technologies	The OECD
NB_PATENT_WB	1990-2014	Number of patent applications, residents and non residents	The World Bank (WDI)
PCT	1990-2015	Number of Patent Cooperation Treaties (PCT) for photovoltaic sector	WIPO: http://www.wipo.int/patentscope/en/
POP	1990-2015	Population (millions)	The World Bank (WDI)
RD_EXP_2010US	1996-2014	Research and development expenditure (constant 2010 billion US$)	The World Bank (WDI)
RD_PCNT_GDP	1996-2014	R&D expenditure (% of GDP)	The World Bank (WDI)
TOT_ELEC_GENERATION	1990-2014	Total electricity production (1000Gwh)	The IEA
TOTAL_WIPO	1990-2015	Total number of WIPO patent scope for photovoltaic sector	WIPO: http://www.wipo.int/patentscope/en/
GDP_PC	1990-2015	GDP per capita at market prices (thousand US$, constant 2010)	The World Bank (WDI)

Table 9. Long-term coefficient summary (GDP_2010US as dependent variable) for different country panels

1990-2014	All countries	Without China	Without USA	Without India	Without Korea
TOT_ELEC_GENERATION	4.120014	5.547009	6.639132	4.334265	3.912795
POP	27.977645	14.060825	39.095425	19.22333	32.56823
CO_2_EMISSION	0.013091	0.016717	0.0187525	0.011749	0.0135615
PCT	-227.4565	-327.7594	-186.0047	-187.7933	-246.2844
TOTAL_WIPO	-16.70155	-46.67148	-26.08587	-13.30097	-13.65674
GERD_USD_PPP_2005	0.04267	0.114576	0.0285955	0.0388355	0.044159
MODULE_SELLING_PRICE	330.90615	246.79185	549.8557	214.1741	281.8323
RD_EXP_2010US	43.435205	48.28993	21.23892	37.347835	33.69479
ERT_PCNT_GDP	-1242.277	910.9851	-658.0189	-1135.016	486.196
NB_INVENTIONS_ALL_TECH	0.03329	-0.035786	0.034088	0.036389	0.0395015
RD_PCNT_GDP	827.2696	1360.344	-1302.238	807.76	913.8286
CO_2_EMISSION_PC	1465.8755	-213.308	526.918	-562.5529	715.23975
NB_PATENT_WB	0.002691	-0.007339	-0.018071	0.002726	-0.002365

Table 10. Trends in GDP, CO_2 emissions, and ERTs for China and the USA over the period 1995-2015

		CHINA	USA
CO_2 emissions (% of the world) in 2013		30.3%	15.3%
ERT variation (%), 2005-2014		18.0%	-0.5%
GDP average growth (%), 1995-2015		9.8%	2.2%
Average CO_2 emission variation	1995-2005	5.2%	1.1%
	2005-2013	7.9%	-1.6%
Average CO_2 emission per capita (metric tons of C)	1995-2005	0.85	5.36
	2005-2013	1.65	4.87
Average CO_2 emission per GDP (Carbon intensity: gram per 2010 US$ GDP)	1995-2005	457.42	121.69
	2005-2013	395.70	99.14
Ratio CO_2 emission / ERT (metric kg of C / USD 2010 PPP)	1995-2005	28.78	12.89
	2005-2013	16.27	12.39
Average ERT to GDP (OECD)	1995-2005	1.43%	0.95%
	2005-2014	2.35%	0.79%

Table 11. Summary of results achieved for the dependent variable GDP_2010US (527 equations)

Panel 12 countries, 1990-2014	Dependent variable: GDP_2010US					
	Long-term coefficient		Short-term coefficient t-1		Short-term coefficient t-2	
	Number of negative values and positive values	Median	Number of negative values and positive values	Median	Number of negative values and positive values	Median
TOT_ELEC_GENERATION	63 - 277	4.120	52 - 2	-0.511	0 - 110	0.507
POP	0 - 202	27.978	0 - 0	-	0 - 0	-
CO_2_EMISSION	1 - 197	0.01309	5 - 0	-0.00075	0 - 0	-
PCT	103 - 0	-227.457	0 - 62	3.593	0 - 32	3.051
TOTAL_WIPO	103 - 0	-16.702	0 - 0	-	0 - 92	0.684
GERD_USD_PPP_2005	28 - 63	0.04267	153 - 0	-0.00655	0 - 19	0.00404
MODULE_SELLING_PRICE	21 - 47	330.906	73 - 0	-30.995	41 - 0	-28.717
RD_EXP_2010US	2 - 56	43.435	79 - 0	-13.962	0 - 1	7.378
ERT_PCNT_GDP	34 - 22	-1242.277	0 - 1	160.065	0 - 0	-
NB_INVENTIONS_ALL_TECH	3 - 30	0.03329	0 - 0	-	0 - 0	-
RD_PCNT_GDP	4 - 21	827.270	60 - 0	-293.069	0 - 0	-
CO_2_EMISSION_PC	5 - 19	1465.876	0 - 0	-	0 - 0	-
NB_PATENT_WB	10 - 12	0.00269	37 - 0	-0.00156	0 - 10	0.00143

Table 12. Summary of results achieved for the dependent variable LOG(GDP_2010US) (181 equations)

Panel of 12 Countries 1990-2014	Dependent variable: LOG(GDP_2010US)					
	Long-term coefficient		Short-term coefficient t-1		Short-term coefficient t-2	
	Number of negative values and positive values	Median	Number of negative values and positive values	Median	Number of negative values and positive values	Median
LOG(POP)	0 - 93	0.708	0 - 0	-	- 0	-
LOG(CO_2_EMISSION)	0 - 89	0.703	0 - 0	-	0 - 64	0.124
LOG(CO_2_EMISSION_PC)	1 - 48	0.751	0 - 0	-	0 - 45	0.112
LOG(NB_RD_P1000)	31 - 6	-0.448	0 - 0	-	0 - 0	-
LOG(TOT_ELEC_GENERATION)	0 - 25	0.847	0 - 0	-	0 - 15	0.143
LOG(MODULE_SELLING_PRICE)	0 - 22	0.257	71 - 0	-0.021	0 - 0	-
RD_PCNT_GDP	1 - 15	0.355	31 - 0	-0.076	0 - 0	-
LOG(RD_EXP_2010US)	3 - 12	0.388	3 - 0	-0.103	0 - 0	-
LOG(GERD_USD_PPP_2005)	3 - 10	0.329	3 - 0	-0.103	0 - 0	-
LOG(PRICE_SI_PV_CELLS)	0 - 8	1.876	8 - 0	-0.076	8 - 0	-0.032
LOG(NB_INVENTIONS_EPV)	3 - 1	-0.444	0 - 8	0.002	0 - 0	-

Table 13. Summary of results achieved for the dependent variable LOG(GDP_PC) (115 equations)

Panel of 12 countries, 1990-2014	Dependent variable: LOG(GDP_PC)					
	Long-term coefficient		Short-term coefficient t-1		Short-term coefficient t-2	
	Number of negative values and positive values	Median	Number of negative values and positive values	Median	Number of negative values and positive values	Median
LOG(POP)	51 - 0	-0.569	0 - 0	-	43 - 0	-1.091
LOG(CO_2_EMISSION_PC)	0 - 46	0.587	0 - 0	-	0 - 47	0.144
LOG(CO_2_EMISSION)	0 - 40	0.591	0 - 0	-	0 - 44	0.143
LOG(MODULE_SELLING_PRICE)	0 - 25	0.260	36 - 0	-0.021	0 - 0	-
RD_PCNT_GDP	1 - 20	0.335	32 - 0	-0.079	0 - 0	-
LOG(NB_RD_P1000)	0 - 21	0.413	0 - 0	-	0 - 0	-
LOG(TOT_ELEC_GENERATION)	6 - 7	0.368	12 - 0	-0.153	0 - 6	0.139
LOG(RD_EXP_2010US)	6 - 6	-0.043	14 - 0	-0.110	0 - 0	-
LOG(GERD_USD_PPP_2005)	3 - 4	0.409	17 - 0	-0.108	0 - 0	-

Table 14. Summary of results achieved for the dependent variable CO_2_EMISSION (175 equations)

Panel of 12 Countries, 1990-2014	Dependent variable: CO_2_EMISSION					
	Long-term coefficient		Short-term coefficient t-1		Short-term coefficient t-2	
	Number of negative values and positive values	Median	Number of negative values and positive values	Median	Number of negative values and positive values	Median
POP	0 - 165	13202.2	0 - 0	-	1 - 0	-11419.5
ERT_PCNT_GDP	74 - 0	-505268.9	0 - 64	21642.8	0 - 1	44859.0
H_TECH_EXP	48 - 10	-14403.3	55 - 0	-424.1	0 - 5	337.3
MODULE_SELLING_PRICE	1 - 40	183434.5	6 - 0	-9549.4	10 - 0	-9465.7
GERD_USD_PPP_2005	31 - 0	-11.440	0 - 5	1.374	0 - 10	1.842
PCT	27 - 0	-52453.4	0 - 5	765.1	0 - 0	-
RD_EXP_2010US	15 - 10	-3997.1	3 - 2	-1059.1	0 - 20	1370.6
RD_PCNT_GDP	23 - 0	-387202.1	0 - 18	69536.8	0 - 1	74349.9
GDP_2010US	16 - 5	-106.8	0 - 4	47.9	0 - 22	78.7
TOT_ELEC_GENERATION	0 - 21	1908.8	21 - 0	-220.7	0 - 0	-
NB_INVENTIONS_ALL_TECH	5 - 14	7.862	23 - 0	-0.611	2 - 0	-0.473
TOTAL_WIPO	13 - 0	-34954.3	0 - 13	291.4	0 - 5	224.1
GDP_PC	8 - 0	-16221.5	0 - 0	-	0 - 4	5812.9
NB_PATENT_WB	5 - 0	-6.186	0 - 0	-	0 - 0	-