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Climate Change: Responsibilities and Policy
Four Essays in Environmental Economics

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Climate Change : Responsibilities and Policy
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Neuchâtel, le 28 septembre 2015

La doyenne

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Abstract

This thesis investigates empirically three important aspects in the context of climate change: regulatory responsibility, the measurement of observed environmental policy stringency as well as the impact of the latter on anthropogenic CO_2 emissions. Although distinct, all three aspects are inherently interrelated, and a proper understanding is crucial in order to effectively combat climate change. Part 1 contains two introductory descriptive analyses on the distribution of greenhouse gas emissions on the world surface. This provides a detailed quantitative basis, allowing to shed light on the responsibility debate in the context of human induced climate change. The results clearly indicate the historical responsibility of the West, but suggest that the responsibility of countries in terms of applied regulations is converging, while the one of specific sectors and zones is rapidly diverging. Part 2 outlines a coherent methodological framework allowing to measure environmental policy stringency and implements the latter for several pollutant specific policies. Part 3 investigates empirically the relationship between greenhouse gas policy stringency and anthropogenic CO_2 emissions. Results indicate that increased greenhouse gas policy stringency lowers national CO_2 emissions, although by a rather small extent. Moreover, results show that increased policy stringency improves CO_2 efficiency of sectors and alters the sectoral composition of economies by increasing the share of relatively clean sectors.

Keywords: environmental policy stringency, regulatory responsibility, emission inequality, CO_2, CH_4, SO_2, composition effect, scale effect, technique effect, center of gravity

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General Introduction

1 Motivation and Structure

An accelerated warming of the climate system increases the likelihood of "severe, pervasive and irreversible" impacts. Those risks can be mitigated by limiting the rate and magnitude of climate change (IPCC, 2014a). To do so, anthropogenic greenhouse-gas (GHG) emissions have to be reduced as they are "extremely likely" to be the dominant cause of the observed global warming (IPCC, 2013). This calls for a tightening of GHG policy regimes and raises a set of questions. First, the question of regulatory responsibility emerges, i.e. who has to implement those stricter policies? Directly linked to this first question, is the question of how strict actual GHG policy regimes of different countries are. Third, what are the actual effects of existing GHG policies? This thesis - consisting of four chapters - attempts to contribute to the existing literature, by filling multiple knowledge gaps regarding those three sets of questions.

The thematic structure of this thesis is divided in three parts.[1] Part one consists of chapter 1 and chapter 2. Those two chapters contain two complementary descriptive analyses, which provide together a detailed quantitative basis, allowing to shed light on the responsibility debate in the context of human induced climate change. Part two, consisting of chapter 3, develops and implements a methodological framework, allowing to measure environmental policy stringency. Part three, consisting of chapter 4, uses one of the developed indexes from chapter 3, and provides an in-depth statistical analysis of the effects of environmental policy stringency on anthropogenic CO_2 emissions.

[1]Please note, that the thematic structure does not correspond to the temporal structure of this thesis. Chapter 3 has been written first, followed by chapter 2, chapter 4 and finally chapter 1.

2 Overview

Chapter 1 provides a descriptive analysis allowing to describe historical responsibilities of climate change. A better understanding of global issues, such as Climate Change, requires indicators that are both global in scope and synthetic in nature. In this chapter, we construct the world's center of gravity for human population, GDP and CO_2 emissions, which collapses into a single point the distribution of each of the three variable upon the Earth's surface. To do so, we take the best out of five recognized data sources covering the last two centuries. This allows to compare the distribution of both economic activity and the major source of greenhouse gases since the first stages of the industrial revolution. As such, it provides a concise description of the dynamics of world imbalances during the last two centuries, illustrating the historic responsibility of the West, which is a cornerstone of present negotiations to tackle Climate Change. We also propose a more appropriate two-map representation of the location of the center of gravity, which allows for a more accurate interpretation of the underlying trends. We find a radical Western shift of GDP and CO_2 emissions centers during the 19th century, in sharp contrast with the stability of the demographic center of gravity. Both GDP and emissions trends are reversed in the first half of the 20th century, after World War I for CO_2 emissions, and after World War II for GDP. Since then, both centers are moving eastward at an accelerating speed. These patterns are consistent with the initial lead of Western countries starting the industrial revolution and the adoption of fossil fuels as its main energy source, the impact of world conflicts, the gradual replacement of coal by oil and gas, and the progressive catch up of Asian countries, leading to a convergence in terms of both GDP and CO_2 emissions per capita in the recent past.

Chapter 2 complements the historical analysis from Chapter 1, by providing a detailed analysis of spatial CO_2 and CH_4 emission inequality over the 1970-2008 period, using Theil index decompositions. The major greenhouse gases, CO_2 and CH_4, are uniformly mixing, but spatial inequalities in emissions do matter in terms of both efficiency and equity of environmental policy formation and implementation. As the recent evidence has mainly focused on convergence issues between countries, this chapter extends the empirical analysis by taking into account within-country inequalities in CO_2 and CH_4 emissions. We show that within-country inequalities account for the bulk of global inequality, and tend to increase over the sample period, in contrast with diminishing between-country inequalities. An original extension to include differences across sectors reveals that between-sector inequality matters more than between-country inequality, and becomes the dominant source of global inequality at the end of the sample period in the CO_2 case. Thus, on the one hand, the decreasing importance of between country and between region inequalities suggests that the regulatory responsibility of countries is converging. On the other hand, the increasing importance of within country and between sector inequalities suggests that the contribution to inequality, and therefore the regulatory responsibility, of specific geographical zones and specific sectors is growing. A final exercise suggests that social tensions arising from the disconnection between emissions and future damages are easing for CO_2 but are rather stable for CH_4. These orders of magnitude should be kept in mind while discussing the efficiency and fairness of alternative paths in combating global warming.

Chapter 3 attempts to systematically tackle one of the biggest obstacles in cross-country empirical research in the area of environmental economics: the absence of a sound indicator quantifying environmental policy stringency. A variety of indicators have been proposed and are currently used. Almost none of them rely on an explicitly stated methodology, violating thereby one of the most fundamental rules of index construction. To overcome this problem, this chapter develops a new general methodological framework for the measurement of environmental policy stringency. The solution I propose allows to separately quantify the input, process and output dimension of various specific - hence well definable - types of environmental policies. I proposes a first implementation using the example of CO_2, CH_4 and SO_2 policy stringency. In addition a general greenhouse gas policy stringency indicator is developed. To do so I combine originally extensive databases on anthropogenic emissions as well as legal databases. Comparisons with available benchmark indicators suggest that the obtained indexes measure what they are supposed to. A first application using one of the developed indexes is proposed in chapter 4.

Chapter 4 investigates how greenhouse gas (GHG) policy stringency affects anthropogenic CO_2 emissions using the GHG policy stringency indicator, developed in Chapter 3, and a structural spatial VAR approach. We estimate an average country-specific elasticity of CO_2 emissions to GHG policy stringency, and assess the role of channels over which policy stringency affects CO_2 emissions. We then ascertain how GHG policy stringency affects sectoral CO_2 efficiency and the sectoral composition of economies. Results indicate that a country can significantly decrease its anthropogenic CO_2 emissions by increasing the stringency of its GHG policy regime. In addition, increasing GHG policy stringency improves sectoral CO_2 efficiency, and decreases production in CO_2

intensive sectors thereby altering the sectoral composition. At last, policy induced CO_2 reduction costs in terms of GDP are relatively large, but 4 times lower for developing compared to developed countries. In short, the results indicate that by increasing the stringency of GHG policy regimes, policy efforts can reduce national CO_2 emissions up to a certain extent. Prospects are therefore encouraging that one can limit the rate and magnitude of climate change and thereby reduce climate change induced risks. However, the presence of a policy induced composition effect might limit the extent to which global emissions are reduced by national policies. This would be especially true if emission outsourcing is found to be the main driver of this composition effect.

Chapter 1

Back to 1820? Spatial distribution of GDP and CO_2 Emissions *

1 Introduction

A better understanding of global issues, such as Climate Change or the adoption of Sustainable Development Goals, requires indicators that are both global in scope and synthetic in nature. In this chapter, we propose to revisit the concept of the world center of gravity, which collapses into a single point the distribution of any variable upon the Earth's surface. This allows to identify non-trivial trends and structural shifts at the global level. To illustrate the relevance of this indicator, we apply it to an original combination of historical data sources, in order to compare the evolution of both GDP and CO_2 emissions on the Earth's surface since 1820.

The first applications of the center of gravity, by Grether and Mathys (2010) and Quah (2011), were limited to global production and recent decades. Although using different projection methods to represent the center of gravity, they relied on the same database for GDP (World Bank indicators) and its ap-

*This paper is co-authored by Jean-Marie Grether (University of Neuchâtel, Faculty of Economics and Business) and Nicole Mathys (Federal Office for Spatial Development and University of Neuchâtel, Faculty of Economics and Business).

proximate within-country spread (using city population data), and confirmed a clear Eastern shift since 1980. These early applications toppled with two major problems namely how to spread more accurately GDP within countries and how to go further backward in time. These issues were addressed in two subsequent papers.

Instead of using cities, Grether and Mathys (2011) rely on gridded data provided by the G-Econ database (Nordhaus et al., 2006a), which provide a more accurate measure of the spatial distribution of population and production. They also use the Maddison (2010) database for older values of GDP but stop in 1950 due to missing data prior to that year. This latter obstacle is lifted by Grether et al. (2012b) who provide a thorough discussion of the original Maddison database and the additional assumptions that are necessary to extend it before 1950. Although pre-industrial data must be taken with a grain of salt, their results are clearly suggestive of a strong Western shift along with the Big Divergence, with a trend reversal in 1920 for the demographic center, and in 1950 for the economic center. This suggests that the former debate of the sixties, whether the unprecedented growth that followed the industrial revolution in Western countries could also be experienced by other countries as well (e.g. Bairoch (1971)), could have been clarified much earlier if better data and more accurate indicators had been made available.

One important drawback of these last two historical papers is that, for all years for which gridded data are still not available, the assumption is simply that grid shares at the country level are kept unchanged with respect to the closest available year (i.e. 1990 for G-Econ). This is of particular concern for countries like the US or China, which cover large areas, represent a significant share of world totals, and where the distribution of people and economic activity has suffered structural changes over the last two centuries. The present chapter offers a welcome improvement with respect to that shortcoming, by exploiting the Hyde 3.1 database (Klein Goldewijk et al., 2011), which provides gridded population data at a very disaggregated level. This database goes back as far as 1750, and has already been exploited by long run studies of land-use by human populations (Ellis et al., 2013) and its relationship with global warming (Matthews et al., 2014). This allows to spread national totals regarding GDP (or CO_2 emissions) according to varying population shares back in the past rather than by applying fixed shares.

Apart from this unprecedented accuracy, the present chapter extends the literature in two other directions. First, it adds an environmental dimension to the analysis, namely CO_2 emissions, relying on gridded data provided by the EDGAR database since 1970, and on the CDIAC database for earlier years. This allows to compare the distribution of both economic activity and the major source of greenhouse gases since the first stages of the industrial revolution. As such, it provides a concise description of the dynamics of world imbalances during the last two centuries, illustrating the historic responsibility of the West, which is a cornerstone of present negotiations to tackle Climate Change (e.g. Barrett and Stavins (2003) or Mattoo and Subramanian (2012)). It turns out that the emission center of gravity mimics the Western shift of the economic center during the 19th century, but shifts back towards Asia thirty years earlier, at the beginning of the 20th century.

Finally, we provide a thorough discussion on how best to represent a world center of gravity onto a map. This is not evident, as the usual distortions of distances by latitude and longitude are compounded by the fact that the center of gravity locates underground, not on the Earth's surface. We propose here an original two-map approach, which is both visually telling and distortion-free in representing the Cartesian coordinates of the center of gravity. This is important as the alternative projection methods used until now tend to magnify errors in measurement when the center of gravity is close to the center of the Earth, which happens to be the case in recent decades.

2 Methodology

2.1 Cartesian coordinates of world centers of gravity

Assume the surface of the Earth is covered by a regular grid of N cells. Each cell i, $i = 1, ..., N$, is identified by the latitude (φ) and longitude (λ) of its lower-left corner. For each cell, there is an estimate of the underlying variable V, i.e. CO_2 emissions (E) for the world emission center of gravity, GDP (G) for the world economic center of gravity, or population (P) for the world demographic center of gravity.

The Cartesian coordinates of each center of gravity are determined according to the three-step methodology previously introduced by Grether and Mathys (2010). First, the share of each cell in the world total is calculated, i.e. $s_{iV} = \frac{V_i}{\sum_{i=1}^{N} V_i}$. Second, the Polar coordinates of each grid cell are converted into their corresponding Cartesian coordinates, denoted by x, y and z. For that purpose, the Earth is assumed to be a perfect sphere, a reasonable assumption given the approximations affecting the measurement of the underlying variables. Cartesian coordinates may be expressed in kilometers, or as a fraction of the Earth's radius, R (6371km).[1] Third, the coordinates of the world center of gravity are obtained as weighted averages of the Cartesian coordinates of each grid cell, using grid cell shares as weights:

$$x_v = \sum_{i=1}^{N} s_{iV} x_i \qquad y_v = \sum_{i=1}^{N} s_{iV} y_i, \qquad z_V = \sum_{i=1}^{N} s_{iV} z_i \tag{1}$$

The obtained point, $P_V^*(x_V, y_V, z_V)$, where $V = E, G, P$, locates within the sphere. The length of the associated vector, with its origin in the Earth's center, is obtained as:

$$\left\| \overrightarrow{OP_V^*} \right\| = \sqrt{x_V^2 + y_V^2 + z_V^2} \tag{2}$$

This length can be used as a rough indicator of the concentration of the underlying variable on the Earth's surface. An extreme concentration in a single point would lead to a gravity center right on the Earth's surface, and a length just equal to the Earth's radius.

2.2 Existing conventions to represent the location of world centers of gravity

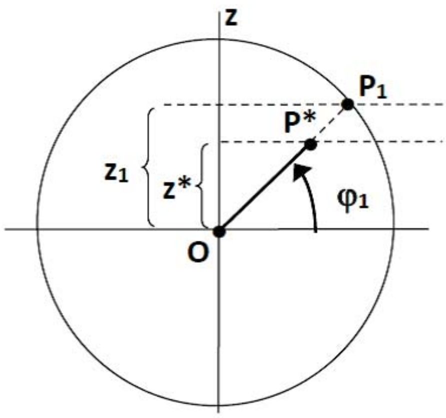
The literature on how to map the Earth's surface on a two-dimensional plane dates back to more than two thousand years (see Snyder (1987) for a detailed survey including both technical and historical references). There is no universally accepted technique, as every method (cylindrical, conic or azimuthal, and their sub-cases) presents its shortcomings regarding specific distortions (e.g. on distances, areas or angles). The problem is further compounded here by the fact that the points we are interested in, i.e. the centers of gravity, are located *within* the sphere, not on its surface.

To the best of our knowledge, two projection techniques have been proposed till now for the world centers of gravity, as illustrated by Figure 1. The first one,

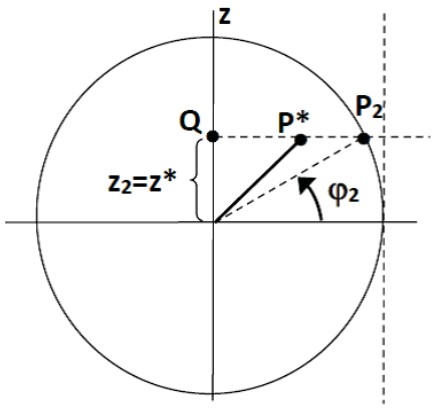
[1] In a 3-dimensional space where the origin is at the center of the Earth, axis x (projection of the Greenwich meridian) and y (projection of the 90°E meridian) define the equatorial plane, and axis z is the North-South polar axis, the corresponding formulas are : $x_i = Rcos(\varphi_i)cos(\lambda_i)$, $y_i = Rcos(\varphi_i)sin(\lambda_i)$, $z_i = Rsin(\varphi_i)$, where R is the Earth's radius. See the technical Appendix to Grether and Mathys (2011) for a detailed description.

proposed by Grether and Mathys (2010), consists of projecting orthogonally the center of gravity, P^*, upon the Earth's surface (Figure 1a). It leaves unspecified the technique used to represent the projection point, P_1, with latitude φ_1. The second technique, proposed by Quah (2011), directly projects the center of gravity on a cylinder wrapping the globe along the Equator (Figure 1b), which leads to a lower latitude for the projection point, $\varphi_2 < \varphi_1$.

Figure 1: Alternative projections of the world's center of gravity



(a) Grether and Mathys (2010)



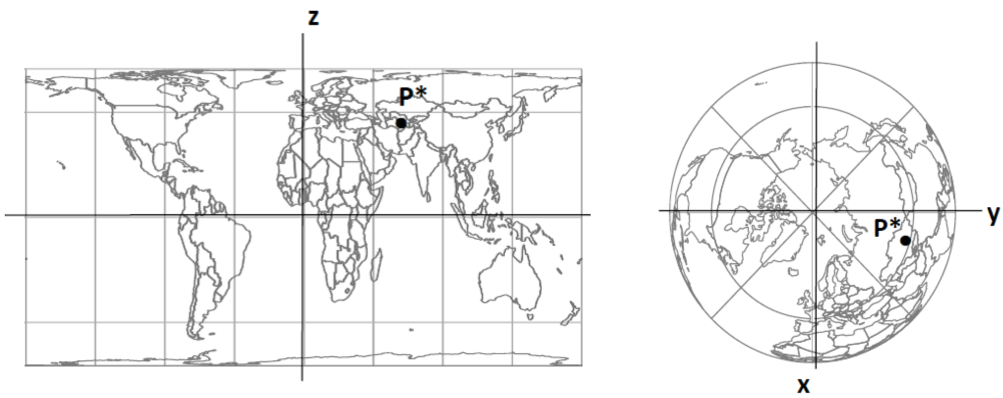
(b) Quah (2011)

Both techniques may be criticized on the ground that they are insensitive to specific directional movements of the center of gravity, depending on the distribution of the underlying variable over time. The convention by Grether and Mathys (2011) does not capture changes of P^* along the OP_1 axis. The convention by Quah (2011) is insensitive to changes of P^* along the QP_2 line. Which type of changes matters more in practice is an empirical question, which could guide the choice between these two projection techniques, or any other alternative deemed more relevant depending on the specific variable or time period considered. However, any convention relying on a single two-dimensional map will remain affected by some kind of distortion. That is why we privilege here Cartesian over Geographic coordinates, and use two maps instead of a single one. We argue in the next subsection that this is the most accurate and tractable way to represent a point located deeply underground.

2.3 A new, distortion-free convention

The first map, on the left of Figure 2, is consistent with the technique of Quah (2011) that is, a cylindrical projection. It provides, on the vertical axis, a distortion-free representation of the z Cartesian coordinate described in subsection 2.1. The horizontal axis represents longitude, which is subject to distortions, because there is an infinity of (x, y) combinations *within the sphere* corresponding to the same longitude. The second diagram on the right of Figure 2, provides an explicit representation of x and y, with the $x(y)$ axis representing the projection of the Greenwich (90 degree) meridian. All three Cartesian coordinates are expressed as a fraction of the Earth's radius.[2]

Figure 2: Cartesian coordinates of the gravity center in two maps



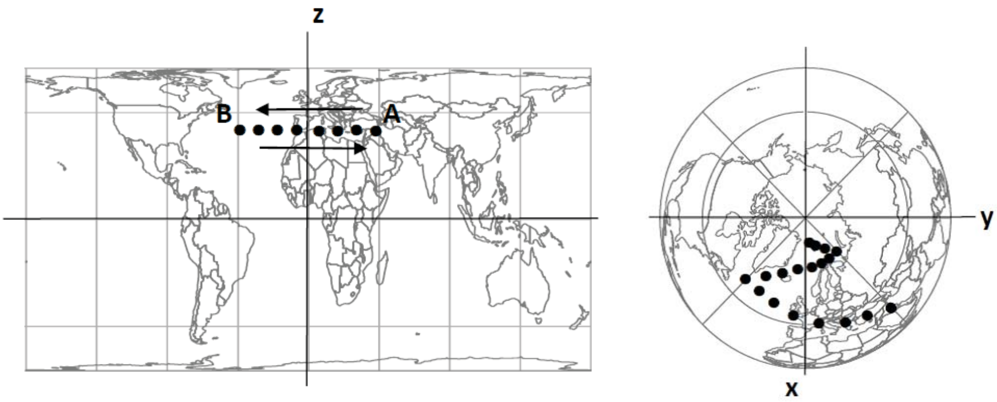
(a) cylindrical projection **(b)** azimuthal projection

The combination of these two maps allows describing without distortion any underground movement of the center of gravity, including those above-mentioned peculiar cases for which previously used conventions are insensitive to. Two stylized examples will help to illustrate the complementarity of both maps. In each case, one of the two maps gives a confusing vision of the evolution of the center of gravity, while the other map unveils what actually happens. We

[2]Countries' contours correspond to a Lambert equal-area cylindrical projection in the left map, and to an azimuthal projection in the right map. Figures 2-4 limit the number of meridians and parallels to streamline presentation. Consecutive figures with actual results report meridians and parallels every 10°, along with ticks to indicate half of the Earth's radius on the x,y,z axis.

dub the first case the "wiper effect". It is represented in Figure 3, where the left map suggests that the center of gravity shifts from point A to point B, then back again, and so forth, as a pendulum covering apparently the same horizontal distance period after period. However, what happens in reality, as shown by the right map, is that the center of gravity gets ever closer to the center of the Earth, along a zigzag trajectory analogous to the one of a bug crawling from the extremity of a car wiper to its rotating base. Again, this illusion is due to the fact that an infinity of within-sphere (x, y) combinations are compatible with the same longitude.

Figure 3: The "wiper" effect

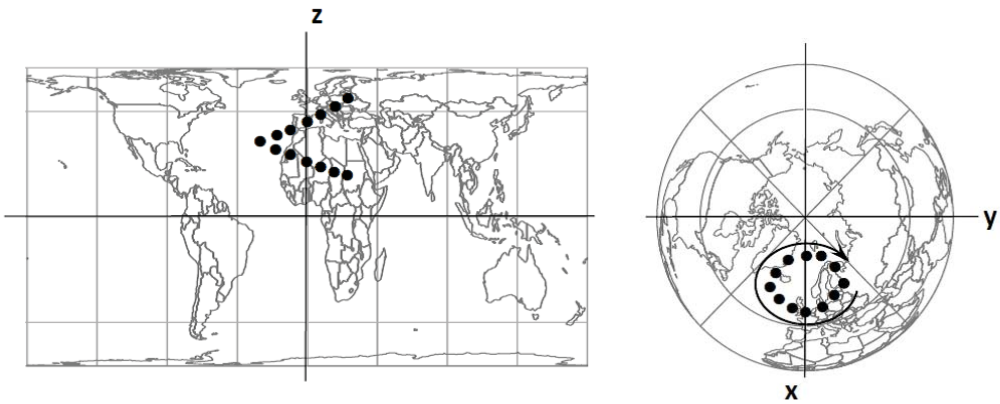


(a) **(b)**

The right map is not exempt from optical illusion either. In the second case, illustrated in Figure 4, the center of gravity appears to be going round a regular ellipse on the right map. However, the left map shows that its height above the equatorial plane is regularly decreasing. We call that movement along a downward spiral a "staircase" effect.

Other optical illusions could still be considered but are not reported here for the sake of conciseness, and as we limit the presentation to the two cases which do affect our own results. The key point is that, although we keep on using latitudes and longitudes to characterize locations on maps, the center of gravity is an underground point which is best identified in space by using three Cartesian coordinates rather than two Geographic coordinates.

Figure 4: The "staircase" effect



(a) **(b)**

3 Data sources

Data needed for calculations are obtained by combining five distinct data sources. On the one hand, three data bases provide information at the grid level. The HYDE 3.1 database (Klein Goldewijk et al., 2011) provides historical gridded population data from 10000 B.C. to 2005 A.D. Since 1820, the data are available in 10 year intervals, and has a grid resolution of 5 by 5 arc minutes. The G-Econ research project (see G-Econ (2011)) provides gridded GDP data at a 60 arc minutes level of resolution for the years 1990, 1995, 2000 and 2005. The Emission Database for Global Atmospheric Research (EDGAR, see European Commission and Joint Research Centre (JRC)/Netherlands Environmental Assessment Agency (PBL) (2011)) reports yearly data on CO_2 emissions from fuel combustion and non-metallic mineral processes (including cement production)[3] , excluding short-cycle organic carbon from biomass burning at a 0.1° level of resolution. This data covers the period of 1970 to 2008. On the other hand, two other data bases cover larger periods but at the national level only, i.e. the The Maddison Project (2013), which contains estimates of GDP and population from 1 to 2010 A.D., and CDIAC (see Boden et al. (2013)), which provides CO_2 estimates from fossil-fuel consumption and cement production over the

[3]Note that Edgar covers more carbon dioxide sources, but to correctly match Edgar with CDIAC (which covers only CO_2 emissions from fossil-fuel consumption and cement production), we retain from EDGAR only CO_2 emissions from IPCC source category 1A (fuel combustion) and 2A (non-metallic mineral processes).

1751-2010 period.

3.1 Population

The only modification of the HYDE database is to extend it from 2005 to 2010. To do so, we apply to each cell's population in 2005 the population growth rate 2005-2010 of the corresponding country as obtained from the national figures of the Maddison database. Country attribution of each cell is obtained by merging HYDE with the global database on administrative boundaries GADM (2012). As explained below, this HYDE gridded population database at a very high degree of resolution provides the basis to extend the GDP and emission gridded data backward in time.

3.2 GDP

First, the G-Econ 2005 gridded GDP data are extended to 2010, using Maddison country GDP data for growth rates and by relying on the same method as described above for population. Second, we extend the gridded GDP series backward to 1820 in the following way. We combine the HYDE and the Maddison databases by assuming that within-country GDP is uniformly distributed per capita. This allows to spread national GDP figures from the Maddison database according to the gridded population shares obtained from the HYDE database. The obtained Maddison/HYDE gridded GDP figures are of course an approximation, but given data availability, it is the best way to capture within-country spatial variations backward in time. We then aggregate the so-obtained 5 arc minutes cells to cells with a 60 arc minutes resolution in order to match them with the G-Econ data. Finally, we merge the Maddison/HYDE data, covering the decades 1820 to 2000, with the G-Econ database, which covers the years 1990 to 2010.[4] Whenever possible, we construct 5 year averages around decimal years to minimize the influence of potential extreme events.

3.3 CO_2 emissions

The procedure is similar to the one followed for GDP. First, gridded EDGAR emission data for 2008 are extended to 2012 by using 2008-2010 and 2010-2012

[4] To avoid potential jumps in the final series, we smooth the transition from one database to the other by using a mix of both cell GDP datasets for overlapping decades 1990 and 2000. For the year 1990, we calculate final cell GDP as 70% of Maddison/HYDE cell GDP and 30% of G-Econ cell GDP, while for the year 2000 we calculate it as 30% Maddison/HYDE cell GDP and 70% G-Econ cell GDP.

national growth rates obtained from the EDGAR FT2012 database (an extended version of Edgar v4.2, containing country data). Second, to extend data backward in time, the HYDE and CDIAC databases are combined assuming emissions per capita are uniformly spread within countries. Then the obtained CDIAC/HYDE data are aggregated to a 60 arc minutes resolution to harmonize with the GDP aggregation level. Finally, we merge the CDIAC/HYDE data, covering the years 1820 to 1990 with the EDGAR database which covers the years 1970 to 2010.[5] Whenever possible, we construct 5 year averages around decimal years to minimize the influence of potential extreme events.

4 Results

Figures 5, 6 and 7 report the two-map diagrams for the three centers of gravity, i.e. for population, GDP and CO_2 emissions. We remind the reader that the country frontiers are only reported here for graphical convenience. Normally the center of gravity itself always locates well below the Earth's surface. Its height (coordinates along orthogonal meridians) above (within) the equatorial plane is (are) given in the left (right) map.

Figure 8a compares the length of the gravity vectors, as the distance between the gravity center and the Earth's center. It is a rough measure of the concentration of the underlying variable on the Earth's surface. It also helps figuring out the radius of the inner-Earth imaginary concentric sphere upon which the center of gravity locates. Figure 8b compares the speed of the gravity centers, i.e. the distance they cover per decade.

Regarding interpretation of trends, the coordinates of the world center of gravity being a weighted average of individual cell's coordinates, it is intuitive that changes over time are mostly driven by variations in (large) country shares.[6] To condense presentation, we will only refer to the most important changes in the text below. The interested reader can also refer to the Appendix for the evolution of the share of the largest countries during the 1820-2010 period.

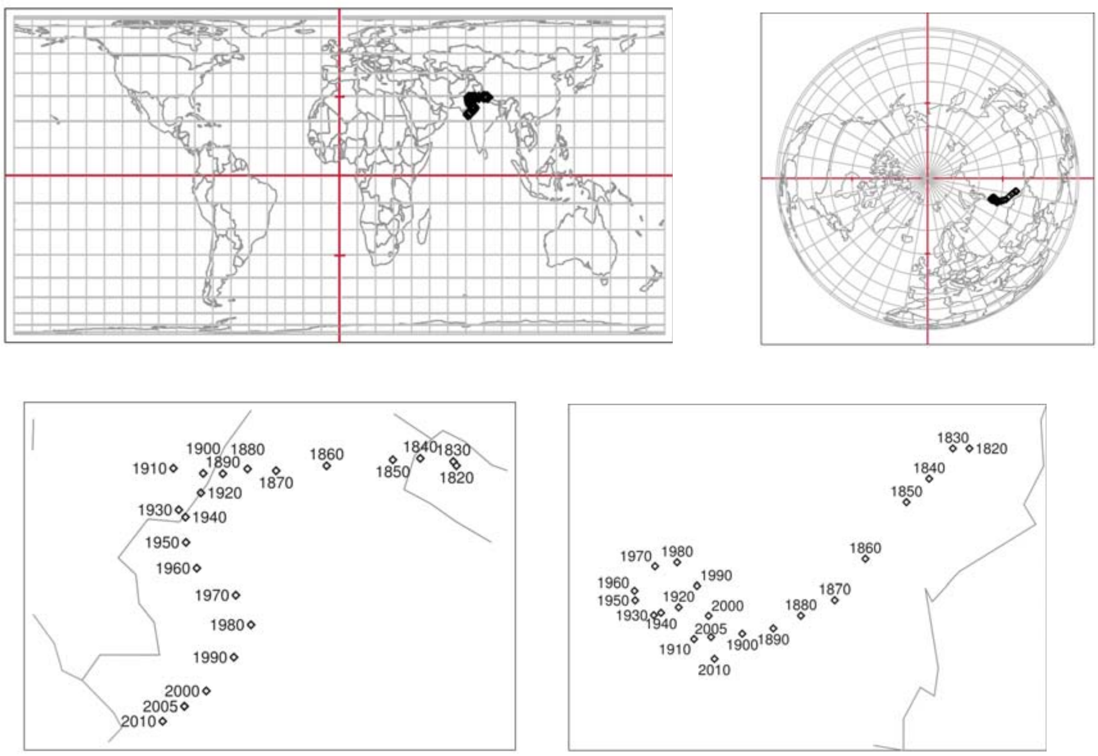
[5] To avoid potential jumps in the final series, we smooth the transition from one database to the other by using a mix of both cell CO_2 datasets for the years 1970, 1980 and 1990, as we did for GDP. For 1970 (1980, 1990), we calculate final cell CO_2 emissions as 75% (50%, 25%) of CDIAC/HYDE cell emissions and 25% (50%, 75%) of EDGAR cell emissions.

[6] In theory, within-country variation should also be addressed, but in practice, most of the variation comes from between-country changes. See also Grether et al. (2012b) for a decomposition of changes of the economic center of gravity into between-continent and within-continent effects.

4.1 Population

As could be expected, the population center of gravity is basically located under Asia (Northern India in the left maps and along the Russian-Kazak frontier in the right maps). At the beginning of the period, its length is close to 5000 km, i.e. around 0.75R, where R is the Earth's radius (6371 km). This is the result of 0.5R elevation over the equatorial plane (corresponding to a Northern latitude of 30°) and approximately 0.6R rightward orientation on the projection of the 90° meridian (the coordinate along the projection of the Greenwich meridian is almost negligible). In short, human population is initially quite concentrated in the Asian part of the Northern hemisphere.

Figure 5: Center of gravity for population



The bottom maps reveal a small but steady shift during the sample period, in two distinct phases. During the first phase, which lasts until 1910, the center of gravity shifts westward, with no latitudinal change. This is consistent with the gradual decline of China and India, whose combined share in world population drops from 55% to 40% along that sub-period. It is also concomitant with a leftward shift of the horizontal component of the left maps, and a corresponding decline in the length of the gravity vector by around 15%. That is, human population becomes more homogeneously spread, with a decline in Eastern and a rise in Western locations, in particular the USA.

During the second phase, starting in 1920, there is a clear Southern shift, slightly eastward until 1980, and westward since then. This is consistent with Western countries plateauing in terms of population, the combined share of China and India remaining roughly constant, and a relative increase of Southern countries in East Asia first, and in Africa second. Overall, there is again an increase in the dispersion of human population, although the decline of the length of the gravity vector is more moderate than in the first phase.

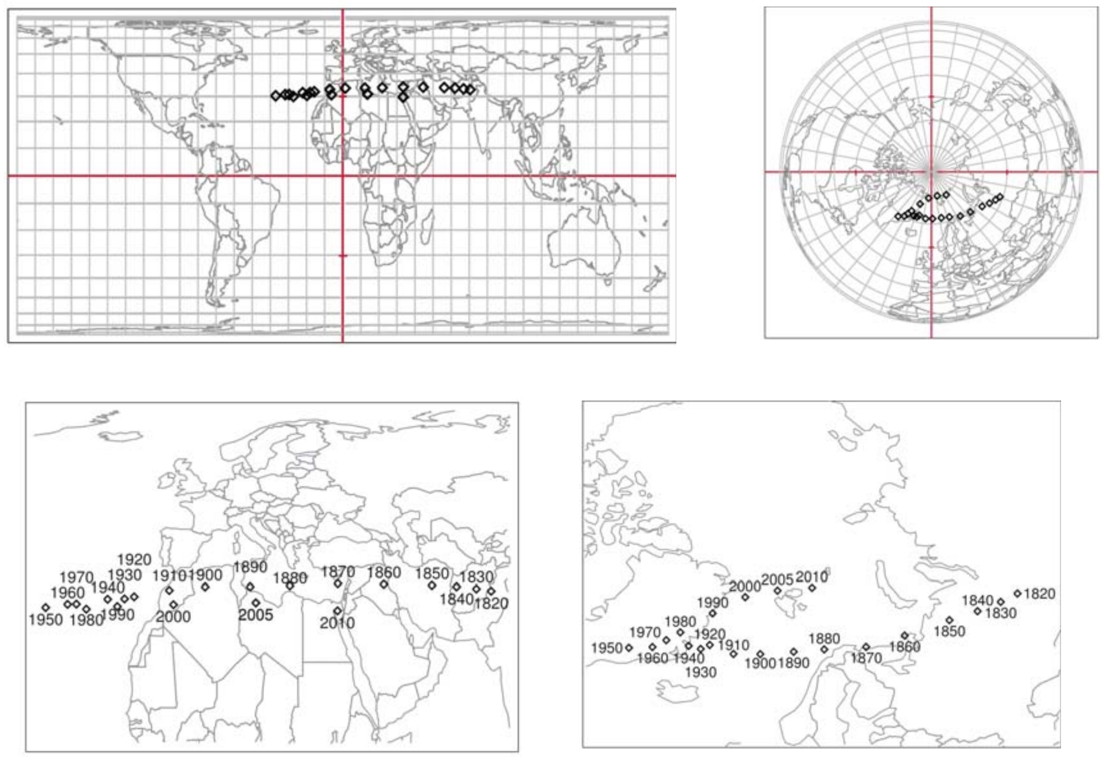
These shifts in the demographic gravity center are consistent with historical trends, but of modest magnitude, with an average speed of less than 200km per decade. The trends exhibited by the other two variables reveal more profound changes.

4.2 GDP

The trajectory of the economic center of gravity is also in two phases, but the striking features are that apparent distances covered are far larger than for the demographic center, whereas the elevation upon the equatorial plane is almost unchanged, with most points locating along the 30°N parallel on left-hand side maps. Starting 1820, the location is almost identical to the demographic center of gravity, reflecting the small differences in GDP per capita across countries prior to the industrial revolution. Then the Big Divergence leads to a strong western shift of the economic gravity center, with a speed two to three times larger than for the demographic center of gravity, and during a longer period. Although the 1930s and 1940s slow down the process, the immediate aftermaths of World War II brings it its last big western push, with a 1950 location close to the middle of the Atlantic. During that same sub-period, the combined share of China and India in world GDP has dropped from 45% to less than 10%, while that of the USA has risen from a few percentage points to more than 25%.

Since 1950, the eastward shift has been steady, driven by European reconstruction first, and then by the Asian comeback. It seems to accelerate a lot

Figure 6: Center of gravity for GDP



between 2000 and 2010, when the center of gravity jumps by more than 40° of longitude. However, while interpreting left maps, one has to remember that longitudes are not a precise concept in terms of distances. It does not only depend on latitude (which is here roughly constant), but also on the distance from the North-South axis, i.e. the inward location of the gravity center within the sphere, which is indicated on the right map. And, precisely between 2000 and 2010, it happens that the center of gravity gets quite close to the Earth center, ending a continuous decrease in the length of the vector since 1950. As a result, the effective speed in 2010 remains smaller than in 1950 that is, it is indeed large but not extraordinarily so. This explains the apparent jump and illustrates again how relying on a unique map to represent a three dimensional movement is misleading.

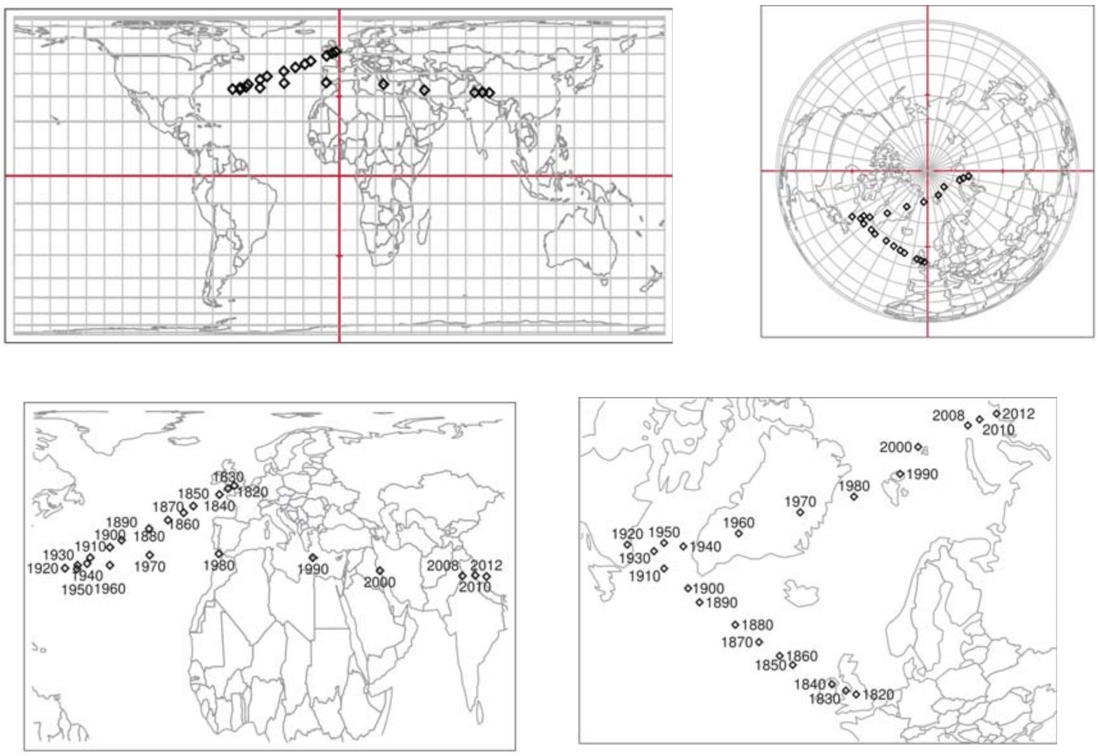
4.3 CO_2 emissions

The trajectory of the center of gravity for emissions is even more remarkable than for GDP. It is initially an almost purely British phenomenon, with a center of gravity locating just underneath the UK, with a length corresponding to 98% of the Earth's radius. As the industrial revolution spreads, and the use of coal as the main energy source with it, this center begins its descent towards the South-West and the Earth's center. Its most westward location is in 1920, when its projection gets close to the US coast and its length has decreased to 81% of the Earth's radius. During that first period, the speed is similar to the one recorded for the economic center of gravity, although larger for the last two decades of the sub-period (1910 and 1920). Overall, the 19th century is a period during which GDP and CO_2 emissions tend to evolve synchronically and westward. This is due to the progressive replacement of the UK by the US as the major source of world emissions. US dominance peaks in 1920, with a share of 50% of world emissions.

Comparative dynamics of GDP and emissions are altered after World War I. While economic expansion pursues its westward trend, the center of gravity of CO_2 emissions shifts towards the East in 1930 and 1940. This suggests a decoupling between economic activity and pollution, which is probably linked with the early adoption of oil as an alternative, less emission-intensive, source of energy by the US (i.e. the major polluter), while other major polluters remain more coal-dependent. Indeed, according to Smil (2010), the share of coal in US energy supply peaks in 1910, while it does so only 40 years later in the UK and the USSR. As a result, the share of the US in world emissions declines strongly in 1930-1940, whereas its GDP share remains stable. This explains the earlier reversal of the emission center of gravity with respect to the economic one. Economic trends remain powerful however, and the US growth spurt following the end of World War II temporarily interrupts the eastern trend in 1950, when both centers of gravity shift westward again, albeit more modestly for the emission center.

From 1950 onward, the emission center of gravity is heading East, as the economic one. This is in line with a decline in US dominance in terms of both GDP and emissions, although the decline is a lot larger for emissions, with a US share in world emissions dropping from above 40% in 1950 to 20% in 1980. This coincides with very large distances covered by the emission center of gravity, close to 1000 km per decade, as reported by figure 8. This suggests again that the transition towards non-coal energy sources such as oil and gas has been

Figure 7: Center of gravity for CO_2 emissions

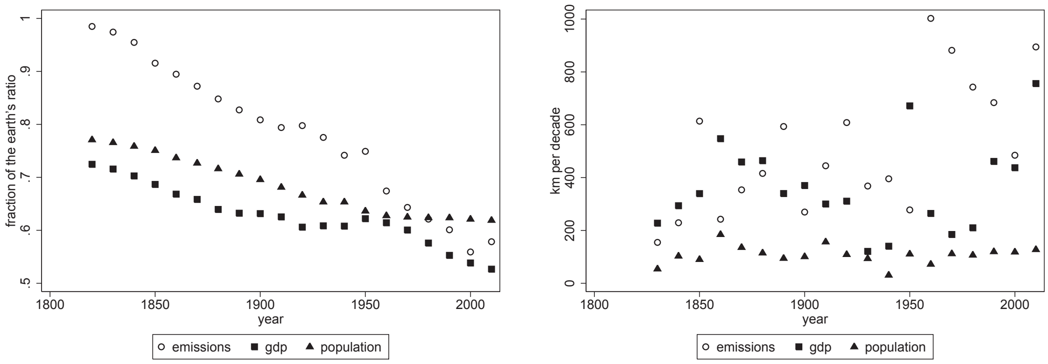


quicker in the US compared to other large emitters (the share of coal falls below 50% as early as 1940 for the US, but only in 1960 for the UK or Japan, and 1970 for Russia, see Smil (2010).

During the first two decades following the end of the cold war, 1990 and 2000, the eastern shift is slowed down, as the US share in world totals either stabilizes for emissions or even increases slightly for GDP. This is in line with a pause in the erosion of US dominance and the demise of the USSR.[7] But the movement accelerates again in the last decade, 2010, for both GDP and emissions. This corresponds to the rise of Asian countries, in particular China, which remains

[7] We warn again the reader against using the left map only to estimate distances covered by the emission center of gravity in 1990 and 2000. They appear large, in particular in contrast with 1960. However, as shown by the right map, it is a typical "wiper" effect due to the fact that the center of gravity locates closer and closer to the Earth's center from 1950 onward. In reality distances covered are considerably smaller in 1990 or 2000 than in 1960 (see figure 8).

Figure 8: Length and speed for the centers of gravity



(a) **(b)**

heavily dependent on coal as an energy source. By the end of the sample period, the emission center of gravity locates quite close to the demographic center of gravity.

In a nutshell, the evolution of the emission center of gravity suggests radical changes in the spatial distribution of CO_2 emissions on the Earth's surface. In two centuries, it shifts from an extremely concentrated location to one which is strikingly similar to the distribution of world population. This calls for a complementary analysis in the last subsection.

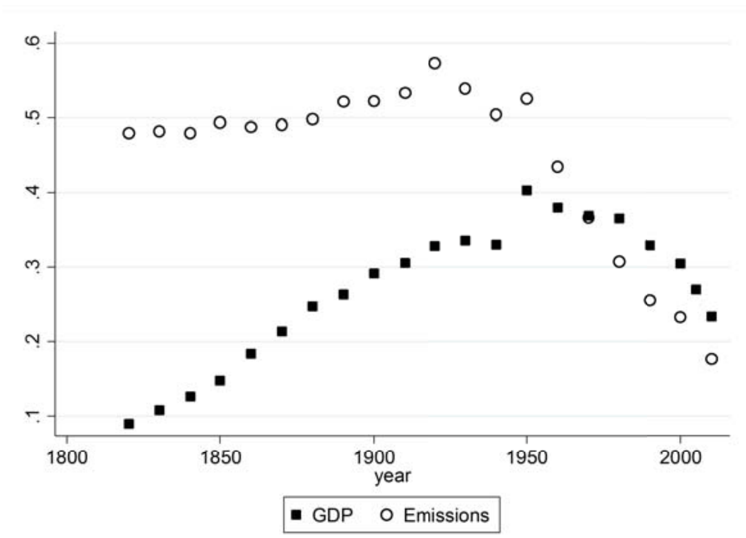
5 Spatial imbalances: measurement and discussion

People are unequally spread across the planet's surface, i.e. mainly in the Northern Hemisphere, and mostly in Asia. This encapsulates into a location of the demographic center of gravity which is roughly stable over time, at 0.5R (R=6371km) above the equatorial plane and 0.5R to the right of the Greenwich meridian. If GDP and emissions were equally shared among people, the corresponding centers of gravity would locate at the same place, i.e. below Northern India, at roughly 70% from the center of the Earth. This is not what happened during the last two centuries. From there the idea of using the distance between the demographic center of gravity and the comparison one as a proxy for the spatial imbalances characterizing the per capita distribution of the underlying variable (either GDP or emissions).

More specifically, following Zhao et al. (2003), we define the index of spatial imbalances as the ratio between the actual distance between the demographic center of gravity and the one it is compared to, and the potential maximum for that distance, i.e. the length of the demographic center of gravity vector plus the Earth's radius.[8] Applied to GDP and emissions, this leads to the values reported in Figure 9.

What happens for GDP confirms the trend reversal pattern already identified in figure 6. Spatial imbalances start below 10%, and then increase during the Big Divergence, as economic growth takes off in Western countries and their offshoots. The peak is reached in 1950, with an index slightly over 50%. After that, European and then most importantly Asian catch-up decrease spatial imbalances back to 20% at the end of the period.

Figure 9: Indices of spatial imbalances



[8]For example, if the demographic center of gravity is denoted by D, the economic center of gravity by G, and the Earth's center by O, then the index of spatial imbalances for GDP is given by $\frac{\left\|\overrightarrow{DG}\right\|}{\left[\left\|\overrightarrow{DO}\right\|+R\right]}$, where R is the Earth's radius.

The temporal pattern for emissions is distinct in that it starts from a large level of close to 50% in 1820. The rest of the trajectory is qualitatively similar to GDP, i.e. also an inverted-u shape, but with three differences. First, the rising phase is less steep, with a peak at 60%. This is due to the fact that, apart from going West, which increases the index, the center of gravity of emissions is also going down (Southward), which decreases the index. Second, as already noticed in figure 7, the peak is reached in 1920, not 1950. Third, the decreasing phase is steeper, with a final index of spatial imbalances for emissions around 10% in 2010.

Intuitively, if data had been available for earlier centuries, it is quite probable that the pattern of spatial imbalances for emissions would have looked even more similar to the one for GDP. After all, before any country started its industrial revolution, differences in emissions per capita across countries were probably not large, implying a low level of spatial imbalances. This suggests a kind of leading role of emissions with respect to GDP over a long time span.

Although no formal analysis has been performed, the interpretation would be as follows. Start from a pre-industrial world where production and emissions are roughly homogeneous across people. Then technological innovation and the use of fossil fuels give an early boost to Western countries. The impact on emissions is immediate, while the effect on production takes several decades to materialize. During the rest of the 19th century and the early 20th century, as the West industrializes alone, emissions and production go hand in hand. Then the rapid adoption of less emission-intensive energy sources (oil and gas rather than coal) by the US sends back the emission center of gravity towards the East as early as the 1930s. Economic activity is characterized by more inertia, but when it starts to shift back as well after 1950, this accelerates further the eastern movement in emissions, also enhanced by the shift of more emission-intensive manufacturing activities towards Asia. As it happens, after a long period of divergence, both the economic and the emission centers of gravity seem to be dragged back to their initial 1820 location determined by demography.[9]

The above trends are confirmed when using alternative conventions regarding the smoothing shift from CDIAC to EDGAR data for emissions, or from

[9]The extreme spatial concentration of emissions at the beginning of the sample period is due to the narrow definition of CDIAC historical data, limited to fossil fuel consumption and cement production only. However, to our knowledge, it is the best historical data on CO_2 emissions available at present.

Maddison to GEcon data for GDP. Moreover, temporal patterns for the demographic and economic centers of gravity are similar to those identified by Grether et al. (2012b), even though they did not rely on the Hyde database to capture within-country changes in spatial distributions. Therefore, given data limitations, our results can be considered as reasonably robust.

6 Conclusions

During the two centuries that followed the industrial revolution, economic activity has become more intense, complex and widespread upon the Earth's surface. This has coincided with a redistribution of people, power and pollution across regions. Capturing the major trends underpinning these spatial changes is not straightforward. By synthesizing the spatial distribution of any variable into a single point, the world center of gravity approach allows to reveal interesting dynamics. We have applied that approach to three variables i.e. human population, GDP and CO_2 emissions, for which gridded data were made available along the 1820-2010 period. We have also refined the presentation of results in order to avoid distortions and identify more accurately critical reversals.

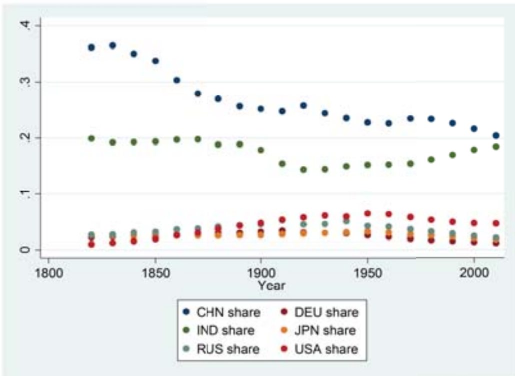
Two major results emerge. First, the world demographic center of gravity is very stable over time, and clearly located under Asia. Second, the other two variables present a strong divergence with respect to demography during the 19th century, and a progressive return towards Asia during the 20th century, with a reversal in 1920 for emissions, and 1950 for GDP. Technological innovation, energy transition, structural change and wars are the main factors underlying these trends and turning points. In a nutshell, it is as if demography acts like a long run anchor, while emissions and GDP are two outcome variables of a technological diffusion process which increases spatial inequalities during the 19th century and progressively decreases them during the 20th century.

Two caveats to conclude. First, results could be refined with better quality data, in particular for the years before 1950. Second, and perhaps more fundamentally, this type of analysis may be discarded as being merely descriptive. We perfectly acknowledge that it is not a causal analysis. However, we believe it clarifies the presentation of trends and the identification of turning points that matter at the global level. As such, it may be applied to the many other cases where the relevant question is how do socio-economic phenomena spread across the Earth's surface.

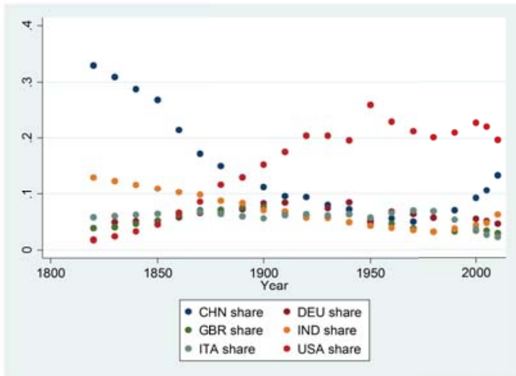
Appendix A

Figure A1 reports, for each variable of interest, the evolution of the share of the largest six countries in world totals over the sample period.

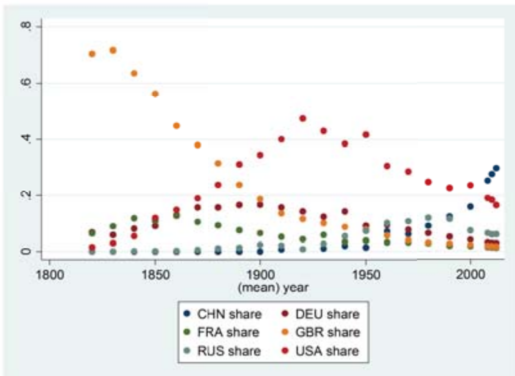
Figure A1: Shares of major countries in world totals 1820-2010



(a) Population



(b) GDP



(c) CO_2 emissions

Chapter 2

Geographical Spread of Global Emissions: Within-country Inequalities Are Increasing *

1 Introduction

The different emission sources of gases contributing to global warming are unevenly spread across the Earth surface. For a climate analyst, this may seem relatively benign given that the major greenhouse gases (GHG), carbon dioxide and methane, are uniformly mixing and thus deploy their effects worldwide. However, from a politico-economic perspective, the attribution of polluting emissions to specific locations is crucial for a variety of reasons. First of all, the main bulk of policies regulate emissions at the production source (command and control instruments, taxes, tradable allowances) and thus the emission distribution matters because policy stringency varies depending on spatial location. On top of that, everything else equal especially monitoring possibilities fixed, the more widespread pollution sources are, the larger the costs of implementing and

*This paper is co-authored by Jean-Marie Grether (University of Neuchâtel, Faculty of Economics and Business) and Nicole Mathys (Federal Office for Spatial Development and University of Neuchâtel, Faculty of Economics and Business).

monitoring reductions in emissions. This efficiency argument must be refined to include marginal abatement costs, which do differ strongly across locations. Moreover, and even more importantly, even though one additional ton of CO_2 equivalent has the same warming effect whatever its origin, its long lasting impact varies widely across locations. This has generated heated debates about who should be made accountable for these damages. While consumption-based accounting focuses on the responsibility of the final consumer, independently of the production site, the location of emission sources determines the responsibility in terms of the applied regulation. It is largely acknowledged that differences in responsibilities should be taken into account in policy negotiations such that the final outcome can be considered as fair.[1] Finally, asymmetries in both exposition to damages and historical responsibilities are crucial in shaping not only the national stance in terms of climate policy, but also lobbying activities within each nation. In short, spatial differences in emissions are critical in shaping the efficiency and fairness of international and national environmental policies and need to be better understood.

Recognizing the importance of patterns of spatial distributions of GHG emissions for environmental policy making, the literature started to analyze them in the late 20th century, using various inequality measures (see for instance Grunewald et al. (2014), Arora (2014), Duro et al. (2013), Duro (2012), Ordas and Grether (2011), Clarke-Sather et al. (2011), Groot (2010), Cantore and Padilla (2010), Coondoo and Dinda (2008), Duro and Padilla (2006), Padilla and Serrano (2006), Heil and Wodon (2000), Heil and Wodon (1997)). Most of the work dealing with emission inequalities focused so far solely on inequalities between countries and on only one particular gas, carbon dioxide. This is probably due to data availability, the importance of carbon dioxide in the context of climate change and to the perception that negotiating units are countries or groups of countries. The contribution of Arora (2014) and Clarke-Sather et al. (2011) which analyze inequality patterns at the sub-national level in India and China constitute a notable exception, with a focus on only one particular country and gas. To our best knowledge, no study exists which analyzes global

[1] The theoretical and empirical literature on climate change policy negotiations emphasizes clearly the importance of fairness as a criteria for successful international and national negotiations (see for instance Cantore (2011), Rübbelke (2011), Kverndokk and Rose (2008), Lange et al. (2007), Paavola and Adger (2006), Barrett and Stavins (2003) Ringius et al. (2002) and Rose et al. (1998)). Using the words of Barrett and Stavins (2003), p.358: "Concerns for fairness are not merely abstract notions. They are important for negotiations. People often refuse offers they perceive to be unfair, even when doing so comes at significant personal cost. In principle, it should be possible to negotiate a treaty that is both efficient and fair."

emission inequality using sub-national disaggregated data.

Accounting for within-country spatial inequality of emissions may improve our understanding for at least three reasons. First, from an analytical point of view, using national instead of sub-national basic units will result in an important underestimation of global geographic inequality. After all, within country inequalities may even be stronger than between country inequalities. Second, the literature on the political economy of environmental policies emphasizes the important role of lobbying groups in the formation of environmental policies (see for instance Oates and Portney (2003) or Aidt (1998)). Hence spatial within country inequalities are important because they might shape national environmental policies via the interaction of different sub-national interest groups. As Clarke-Sather et al. (2011) put it: "internal dynamics of carbon inequality have the potential to shape future energy policies". Finally, we observe today an emerging trend towards sub-national and or sectoral policies regarding greenhouse gases. Scott Barrett for instance proposed to break the problem up and to rely on separate agreements addressing different gases and sectors (Barrett, 2008). Another example would be the World Bank which recently launched its idea of a global network of carbon markets (see World Bank (2013)).

This chapter proposes an in-depth analysis of spatial inequalities in global warming related emissions for two GHGs, carbon dioxide (CO_2) and methane (CH_4). To measure inequality, while being able to incorporate within country inequalities, we need a decomposable inequality index. We thus use a spatial Theil index, which captures how polluting emissions per square kilometer are unevenly spread across the Earth's surface. This index allows to analyze structural determinants of inequalities, as it can be decomposed into the contribution of geographical groups on different hierarchical levels (e.g continents, countries) and emission sources (e.g. sectors). It thereby attempts to provide answers to the following questions: By how much do we underestimate global emission inequality by choosing countries as basic units of analysis? How do the contributions of between and within country inequality evolve over time? Which specific sector/country combinations contribute more than proportionally to global emission inequality? And finally, as an illustration of the importance of these measures in the policy debate, what is the degree of overlapping between the geographical distribution of current emissions and the geographical distribution of future damages?

This chapter contributes in several ways to the existing literature. It estimates for the first time global emission inequality using a sub-national basic unit of analysis. Moreover, instead of limiting ourselves to the carbon dioxide case, we extend the analysis by including methane as an additional gas. On top of that we extend existing Theil index decomposition methods in two directions. The first enables us to determine which part of total inequality is due to differences between countries and between sectors and which part is due to differences within countries and sectors. The second extension allows us to evaluate how far the geographical distribution of damages is disconnected from the distribution of emissions. In order to implement these estimations, we use a unique database on spatial emissions that we combine with several other databases.

2 Data

The selected source of emissions is the Emission Database for Global Atmospheric Research (EDGAR, see European Commission (2011)), which provides sectoral grid emission data (in tons) covering the years 1970 to 2008. To the best of our knowledge, this is the most comprehensive source of disaggregated emissions, as data is available for each bottom left centered 0.1 degree latitude longitude grid on the surface of the planet. In this chapter we take two direct greenhouse gases into account: carbon dioxide (excluding short-cycle organic carbon from biomass burning) and methane. Using the IPCC sector classification, EDGAR also provides the emissions for each grid-cell by sector. Note that the sectors might differ for different gases, as reported in table (A2) in the Appendix, which also displays shares in total world emissions of each sector by gas in 1970 and 2008.

We merged the EDGAR database with the GADM Global Administrative Area database (see Global Administrative Areas (2012)) to attribute each grid-cell to a given country and UN-region[2]. In the case where a grid-cell corresponds to more than one country we attributed the cell to the country in which the majority of the cell is located.

Note that the large majority of the literature used either GDP or population data as weights. We however use area in square kilometers as a weight. This choice is conceptual: we aim to analyze the spatial distribution of emissions, hence emissions per square kilometer are the appropriate measure.[3] We calcu-

[2]For an overview of the different UN regions and their share in world emissions refer to table (A1)

[3]Our goal is to describe and subsequently decompose the spatial distribution of emissions.

lated the planimetric area A of each grid cell by treating the planet as a sphere: $A = \frac{\Pi}{180} R^2 \left|\sin(\mathrm{lat}\frac{\Pi}{180}) - \sin((\mathrm{lat}+0.1)\frac{\Pi}{180})\right| |\mathrm{lon} - (\mathrm{lon}+0.1)|$. $R = 6371$ km is the radius of the Earth while *lat* and *lon* correspond to the bottom left grid-cell corner latitude and longitude in decimal degrees. Given that economic activity also takes place on non-land covered areas (transport, fishing, etc.) the surface variable which is used is the total area of the grid-cell, whether partially covered by water or not.

For our proposed extension to compare between-sector with between-country inequalities, we need a sector area variable. We don't directly observe sector production area but we know how many sectors produce in a given year-cell combination. So we first made the most straightforward hypothesis that all sectors present in a cell share the area equally. As a second way to go we attribute the cell area proportionally to cell sector emissions. The implications of those two hypotheses will be discussed in the result section.

To measure geographical inequalities in damages, we rely on the results from the Global Circulation Models made available by the World Bank on its Climate Change Portal (see World Bank (2014a)). This choice is dictated by our objective to capture geographical distribution at the highest degree of disaggregation. As data on damages is only available for grid-cells at the 1 degree level, emissions had to be aggregated to that level for comparison purposes. The selected proxy for damages is the average estimated share of very warm days over the 2046-2065 period (a very warm day is defined as having a temperature exceeding the 90th percentile bound over the 1961-1990 reference period) times the estimated human population of the cell in 2050 (obtained by multiplying the population figures at the country level for 2050, which come from the World Bank (see World Bank (2014b)), by the 2005 grid-level population shares derived from the G-Econ database (Nordhaus et al. (2006b)). The representative scenario is the A2 scenario of the list elaborated by the IPCC (Randall et al. (2007)), which describes a heterogeneous world with slow rates of convergence and technological change.

For each grid-cell we aggregate all sectoral emissions of a particular gas and

An interesting related topic would be to analyze the causes of this spatial inequality (e.g. differences in the distribution of GDP or population), but this task is out of the scope of the chapter. See Padilla and Duro (2013) for a recent analysis of causes of between EU country emission inequality.

obtain the total emissions of the gas for the given grid-cell[4]. Finally we drop all grid-cells which are not located within country borders (i.e. we drop all cells which are in international waters). This choice is necessary because we are interested in the between and within contribution of different countries to total emission inequality. The coverage of the final sample in 2008 is larger than 96.4% of world emissions for CH_4 and 93.5% for CO_2 emissions. We end up with roughly 1.5 million observations per year and gas for a total of 38 years, two gases (CO_2 and CH_4), more than ten sectors and 228 countries. Due to space constraints we cannot present all detailed results in the result section. They are however available upon request to the authors.

3 Methods

3.1 The basic spatial Theil index of emission inequality

Assume the world is composed of a total of I cells indexed by i. Variable y is used to denote total world emissions ($y = \sum_{i=1}^{I} y_i$) and variable n to denote total world area ($n = \sum_{i=1}^{I} n_i$).

Our main objective is to analyze inequality of emissions per square kilometer hence our basic units are geographic cells.[5] The overall Theil index can then be defined as follows:

$$T = \sum_{i=1}^{I} \frac{y_i}{y} \ln \left(\frac{\frac{y_i}{y}}{\frac{n_i}{n}} \right) \tag{1}$$

Where equation (1) is a reformulation of the originally proposed index by (Theil, 1967). Note that a cell is contributing positively to overall inequality when its emission share in total emissions ($\frac{y_i}{y}$) is larger than its area share in total area ($\frac{n_i}{n}$). The bigger the positive contribution to overall inequality is, the dirtier is the cell and hence the higher is the cell's responsibility in polluting the globe. Analogically, a cell which has a negative contribution to the overall

[4]EDGAR provides a variable capturing total emissions of a given grid-cell. We do not use this variable because the computation of sectoral emissions and total emissions has been done using slightly different methodologies. This leads to a few cases where the sum of sectoral emissions does not correspond to the total emission variable provided by EDGAR.

[5]A basic unit of analysis corresponds to the smallest unit for which data is available and which is used to compute the inequality index. The income inequality literature commonly refers to this as the basic social unit of analysis which might be for instance an individual, a household, a nuclear family or an extended family (Cowell, 2011).

index is a relatively clean cell.[6] By defining the Theil index in this way we also underestimate inequality - because we assume perfect equality within a given 0.1 degree cell - but to a considerably lower extent compared to the case where the basic unit is the country.

3.2 Geographical decomposition of the basic Theil index

We now start decomposing equation (1). First we use the two-stage decomposition proposed by Akita (2003). This approach allows to decompose total emission inequality into:

- between UN-region inequality;
- between country inequality within a given UN-region;
- within country inequality within a given UN-region.

The globe is composed of R UN-regions indexed by r. Each UN-region r can itself be divided into C^r countries indexed by c. Each country c in region r contains $I^{r,c}$ cells. Where $y = \sum_i^I y_i = \sum_{r=1}^R \sum_{c=1}^{C^r} \sum_{i=1}^{I^{r,c}} y_i^{r,c}$ and $n = \sum_i^I n_i = \sum_{r=1}^R \sum_{c=1}^{C^r} \sum_{i=1}^{I^{r,c}} n_i^{r,c}$.

Having this notation in mind, we can rewrite (1) as follows:

$$\begin{aligned} T = & \underbrace{\sum_{r=1}^{R} \frac{y^r}{y} \ln\left(\frac{\frac{y^r}{y}}{\frac{n^r}{n}}\right)}_{\substack{\text{Between UN-region inequality} \\ \equiv BR}} + \underbrace{\sum_{r=1}^{R} \frac{y^r}{y} \sum_{c=1}^{C^r} \frac{y^{r,c}}{y^r} \ln\left(\frac{\frac{y^{r,c}}{y^r}}{\frac{n^{r,c}}{n^r}}\right)}_{\substack{\text{Between countries inequality,} \\ \text{within UN-regions} \equiv BCwr}} \\ & + \underbrace{\sum_{r=1}^{R} \frac{y^r}{y} \sum_{c=1}^{C^r} \frac{y^{r,c}}{y^r} \sum_{i=1}^{I^{r,c}} \frac{y_i^{r,c}}{y^{r,c}} \ln\left(\frac{\frac{y_i^{r,c}}{y^{r,c}}}{\frac{n_i^{r,c}}{n^{r,c}}}\right)}_{\substack{\text{Within country inequality,} \\ \text{within UN-regions} \equiv WCwr}} = BR + BCwr + WCwr \end{aligned} \tag{2}$$

Where y^r (n^r) denotes total emissions (total area) of UN-region r and $y^{r,c}$ ($n^{r,c}$) denotes total emissions (total area) of country c in UN-region r. Equation

[6] For an excellent intuitive interpretation of the Theil index and its various decompositions refer to Conceicao and Ferreira (2000).

(2) allows to analyze the contribution of each UN-region to the between region, between country and within country inequality terms. As an example, if a region has a positive contribution to the between-region term its emission share in total emissions is higher than its area share in total area and the region can be considered to be relatively dirty. At the same time this region's contribution to the between country term might be zero, indicating that all countries within this region are equally dirty. Finally, the contribution of this region to the within country term might be highly positive, indicating that there are important differences between clean and dirty cells within the region's countries. This two-stage decomposition method provides also a first insight on the magnitude of importance of between country and within country inequalities.

3.3 Integration of sectoral contributions in the geographic decomposition

Equation (2) allows to analyze the contributions of different geographical entities to total inequality. As a next step we refine this analysis by applying the methodology proposed by Giammatteo (2007) to equation (2). Giammatteo (2007) took the classical between country and within country decomposition and extended it by his pseudo Theil approach, allowing to analyze the contribution of each sector to the between and the within country term. We have a total of S sectors, indexed by s. So for a given cell i in UN-region r and country c we have $y_i^{r,c} = \sum_{s=1}^{S} y_i^{r,c,s}$. Hence by combining the approach of Akita (2003) (equation (2)) with the one by Giammatteo (2007) we obtain:

$$
\begin{aligned}
T = \sum_{s=1}^{S} & \underbrace{\sum_{r=1}^{R} \frac{y^{r,s}}{y} \ln\left(\frac{\frac{y^r}{y}}{\frac{n^r}{n}}\right)}_{\substack{\text{s}^{th} \text{ source contribution to BR} \\ \equiv Tbr(s)}} + \sum_{s=1}^{S} \underbrace{\sum_{r=1}^{R} \frac{y^r}{y} \sum_{c=1}^{C^r} \frac{y^{r,c,s}}{y^r} \ln\left(\frac{\frac{y^{r,c}}{y^r}}{\frac{n^{r,c}}{n^r}}\right)}_{\substack{\text{s}^{th} \text{ source contribution to BCwr} \\ \equiv Tbc(s)}} \\
& + \sum_{s=1}^{S} \underbrace{\sum_{r=1}^{R} \frac{y^r}{y} \sum_{c=1}^{C^r} \frac{y^{r,c}}{y^r} \sum_{i=1}^{I^{r,c}} \frac{y_i^{r,c,s}}{y^{r,c}} \ln\left(\frac{\frac{y_i^{r,c}}{y^{r,c}}}{\frac{n_i^{r,c}}{n^{r,c}}}\right)}_{\substack{\text{s}^{th} \text{ source contribution to WCwr} \\ \equiv Twc(s)}} \qquad (3) \\
& = \sum_{s=1}^{S} Tbr(s) + \sum_{s=1}^{S} Tbc(s) + \sum_{s=1}^{S} Twc(s)
\end{aligned}
$$

The interpretation of the terms in equation (3) is identical to the one in equation (2). But we are now also able to analyze the contribution of each sector to each of the three terms. The sectoral contributions can be positive (relatively dirty sectors) or negative (relatively clean sector).

3.4 Analyzing the sectoral dimension in more details

As a last step we analyze the sectoral dimension in more detail by proposing an original extension. Instead of analyzing the contributions of each sector to the geographical components (as we do in (3)) we want to be able to not only separate between and within geographical group contributions but also between and within sector contributions. In order to do so we need to change our basic unit replacing emissions per square kilometer in country c (y_i^c) by emissions per sectoral production area ($y_i^{s,c}$), assuming this latter information is available.[7] Instead of analyzing T, the inequality of emissions per square kilometers as we do with (1)-(3), we now analyze inequality of sectoral emissions per sectoral production area, T':

$$T' = \sum_{s=1}^{S} \frac{y^s}{y} \sum_{i=1}^{I} \frac{y_i^s}{y^s} \ln \left(\frac{\frac{y_i^s}{y}}{\frac{n_i^s}{n}} \right) = T + \sum_{s=1}^{S} \frac{y^s}{y} \sum_{i=1}^{I} \frac{y_i^s}{y^s} \ln \left(\frac{\frac{y_i^s}{y_i}}{\frac{n_i^s}{n_i}} \right) \tag{4}$$

Note that T' equals T plus the inequality between sectors within a given 0.1 degree cell. Given that we ignore UN-regions in this specification, the world is composed of a total of C countries, and each country c is composed of I^c cells. Where $y_i^c = \sum_{s=1}^{S} y_i^{s,c}$. Using the standard properties of the Theil index, we can rewrite T' as follows:

[7] For more information refer to the discussion on the impossibility of simultaneously decomposing T into source and group contributions in Giammatteo (2007)

$$
\begin{aligned}
T' = \quad & \underbrace{\sum_{c=1}^{C} \frac{y^c}{y} \ln\left(\frac{\frac{y^c}{y}}{\frac{n^c}{n}}\right)}_{\substack{\text{Between country inequality} \\ \equiv BC}} \quad + \quad \underbrace{\sum_{c=1}^{C} \frac{y^c}{y} \sum_{s=1}^{S} \frac{y^{c,s}}{y^c} \ln\left(\frac{\frac{y^{c,s}}{y^c}}{\frac{n^{c,s}}{n^c}}\right)}_{\substack{\text{Between sector inequality within a country} \\ \equiv BSwc}} \\
& + \underbrace{\sum_{c=1}^{C} \frac{y^c}{y} \sum_{s=1}^{S} \frac{y^{c,s}}{y^c} \sum_{i=1}^{I^c} \frac{y_i^{c,s}}{y^{c,s}} \ln\left(\frac{\frac{y_i^{c,s}}{y^{c,s}}}{\frac{n_i^{c,s}}{n^{c,s}}}\right)}_{\substack{\text{Within sector inequality within a country} \\ \equiv WSwc}} = BC + BSwc + WSwc
\end{aligned}
\tag{5}
$$

Analogically, we can also express T' as follows:

$$
\begin{aligned}
T' = \quad & \underbrace{\sum_{s=1}^{S} \frac{y^s}{y} \ln\left(\frac{\frac{y^s}{y}}{\frac{n^s}{n}}\right)}_{\substack{\text{Between sector inequality} \\ \equiv BS}} \quad + \underbrace{\sum_{s=1}^{S} \frac{y^s}{y} \sum_{c=1}^{C} \frac{y^{s,c}}{y^s} \ln\left(\frac{\frac{y^{s,c}}{y^s}}{\frac{n^{s,c}}{n^s}}\right)}_{\substack{\text{Between country inequality,} \\ \text{within sectors } \equiv BCws}} \\
& + \underbrace{\sum_{s=1}^{S} \frac{y^s}{y} \sum_{c=1}^{C} \frac{y^{s,c}}{y^s} \sum_{i=1}^{I^c} \frac{y_i^{s,c}}{y^{s,c}} \ln\left(\frac{\frac{y_i^{s,c}}{y^{s,c}}}{\frac{n_i^{s,c}}{n^{s,c}}}\right)}_{\substack{\text{Within country inequality,} \\ \text{within sectors } \equiv WCws}} = BS + BCws + WCws
\end{aligned}
\tag{6}
$$

Equation (5) and (6) are two equivalent decompositions. An appealing solution to the existence of such equivalent decompositions is to take the average of the expressions as advocated by Dietzenbacher and Los (1998). Taking the average of equations (5) and (6), we obtain the following decomposition:

$$T' = \overline{W} + \overline{BC} + \overline{BS} \tag{7}$$

Equation (7) - our newly proposed decomposition - has a unique interpretation: Given that $WSwc = WCws$ we can interpret $\overline{W} = WCws = WSwc = \frac{1}{2}(WCws + WSwc)$ as an overall within country/sector component representing inequalities which are due to the differences in emission intensities across cells of a given country and a given sector. $\overline{BC} = \frac{1}{2}(BC + BCws)$ can be interpreted as an average between country effect capturing the part of inequality due to differences in average emissions intensities among countries. And

$\overline{BS} = \frac{1}{2}(BS + BSwc)$ can be interpreted as an average between sector effect, representing inequalities which are due to the differences in average emissions intensities among sectors.

3.5 Linking emissions with damages

Part of the political tensions affecting the climate change debate is due to the fact that damages fall in locations which are not necessarily the major sources of emissions. This subsection establishes and discusses the formal links between emissions and damages inequalities from a spatial perspective. We first re-note the Theil index of spatial inequalities in emissions (equation (1)) by T^y, in order to tell the difference with the Theil index of spatial inequalities in damages, T^d. If d denotes world damages ($d = \sum_{i=1}^{I} d_i$), we have:

$$T^d = \sum_{i=1}^{I} \frac{d_i}{d} \ln\left(\frac{\frac{d_i}{d}}{\frac{n_i}{n}}\right) \tag{8}$$

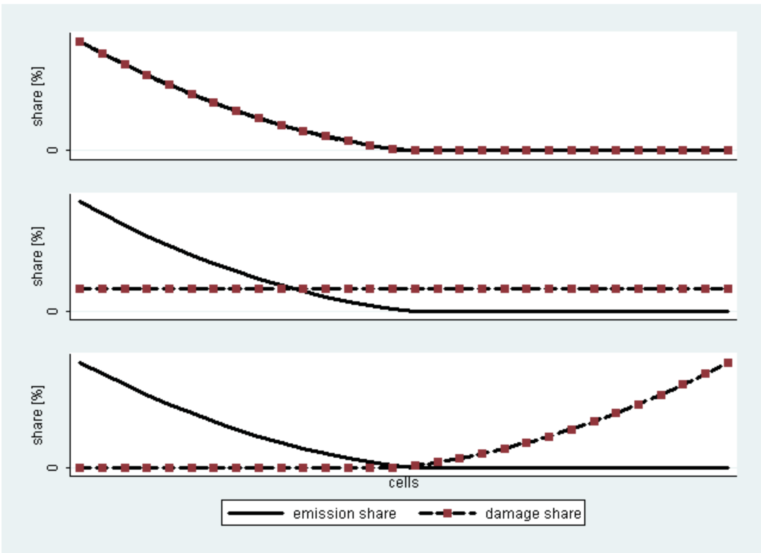
Let us define the damage gap as $\Delta_i \equiv (d_i/d) - (y_i/y)$. Rewriting d_i/d as $(y_i/y)+\Delta_i$, and replacing $ln[(d_i/d)/(n_i/n)]$ by $ln[(d_i/d)/(y_i/y)]+ln[(y_i/y)/(n_i/n)]$, it is straightforward to obtain, from equations (1) and (8):

$$T^d = T^y - \underbrace{\sum_{i=1}^{I} \frac{y_i}{y} \ln\left(\frac{\frac{y_i}{y}}{\frac{d_i}{d}}\right)}_{\text{Disparity index}, DSP} + \underbrace{\sum_{i=1}^{I} \Delta_i \ln\left(\frac{\frac{d_i}{d}}{\frac{n_i}{n}}\right)}_{\text{Overdamage index}, OVD} = T^y - DSP + OVD \tag{9}$$

The first term on the RHS of equation (9) is the Theil index of spatial inequality in emissions. It may be considered as an initial benchmark assumption which is bound to be incorrect (and thus in need of corrections) because in the majority of cases damages are not spread spatially the same way as emissions. So the next two elements on the RHS are correction terms. The first one is also a Theil index of inequality in emissions, but not with respect to geographic area, but with respect to damages. In other words, while T^y picks up by how much emission shares are different from area shares, the first correction term indicates by how much emission shares are different from damage shares, so we will call that term the *disparity* index (DSP). Note that a given value of DSP may be obtained from an array of totally different distributions of damages on the Earth's surface. So we need an additional correction to make the link between damages and geography. This is the intuition behind the second correction term, a covariance which indicates by which extent over-damaged cells, i.e. those where Δ_i is large, also tend to be those where damages are intense, i.e. those where the logarithmic term is positive. Therefore, we will refer to that second correction term as an index of *over-damage* (OVD).[8]

Both indices matter in terms of social tensions, but to illustrate why the DSP (OVD) index enters negatively (positively) into the equation, let us consider a simplified stylized world where emissions and damages are spread over equalized cells, ranked by decreasing order of emission density. In the three panels of Figure 1, the solid decreasing line represents the emission share of each cell. Damages shares are represented by the dashed line, which differs across panels. Damages and emissions have identical distributions in the top panel, damages are equally spread across all cells in the medium panel, and damages and emissions have opposite distributions in the bottom panel. We consider below each panel to unveil the interpretation of the two correction terms.

Figure 1: Stylized worlds



(i) victims=polluters i.e. damages and emissions shares are equal across all

[8]Formally, OVD is I times the covariance between Δ_i and $ln[(d_i/d)/(n_i/n)]$, due to the fact that $\sum_{i=1}^{I} \Delta_i = 0$

countries (top panel). In this obvious case $T^y = T^d$. The two correction terms are zero, both because damages and emissions are evenly spread.

(ii) damages evenly spread across all cells (medium panel). In that case $T^d = 0$. How do we obtain that? The overdamage index is zero because even if some countries emit and others do not, damages per square kilometer are constant. So the compensation comes 100% from the disparity index, which is both nonzero, as emissions and damages are unequally spread across countries, and necessarily equal to T^y, as damage shares and spatial shares are identical for each country in that particular case.

(iii) perfect opposition between victims and polluters (bottom panel). In this case damages occur precisely in cells which do not emit pollution. With respect to the previous case, disparity has increased, so that the addition of the first two terms on the RHS leads to a negative value. However, overdamage is large, with damages biased towards those areas which do not emit to such an extent that spatial inequality in damages (captured by T^d) just mimics spatial inequality in emissions (captured by $T^y = T^d$), although on a completely different subset of cells.

Every element of equation (9) can be decomposed into the sum of a between-region (BR), between-country ($BCwr$) and within-country ($WCwr$) term. For T^d and DSP, the corresponding terms are direct extensions of those appearing in equation (2). For OVD, it is straightforward to show that $BR = \sum_{r=1}^{R} \Delta^r ln\left(\frac{d^r/d}{n^r/n}\right)$, $BCwr = \sum_{r=1}^{R}\sum_{c=1}^{C^r} \Delta^{r,c} ln\left(\frac{d^{r,c}/d^r}{n^{r,c}/n^r}\right)$, and $WCwr = \sum_{r=1}^{R}\sum_{c=1}^{C^r}\sum_{i=1}^{I^{r,c}} \Delta_i^{r,c} ln\left(\frac{d_i^{r,c}/d^{r,c}}{n_i^{r,c}/n^{r,c}}\right)$, where $\Delta^r = (d^r/d) - (y^r/y)$, $\Delta^{r,c} = (d^{r,c}/d) - (y^{r,c}/y)$ and $\Delta_i^{r,c} = (d_i^{r,c}/d) - (y_i^{r,c}/y)$.

4 Results and Discussion

Results are reported on the basis of figures and summary tables, starting from the description of global patterns, and then focusing on the identification of the major inequality drivers between countries or between sectors. Comments mainly refer to the CO_2 case, but CH_4 is also discussed in case of important differences.

Beforehand, based on the affinity between polluting emissions and specific sectors, let us mention two roughly expectable outcomes. First, as illustrated by the world shares reported in table A2, carbon dioxide emissions are mainly released by fuel consumption for power generation and manufacturing, while methane is more linked to agriculture. As agriculture is more evenly spread, we may expect a lower spatial inequality index for methane. Second, whether based on factor endowments or economies of scale, trade between different locations allows for specialization and industrial clustering, which tends to increase spatial inequalities. As barriers to trade are typically less important within countries, everything else equal, we may expect more trade intensity, and thus larger spatial inequalities within countries than between them.

However, sectoral affinity is far from being the unique contributor to spatial inequalities. Differences in technology and environmental policies also matter. As we may expect more homogeneity along those dimensions within a given country, these effects work oppositely to trade forces, leading to less spatial inequalities within countries, not more. Further complications appear when considering the evolution over time, in particular economic growth during the last four decades. This phenomenon has been accompanied by both increased specialization and trade on the one hand, and by more technological, economic and policy convergence on the other hand. The net impact of these different forces on spatial inequalities in emissions is unclear, which increases the interest in the empirical analysis below.

4.1 Global patterns

Theil indices decomposed according to equation (2) are reported in Figure (2). Our two major expectations are confirmed. First, of the two gases, methane turns out to be more evenly spread, with an overall index slightly above 2, versus 3 for CO_2. This is consistent with the view that CH_4 anthropogenic emissions are mainly due to rural activities. Second, there is a striking similarity among the two gases regarding the dominance of within-country inequalities, which represent for both gases roughly 75% of the total. According to the above-mentioned arguments, this suggests that the agglomeration and specialization forces generated by freer trade within countries tend to overcome the influence of a unique regulatory framework.

Regarding changes over time, there is again a strong similarity across gases. Between-region and between-country inequalities are on average declining over the period, while within-country inequalities tend to increase, in particular at the end of the time interval. Again, this appears consistent with a period of globalization and growth during which, on the one hand, countries tend to converge in income per capita, which is positively correlated with environmental consciousness and policies, and on the other hand with increased specialization through trade, which leads to larger spatial inequalities within countries. For CO_2 and CH_4, two peaks can be identified in the years 1997/1998. Those peaks are the results of the enormous forest fires in those two years in Indonesia (probably the largest forest fires ever recorded in history).

Figure (2) is also illustrating the importance of the basic unit used to compute global emission inequality. By choosing countries as basic units, i.e. by making the assumption of perfect equality within countries, one underestimates global spatial emission inequality by a large amount. The dominant approach in the literature underestimates global spatial emission inequality for CO_2 and CH_4 on average by roughly $\frac{3}{4}$. Taking countries as basic units not only results in an important underestimation of global emission inequality, but impacts also on the observed overall trends. While previous studies find a decrease of global (carbon dioxide) inequality since the 70s (see for instance Grunewald et al. (2014) or Duro and Padilla (2006)), we show that global emission inequality is either roughly constant (CO_2) or even slightly increasing (CH_4).

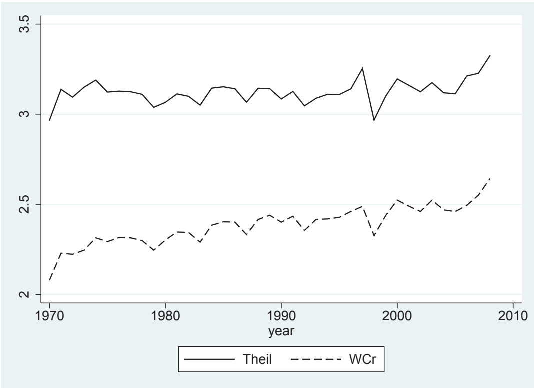
4.2 Which regions/sectors contribute more to inequality?

The above-mentioned global patterns may hide important differences across regions and sectors. This calls for a more detailed analysis at the disaggregated level. Two reminders are in order to avoid misunderstandings while interpreting the results.

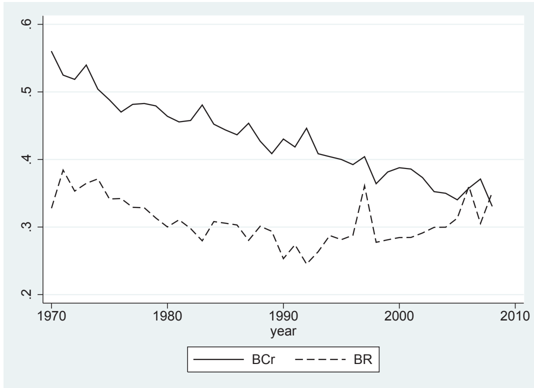
First, some contributions are negative, as every element of the Theil index is reported for the between-region part of the index (column “BR” of table (1)). In that case, a negative (positive) figure just indicates that this particular region has an emission density which is smaller (larger) than average.

Second, what we measure here are spatial inequalities of emissions, not emission shares. That is, if the results below suggest a particular region or sector does not contribute much to overall inequality, it does not mean that its share in global emission is commensurate. It just means that emissions in that par-

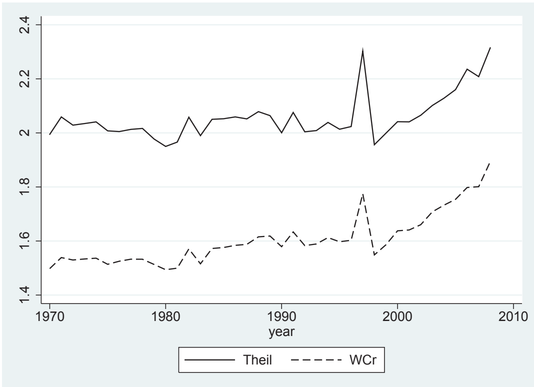
Figure 2: Geographic Decomposition of the Theil index T



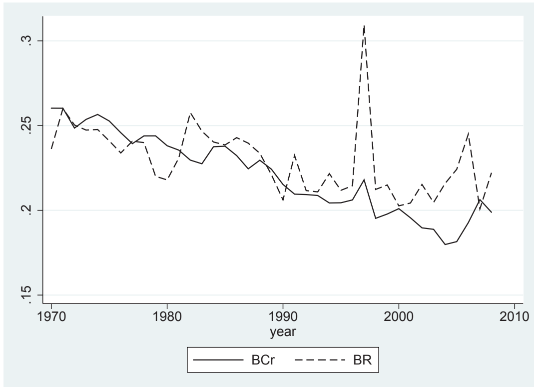
(a) CO2: Theil Index and Within Country Component



(b) CO2: Between Region and Between Country Component



(c) CH4: Theil Index and Within Country Component



(d) CH4: Between Region and Between Country Component

ticular region or sector are rather evenly spread geographically.

Table (1) provides absolute contributions to inequality by regions for 1970 and 2008. Based on column “Theil”, the major contributors for CO_2 turn out to be the four most industrialized regions i.e. Europe, North America, Former Soviet Union and East Asia, which represent together on average a rough 85% of total inequality. This common average contribution to inequality drops to 70% for CH_4, as South Asia and South East Asia are more important, a difference which could have been expected on the basis of the sectoral affinity argument.

For a given region, a large contribution may be due to three different factors: (i) because this region has a larger density of emissions per square kilometer than the average (column "BR") or (ii) because the countries in this region are strongly dissimilar between them (column "BCwr") or still (iii) because there are large spatial inequalities within the countries of this region (column "WCwr"). On average, for the four major industrialized regions, and whatever the gas, the most important factor is always the within-country component, while the less important factor is either the between-country component for the two smaller and more homogeneous regions (Europe and East Asia) or the between-region component for the other larger regions (North America and the Former Soviet Union).

Regarding changes over time, reported in the last columns of Table (1), there again, and whatever the gas, the larger changes are experienced by the four major industrialized regions, with an increase for East Asia and a decrease for the other three regions. The only exception is methane in the case of the Former Soviet Union, for which there is practically no change over the 1970-2008 period. Moreover, the major components of these temporal changes are the between-region component and the within-country component. The important change of the between-region component suggests a strong redistribution of world emission shares among three of theses large industrialized regions, while the important change of the within-country component reflects increased specialization and clustering within the countries of the regions.

The contributions of each sector to global spatial inequality (equation (3)) are reported in Table (2). Energy production and use is the major contributor but with important differences across gases (see "Theil" column). Carbon dioxide emissions are basically linked to fuel consumption, which accounts on average for more than 80% of spatial CO_2 inequality. Within that broad category, public electricity and heat production is the most important subsector, representing on average close to 50% of spatial inequalities sources for CO_2. In the case of methane, the contributions are more equally spread across three broad categories: fugitive emissions (related to coal, gas and oil production, by decreasing order), agriculture (due to enteric fermentation and soil management) and waste management. Whatever the gas, for each major sector, the most important average contribution comes from the within-country component, which is always at least twice as large as the other two components. The only exception is agriculture in the case of methane, where the average between-country (between-region) component is less than 30% smaller than the

Table 1: Absolute contributions to between region, between country, within country and total inequality by UN-region and gas.
(Note: Numbers might not add up due to rounding)

Gas	UN-Region	Absolute contributions, 1970				Absolute contributions, 2008				Absolute difference, 2008-1970			
		BR	**BCwr**	**WCwr**	**Theil**	**BR**	**BCwr**	**WCwr**	**Theil**	**BR**	**BCwr**	**WCwr**	**Theil**
CO2	East Asia	0.01	0.08	0.14	0.22	0.31	0.07	0.76	1.15	0.30	-0.01	0.62	0.93
	Europe (excl. FSU)	0.39	0.11	0.35	0.85	0.16	0.04	0.24	0.45	-0.23	-0.07	-0.11	-0.40
	Former Soviet Union	-0.02	0.05	0.57	0.59	-0.06	0.01	0.39	0.35	-0.04	-0.04	-0.18	-0.24
	Middle East and North Africa	-0.03	0.01	0.03	0.02	-0.03	0.03	0.13	0.13	0.00	0.02	0.10	0.11
	North and Central America	0.10	0.13	0.74	0.97	0.02	0.08	0.62	0.72	-0.08	-0.05	-0.12	-0.25
	Oceania and Pacific Islands	-0.02	0.00	0.04	0.02	-0.02	0.00	0.07	0.05	0.00	0.00	0.03	0.03
	South America	-0.04	0.01	0.05	0.02	-0.05	0.00	0.07	0.03	-0.01	-0.01	0.02	0.01
	South Asia	-0.01	0.04	0.07	0.10	0.02	0.01	0.22	0.24	0.03	-0.03	0.15	0.14
	South East Asia	-0.01	0.01	0.02	0.01	0.05	0.01	0.06	0.13	0.06	0.00	0.04	0.12
	Sub-saharan Africa	-0.04	0.13	0.07	0.15	-0.06	0.07	0.07	0.08	-0.02	-0.06	0.00	-0.07
CH4	East Asia	0.12	0.03	0.26	0.41	0.20	0.03	0.61	0.84	0.08	0.00	0.35	0.43
	Europe (excl. FSU)	0.17	0.05	0.20	0.42	0.05	0.02	0.07	0.13	-0.12	-0.03	-0.13	-0.29
	Former Soviet Union	-0.05	0.02	0.33	0.30	-0.05	0.01	0.38	0.34	0.00	-0.01	0.05	0.04
	Middle East and North Africa	-0.03	0.02	0.07	0.07	-0.03	0.02	0.12	0.11	0.00	0.00	0.05	0.04
	North and Central America	-0.02	0.06	0.33	0.36	-0.05	0.03	0.24	0.22	-0.03	-0.03	-0.09	-0.14
	Oceania and Pacific Islands	-0.02	0.00	0.03	0.02	-0.02	0.00	0.05	0.03	0.00	0.00	0.02	0.01
	South America	-0.04	0.01	0.06	0.03	-0.03	0.01	0.13	0.11	0.01	0.00	0.07	0.08
	South Asia	0.12	0.04	0.11	0.27	0.14	0.03	0.14	0.31	0.02	-0.01	0.03	0.04
	South East Asia	0.04	0.01	0.05	0.11	0.05	0.01	0.08	0.15	0.01	0.00	0.03	0.04
	Sub-saharan Africa	-0.06	0.02	0.04	0.01	-0.05	0.04	0.08	0.07	0.01	0.02	0.04	0.06

Table 2: Absolute contributions to between region, between country, within country and total inequality by IPCC-sector and gas, 1970-2008.
(FC = Fuel consumption, FE = Fugitive emissions; Note: Numbers might not add up due to rounding)

CO2	Sector	Absolute contributions, 1970				Absolute contributions, 2008				Absolute difference, 2008-1970			
		BR	BCwr	WCwr	Theil	BR	BCwr	WCwr	Theil	BR	BCwr	WCwr	Theil
Energy	FC in electricity and heat production	0.109	0.104	0.848	1.061	0.155	0.118	1.665	1.938	0.046	0.014	0.817	0.877
	FC in other energy industries & waxes	0.014	0.022	0.161	0.197	0.012	0.006	0.079	0.097	-0.002	-0.016	-0.082	-0.100
	FC in manufacturing	0.109	0.094	0.351	0.554	0.087	0.033	0.276	0.395	-0.022	-0.061	-0.075	-0.159
	FC in international and domestic aviation	0.007	0.004	-0.002	0.008	0.006	0.003	-0.003	0.006	-0.001	-0.001	-0.001	-0.002
	FC in road transportation	0.043	0.040	0.186	0.269	0.040	0.049	0.190	0.279	-0.003	0.009	0.004	0.010
	FC in non-road ground transport	0.005	0.006	0.000	0.011	0.000	0.001	-0.005	-0.004	-0.005	-0.005	-0.005	-0.015
	FC in international and domestic shipping	0.002	0.001	-0.003	-0.001	0.002	0.000	-0.003	0.000	0.000	-0.001	0.000	0.001
	FC in residential	0.097	0.061	0.213	0.372	0.041	0.029	0.153	0.223	-0.056	-0.032	-0.060	-0.149
	FE from oil production	-0.003	0.017	0.157	0.171	0.000	0.006	0.097	0.104	0.003	-0.011	-0.060	-0.067
Industrial processes	Non-metallic mineral processes	0.013	0.007	0.046	0.066	0.026	0.006	0.130	0.162	0.013	-0.001	0.084	0.096
	Chemical processes solvents	0.006	0.005	0.026	0.037	0.006	0.006	0.044	0.056	0.000	0.001	0.018	0.019
	Metal processes	0.006	0.002	0.033	0.041	0.002	0.001	0.016	0.019	-0.004	-0.001	-0.017	-0.022
Agriculture	Agricultural soils	0.001	0.001	-0.002	0.000	0.001	0.001	-0.004	-0.002	0.000	0.000	-0.002	-0.002
Land use	Large scale biomass burning	-0.083	0.196	0.058	0.171	-0.030	0.073	0.004	0.047	0.053	-0.123	-0.054	-0.124
Waste	Waste incineration	0.000	0.001	0.001	0.003	0.001	0.001	0.002	0.003	0.001	0.000	0.001	0.000
Others	Fossil fuel fires	0.000	-0.001	0.005	0.004	0.001	0.000	0.001	0.003	0.001	0.001	-0.004	-0.001
CH4	**Sector**	**BR**	**BCwr**	**WCwr**	**Theil**	**BR**	**BCwr**	**WCwr**	**Theil**	**BR**	**BCwr**	**WCwr**	**Theil**
Energy	FC in energy production & manufacturing	0.001	0.002	0.013	0.016	0.001	0.002	0.022	0.025	0.000	0.000	0.009	0.009
	FC in non-road transportation	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
	FC in road transportation	0.000	0.001	0.007	0.009	0.000	0.000	0.002	0.003	0.000	-0.001	-0.005	-0.006
	FC in residential	0.022	0.008	0.015	0.044	0.016	0.007	0.010	0.033	-0.006	-0.001	-0.005	-0.011
	FE from solid fuel	0.043	0.043	0.565	0.651	0.073	0.026	0.777	0.876	0.030	-0.017	0.212	0.225
	FE from oil production	-0.019	0.013	0.253	0.247	-0.011	0.002	0.174	0.165	0.008	-0.011	-0.079	-0.082
	FE from gas production	-0.004	0.016	0.206	0.218	-0.015	0.017	0.488	0.490	-0.011	0.001	0.282	0.272
Industrial processes	Industrial process and product use	0.000	0.000	0.001	0.002	0.000	0.000	0.002	0.002	0.000	0.000	0.001	0.000
Agriculture	Enteric fermentation	0.032	0.054	0.070	0.157	0.034	0.051	0.085	0.170	0.002	-0.003	0.015	0.013
	Manure management	0.013	0.011	0.004	0.028	0.008	0.008	0.006	0.023	-0.005	-0.003	0.002	-0.005
	Agricultural soils	0.127	0.057	0.214	0.398	0.084	0.026	0.081	0.191	-0.043	-0.031	-0.133	-0.207
	Agricultural waste burning	0.001	0.001	0.000	0.002	0.001	0.001	0.000	0.002	0.000	0.000	0.000	0.000
Land use	Large scale biomass burning	-0.030	0.019	-0.004	-0.015	-0.015	0.025	0.002	0.012	0.015	0.006	0.006	0.027
Waste	Solid waste disposal & incineration	0.025	0.029	0.074	0.129	0.010	0.018	0.114	0.142	-0.015	-0.011	0.040	0.013
	Waste water	0.023	0.008	0.077	0.108	0.034	0.015	0.131	0.179	0.011	0.007	0.054	0.071
Others	Fossil fuel fires	0.000	0.000	0.000	0.001	0.000	0.000	0.000	0.001	0.000	0.000	0.000	0.000

average within-country component for enteric fermentation (agricultural soils).

Temporal changes are reported in the last columns of Table (2). For the gas related to fuel consumption, CO_2, electricity and heat production becomes more important, while residential and manufacturing are losing ground. This probably reflects both growth in energy demand (scale effect) and abatement activities (technical effect). Note that the relative change of the between-region component is the larger one in those subsectors with decreasing importance, suggesting abatement efforts have been biased towards the "old" industrialized regions, which exhibit declining shares in global emissions. For methane, the evolution is more complex, with an increase in the contribution of gas production and a decrease in agriculture soil of similar magnitude, and a similar compensation pattern between coal (increase) and oil (decrease) production.

4.3 Which source of inequality matters most: between countries, between sectors or within them?

Although the analysis above reported contributions for specific sectors, the decomposition of the inequality index itself remained spatially-oriented, i.e. according to the between-region or within-region components. In fact, when emissions on a specific spot of the Earth's surface are particularly large, this may be because they arise from a highly polluting country, or a highly polluting sector, or still a highly polluting spot within that particular country-sector combination. The last decomposition exercise provides an estimate of which of these three sources of inequality matters more for each gas.

To perform that decomposition, based on equation (7), in the absence of additional information, we need to make assumptions regarding the spatial distribution of sectoral emissions within each cell. We consider two extreme scenarios: under hypothesis 1, cell area is split equally between sectors ($n_i^s = \frac{1}{S} n_i$), whereas under hypothesis 2, cell area is split in proportion to reported emissions ($n_i^s = \frac{y_i^s}{y_i} n_i$). Hypothesis 2 may appear more intuitive at first, but has the important drawback of assuming away any within-cell inequalities across sectors (the second term of equation (4) becomes zero and hence T'=T). Unfortunately, we do not have any empirical evidence which could guide us towards the best assumption. Hypothesis 1 seems however more realistic. Therefore, we will focus on results under hypothesis 1 and only consider hypothesis 2 as a robustness check.

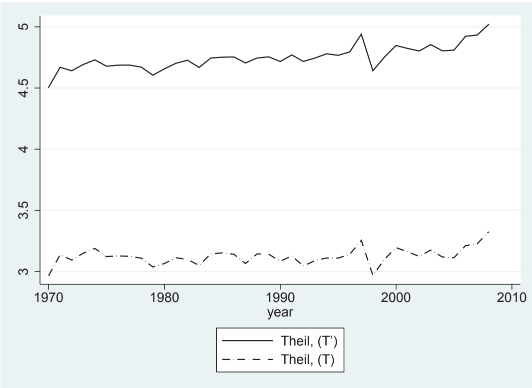
The patterns reported in Figure (3) are reminiscent of the above-commented results. First, for both gases, the between-country component is the smallest one, and is declining over time. Second, CO_2 exhibits a clear trend, with a growing between-sector component which becomes the dominant source of spatial inequalities at the end of the period. Third, for methane emissions, which are more evenly spread across sectors, it is the within-country-within-sector element which is the growing and dominant component. Results under hypothesis 2 confirm these broad trends and are reported in Appendix Figure (A1). Overall, these results confirm those from section 4.2, suggesting that recent decades have been characterized by more specialization across sectors than across countries, particularly for carbon dioxide. Moreover, even after controlling for differences across sectors, within-country inequalities remain important.

4.4 Where does the damage fall?

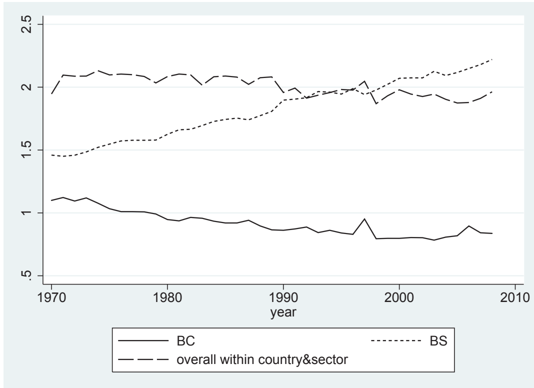
As a final exercise, we want to compare produced emissions with potential future damages from climate change, relying on the decomposition provided by equation (9). Local damages from emissions, such as local air pollution take place around the emission source and therefore inequalities of these local damages are the same as our reported inequalities of emission sources. In this section we extend the inequality analysis to damages from climate change. This allows us to investigate the discrepancy between emitters of greenhouse gases and places suffering most from negative effects from climate change.

Three introductory comments are in order. First, generally speaking, damages may come from a variety of phenomena, and are characterized by huge uncertainties. A detailed analysis being out of scope for this chapter, we simply focus on a single and very rough proxy for damages: the product between hot days and estimated human population in 2050. The combination of these two elements in the proxy for damages means that most damages happen in densely populated regions of emerging economies in low latitudes (in particular South Asia and Sub-saharan Africa, see table A1 in the Appendix) rather than in the temperate zones where developed countries locate. This will be important regarding interpretations. Second, as both damages and emissions are linked to demography, we might expect a certain degree of similarity between the two spatial distributions. However, this similarity is far from perfect, because the

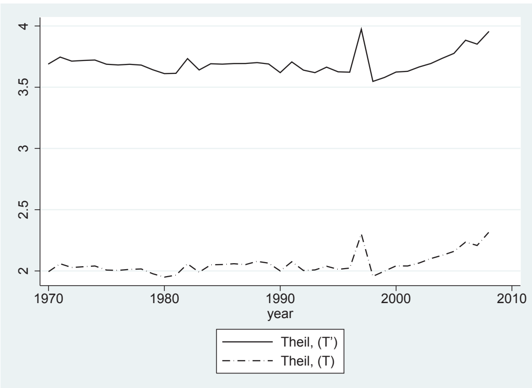
Figure 3: Average decomposition of the Theil index T', H1



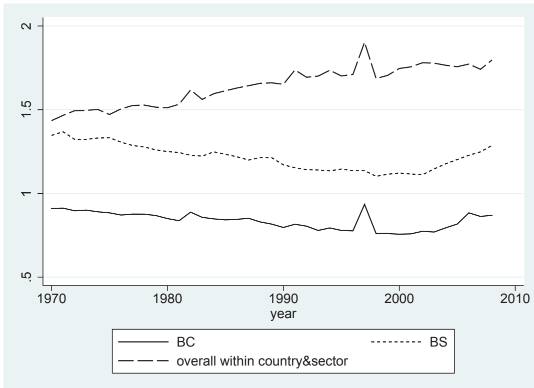
(a) CO2: Theil Indexes T' and T



(b) CO2: Between Country, Between Sector and Overall Within Country and Sector Component



(c) CH4: Theil Indexes T' and T

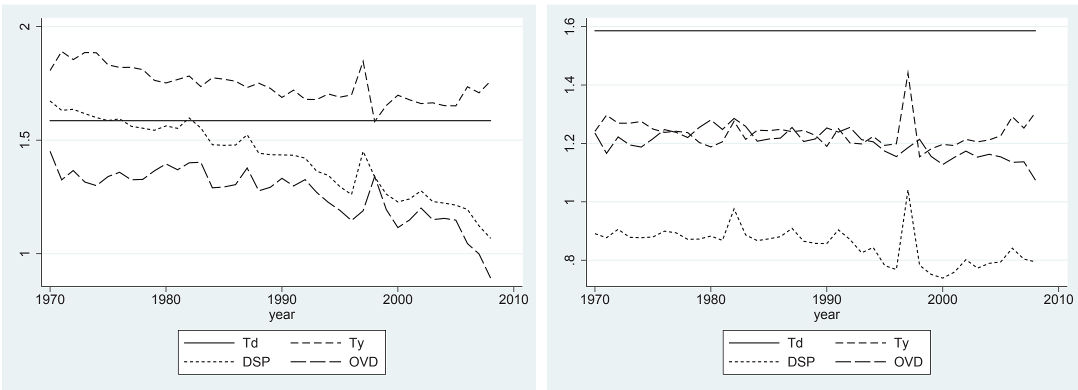


(d) CH4: Between Country, Between Sector and Overall Within Country and Sector Component

intensity of the demographic link is conditioned by climate regarding damages, and by economics regarding emissions, the latter effect depending on the type of gas considered (CO_2 or CH_4). Third, due to data availability, we have to re-aggregate emissions at the 1-degree latitude and longitude grid cells (see above data section). This leads to smaller estimates of spatial inequalities in emissions than in the rest of the chapter. In other words, to compare emissions with damages, we have to relax one of our main objectives, which is to capture within-country inequalities with the largest possible details. Still, the obtained results suggest this avenue of research may be promising.

The main results are reported in Figure (4). Note first that emission inequalities are not rising any more, but rather decreasing for CO_2 and stable for CH_4. This is due to the fact that by working at the 1-degree grid cell level, an important part of within-country inequalities has vanished. Second, the Theil index of spatial inequalities in damages, constant as it refers to the assumed situation in 2050, is in between the emission Theil index for the two greenhouse gases considered. As already mentioned above, this is due to the fact that CO_2 emissions are essentially related to fuel combustion, and therefore income levels, while CH_4 emissions are more related to agriculture and fuel extraction, the latter activities being more widespread at the Earth's surface. According to equation (9), this also means that the disparity index (DSP) is larger (smaller) than the overdamage index (OVD) for CO_2 (CH_4).

Figure 4: Decomposing the emission-damage link



(a) CO2: emission-damage link **(b)** CH4: emission-damage link

For CO_2, we observe a decreasing trend of all time-varying indices. This is essentially due to the economic catch-up of large emerging economies, in particular in Asia, which makes emissions more equally spread around the globe. In the case of the DSP index, for which the between-region share is larger than 50%, most of the change is due to the decreasing influence of Europe and the Former Soviet Union, and the increasing influence of East Asia.[9] Although the evolution of the OVD index is similar, there are two important differences.

[9] Results at the regional level are not reported due to space constraints. They are available from the authors upon request.

First, the major contributors are South Asia and Sub-Saharan Africa, two populous regions which are strongly exposed to heat waves and emit relatively few emissions. Second, for that index, within-country inequalities matter as much as between-region ones, and the major source of change happens within China, where large portions of its territory switch from over-damaged to under-damaged areas *vis-à-vis* their emission shares.

Emissions of CH_4 being less connected to income levels, they are both more equally spread across the Earth's surface and less sensitive to the structural changes that followed the economic convergence of emerging economies in recent decades.

5 Conclusion and Policy Implications

This chapter estimates for the first time spatial inequalities in emissions, using the Theil index at the world wide level and decomposes overall inequalities into between region, between country and within country inequalities. We take full advantage of disaggregated grid-level emission data to identify a number of interesting stylized facts, of which three at least deserve a particular mention.

First, although the political stalemate on climate change has much to do with opposition between large regions, in particular between the old industrialized world and emerging economies, we show that inequality across regions is the least important component of global spatial inequalities. Inequalities within countries matter much more, as they account for roughly three-quarter of total inequality, and they are on the rise. After all, this could be expected in a period of globalization that exacerbates both specialization and agglomeration forces. However, and quite surprisingly, this aspect has been fairly neglected by the literature over the last decades, which implies that additional empirical and theoretical work is needed.

Second, we have shown that an important part of within-country inequality is due to differences across sectors. Although the major sectors are generally all related to energy, there are important contrasts between gases. On the one hand, carbon dioxide is strongly linked with fuel consumption, in particular with the electricity and heat production subsector. This particular subsector is a growing source of spatial inequalities in recent decades, contrarily to emissions from manufacturing and residential, which are more evenly spread geographically, and where abatement activities may have been more prevalent. On the other hand, methane is not linked to fuel consumption, but to fugitive emissions from fuel production and to two other sectors unrelated to energy i.e. agriculture and waste management. In that case, the growing sources of spatial inequalities over the period are coal and gas production, whereas oil production and agricultural soils exhibit a downward trend.

Third, although sectoral differences do account for a substantial part of within-country spatial inequalities, they also leave unexplained an important share of those, in particular in the case of methane. This may be due to a number of reasons, from topography to sectoral disaggregation, and calls for further investigation.

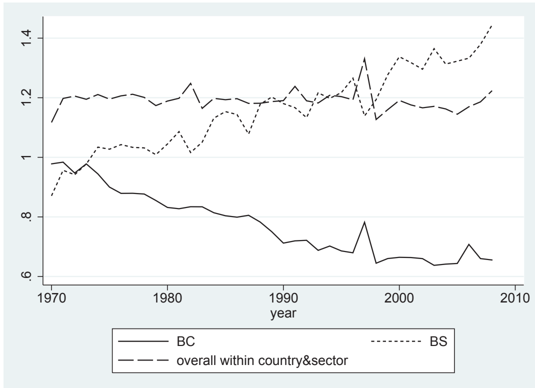
To illustrate the link between these stylized facts and the (regulatory) responsibility debate, we compared the Theil indices of spatial inequalities of contemporaneous emissions with the corresponding Theil index of future damages, using very warm days estimated for 2050 as a crude proxy for these damages. It turned out that results depend a lot on the type of gas. For CO_2, damages are more widespread than emissions, and the social tensions arising from the emission-damage gap tend to soften over time. For CH_4, damages are more concentrated than emissions, and social tensions remain roughly stable over the last four decades.

These novel results should be kept in mind when discussing the efficiency and fairness of pollution controls. Moreover they provide an empirical benchmark for the evaluation of alternative regulatory strategies. On the one hand, the decreasing importance of between country and between region inequalities suggests that the regulatory responsibility of countries is converging. On the other hand, the increasing importance of within country and between sector inequalities suggests that the contribution to inequality, and thus the regulatory responsibility, of specific geographical zones and specific sectors is growing. Moreover, depending on the gas, different zones and different sectors account for this increase. Combined, those two results provide empirical support for suggestions like the one made by Barrett (2008) who is proposing to break the climate change regulation problem up, by relying upon gas-specific, sub-national and sectoral policies.

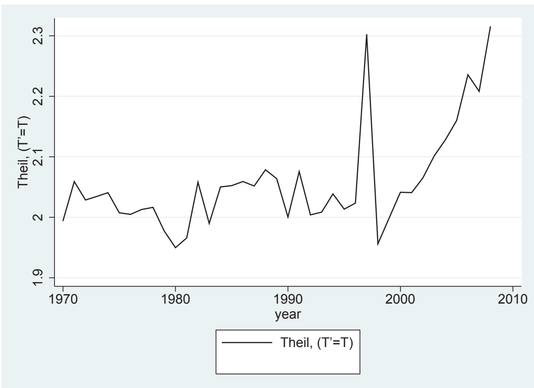
Appendix A

Figure A1: Average decomposition of the Theil index T', H2

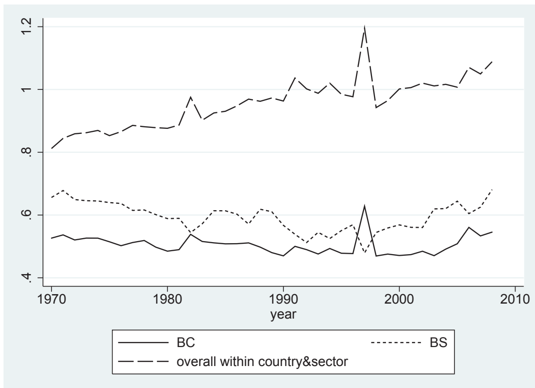
(a) CO2: Theil Indexes T' = T



(b) CO2: Between Country, Between Sector and Overall Within Country and Sector Component



(c) CH4: Theil Indexes T' = T



(d) CH4: Between Country, Between Sector and Overall Within Country and Sector Component

Table A1: UN-regions
(Note: Numbers might not add up due to rounding)

Gas	UN Region Code	UN Region Name	Emission share, 1970	Emission share, 2008	Damage share, 2046
CO2	EAA	East Asia	0.0934	0.2748	0.1494
	EUR	Europe (excl. FSU)	0.2173	0.1276	0.0424
	FSU	Former Soviet Union	0.1424	0.086	0.0254
	MNA	Middle East and North Africa	0.0162	0.0445	0.0676
	NAM	North and Central America	0.2531	0.1909	0.0714
	OCE	Oceania and Pacific Islands	0.0091	0.0136	0.0038
	SAM	South America	0.0761	0.0465	0.0491
	SAS	South Asia	0.0476	0.07	0.2829
	SEA	South East Asia	0.0171	0.0703	0.0764
	SSA	Sub-saharan Africa	0.1279	0.0759	0.2315
CH4	EAA	East Asia	0.176	0.2205	0.1494
	EUR	Europe (excl. FSU)	0.1317	0.0708	0.0424
	FSU	Former Soviet Union	0.1049	0.1037	0.0254
	MNA	Middle East and North Africa	0.0377	0.045	0.0676
	NAM	North and Central America	0.1447	0.1098	0.0714
	OCE	Oceania and Pacific Islands	0.0227	0.0198	0.0038
	SAM	South America	0.0834	0.0996	0.0491
	SAS	South Asia	0.1362	0.1453	0.2829
	SEA	South East Asia	0.0617	0.0702	0.0764
	SSA	Sub-saharan Africa	0.101	0.1153	0.2315

Table A2: IPCC sectors
(FC = Fuel consumption; FE = Fugitive emissions; Note: Numbers might not add up due to rounding)

CO2	**Sector**	**IPCC-code**	**Share of world total, 1970**	**Share of world total, 2008**
Energy	FC in electricity and heat production	1A1a	0.1865	0.3347
	FC in other energy industries & waxes	1A1c+2G	0.0354	0.0276
	FC in manufacturing	1A2	0.1855	0.1459
	FC in international and domestic aviation	1A3a	0.0130	0.0167
	FC in road transportation	1A3b	0.0870	0.1346
	FC in non-road ground transport	1A3c+1A3e	0.0167	0.0084
	FC in international and domestic shipping	1A3d	0.0049	0.0038
	FC in residential	1A4	0.1455	0.0939
	FE from oil production	1B2a	0.0381	0.0238
Industrial processes	Non-metallic mineral processes	2A	0.0211	0.0391
	Chemical processes solvents	2B+3	0.0088	0.0138
	Metal processes	2C	0.0118	0.0053
Agriculture	Agricultural soils	4C+4D	0.0026	0.0032
Land use	Large scale biomass burning	5A+C+D+F+4E	0.2401	0.1470
Waste	Waste incineration	6C	0.0006	0.0009
Others	Fossil fuel fires	7A	0.0024	0.0014
CH4	**Sector**	**IPCC-code**	**Share of world total, 1970**	**Share of world total, 2008**
Energy	FC in energy production & manufacturing	1A1+1A2	0.0123	0.0170
	FC in non-road transportation	1A3a+c+d+e	0.0001	0.0001
	FC in road transportation	1A3b	0.0033	0.0017
	FC in residential	1A4	0.0402	0.0343
	FE from solid fuel	1B1	0.1027	0.1323
	FE from oil production	1B2a	0.0590	0.0414
	FE from gas production	1B2b	0.0596	0.1320
Industrial processes	Industrial process and product use	2	0.0007	0.0007
Agriculture	Enteric fermentation	4A	0.2844	0.2833
	Manure management	4B	0.0363	0.0325
	Agricultural soils	4C+4D	0.1881	0.1043
	Agricultural waste burning	4F	0.0034	0.0044
Land use	Large scale biomass burning	5A+C+D+F+4E	0.0856	0.0499
Waste	Solid waste disposal & incineration	6A+6C	0.0645	0.0812
	Waste water	6B	0.0593	0.0846
Others	Fossil fuel fires	7A	0.0006	0.0004

Chapter 3

How Should We Measure Environmental Policy Stringency ? A New Approach

1 Introduction

The absence of a broadly accepted indicator of environmental policy stringency is currently limiting applied research in several fields of economics. Words of caution mentioning limits of existing indicators can be found in a majority of papers. But surprisingly few papers have been exclusively devoted to the construction of such indexes. In one of those, Knill et al. (2012) conclude that the choice of indicators of environmental policy stringency is rarely theoretically motivated but rather driven by data availability. This chapter proposes and implements a new methodology attempting to overcome those problems.

2 An overview on existing indicators

A variety of indicators have been proposed so far. Focusing on indicators available for several countries and at least one common year, one can distinguish four groups: survey indicators, monetary indicators, policy specific indicators, performance indicators and composite indicators. The following overview is not exhaustive. Selected examples are presented for each group of indicators.

2.1 Survey indicators

Dasgupta et al. (2001) develop an index of environmental policy stringency based on reports prepared for the United Nations Conference on Environment and Development (UNCED). Those reports contain self-reported information from country officials on a variety of questions. They are complemented by responses from several NGO's, attempting to make the data less exposed to biases from self-reporting. Using the methodology of Dasgupta et al., Eliste and Fredriksson (2002) extended the database for another 31 countries but only for the agricultural sector. Recent papers (see for instance Kalamova and Johnstone (2011) or Timmins and Wagner (2009)) frequently use the indicator of environmental regulatory stringency developed by the World Economic Forum (WEF). The WEF obtains the data by asking "business leaders" the survey question: "How would you assess the stringency of your countries' environmental policy? (scale: 1=very lax – 7=among the world's most stringent)." A question asked each year in the World Executive Opinion Survey (Browne et al., 2012). This indicator is available for more than 100 countries on a yearly base since 2004. Those survey based indicators depend by construction solely on the perceptions of the survey respondents. They are not based on hard data on environmental policy.

2.2 Monetary indicators

Magnani (2000) and Pearce and Palmer (2001) use public expenditures for environmental protection as a measure of environmental policy stringency. Their data covers OECD countries during the nineties and has been collected by the OECD Environmental Program. Those indicators capture expenditure based policy instruments only, excluding the wide variety of other instruments. On top of that, due to the existence of potential efficiency differences among countries it is also unclear whether higher per capita expenditures imply stricter environmental policies. It is possible that a country with high per capita expenditures uses those expenditures in a highly inefficient way such that another country with lower per capita expenditures does a better job. Another monetary indicator which is frequently used is pollution abatement costs. Some authors, as for instance Friedman et al. (1992), Crandall (1993), Co and List (2000) use total statewide pollution abatement costs as an indicator. Others like Keller and Levinson (2002) adjust them for each state's industrial composition. A third group of researchers use sectoral rather then state wide data on abatement costs (see Brunnermeier and Cohen, 2003). A fourth group uses an indicator based on capital expenditures and operating costs in environmental protection activities (see Jug and Mirza (2005)). Important disadvantages of those types of indicators have been pointed out by Copeland (2008). For firms it is difficult to correctly disentangle abatement cost from other cost. Moreover firms might have an incentive to strategically under or over report their abatement cost. Finally, reported abatement cost may be endogenous and thus induce biases in the analysis. Illustrating this argument, Copeland advances an example in which firms have heterogeneous costs of responding to environmental regulations. Assuming that the competitiveness hypothesis is correct, stringent pollution policies might drive firms with the highest abatement costs out of business. This opens the possibility that even in regions with relatively strict environmental policies, observed abatement costs may be low.

2.3 Policy specific indicators

Nakada (2006) assesses environmental policy stringency using the timing of the ratification of the Kyoto protocol. He generates a dummy variable, taking the value of zero if a country hasn't ratified the Kyoto protocol by the year 2003 and the value of 1 if a country has ratified the Kyoto protocol by the year 2003. Smarzynska and Wei (2004) use an indicator based on the ratification of four international treaties in environmental politics. They adjust their initial measure by multiplying it with the ratio of environmental NGO's per million of people in a given country, claiming that this adjustment reflects the degree of enforcement of those treaties. Those treaty based indicators remain highly specific, excluding all other instruments of environmental policy. Knill et al. (2012) develop an indicator of clean air policy, capturing national statutory laws on the book. Their index is available for 24 OECD countries covering the time span from 1976 to 2003. Their indicator codifies the different clean air laws of countries either as "policy expansion" or as "policy dismantling". The data has been taken from their own database (compiled by the CONSENSUS project). Their indicator has the advantage that it relies on a well defined methodology, resulting in two indicators, one called "policy density" the other "policy intensity".

2.4 Performance indicators

Several researcher as Hilton and Levinson (1998), Deacon (1999), Damania (2001), Broner and Bustos (2012) or Grether et al. (2012a) use the lead content in gasoline as an indicator. The data is taken from the Octel Worldwide Gasoline Survey. According to some of those authors, given the absence of a sound index of environmental policy stringency, their index covers at least one of the most important environmental issues of the late 20th century. A second group of performance indicators are based on emission or energy consumption data. Some researchers simply take emitted emission as a measure for environmental policy stringency. As an example, Kostad and Xing (2002) use total SO_2 emissions on a country level and Smarzynska and Wei (2004) overall CO_2 emission reduction data. Again others base their index on energy intensity data (see for instance Cole and Elliot (2003)). Harris et al. (2003) use energy consumption data as their measure. A third group uses the Environmental Performance Index (EPI) published by The Yale Center for Environmental Law and Policy (YCELP) (Emerson et al., 2012). Although the YCELP does not claim that their index is a measure of environmental policy stringency, some researchers use it as such. All those different approaches have one point in common: they are performance indicators. By construction, performance indicators quantify the problem environmental policies try to solve and not the stringency of the policies themselves. After all, variations in emitted emissions or in the lead content of gasoline can be due to a wide variety of factors which might be unrelated to policies.

2.5 Composite indicators

Only one composite indicator quantifying environmental policy stringency is currently available and has been proposed very recently[1] by Botta and Kozluk (2014). Botta and Kozluk (2014) define environmental policy stringency as a higher explicit or implicit cost of polluting or environmentally harmful behavior. They construct two composite indicators - one for the energy sector and an extension off the latter which should proxy economy-wide stringency - for 24 OECD countries covering the years 1990 to 2012. The economy-wide composite indicator is the result of the equal weighted sum of two scores, the market-based score and the non market-based score. To construct the market-based

[1] This index has been proposed more than a year after the main bulk of work on the present chapter had been finished and the corresponding working paper submitted. For the sake of completeness, I added this section in the final manuscript.

score, they construct four sub-scores (taxes, feed in tarifs, deposit and refund schemes and trading schemes), containing selected instruments. Each sub-score consists of a categorical score (ranking from 0 to 6), where higher scores reflect higher stringency, e.g. the higher a de-jure NO_X tax rate, the higher the corresponding score. They proceed identically for the non-market based score and construct two sub-scores (standards and R&D subsidies). While their index has the advantage to rely on a well defined methodological framework, several disadvantages can be identified. First, the index is only available for selected developed countries. Second, they exclude a variety of instruments (voluntary approaches, land use regulations and other "soft" policies (see Botta and Kozluk (2014)), and thus introduce a potential bias as some countries rely heavily on such instruments. Third, their index is a mix of an input and a process indicator of environmental policy (see Section 3.2). And fourth, while they state that they apply equal weights in order to construct the market-based and non-market based group reflecting the "lack of priors" Botta and Kozluk (2014) then arbitrarily weight both main groups equally, resulting in different weights for the sub-scores, depending whether they are in the market-based or non-market based group.

3 Methodological framework for environmental policy indexes

3.1 What is badly defined is likely to be badly measured

Besides the specific shortcomings of the indicators discussed in section 2, a general problem is common to almost all of them. They are not constructed upon an explicitly stated methodological framework, the contributions of Knill et al. (2012) and Botta and Kozluk (2014) constituting a notable exception. This shortcoming ignores one of the most fundamental rules found in the literature on index construction. As Nardo et al. (2008) put it:

> A sound theoretical framework is the starting point in constructing (...) indicators. The framework should clearly define the phenomenon to be measured and its sub-components, selecting individual indicators and weights that reflect their relative importance and the dimensions of the overall composite. This process should ideally be based on what is desirable to measure and not on which indicators are available. Nardo et al. (2008), p. 22.

A good index has to be based on a theoretical description of the phenomenon it tries to measure, making it possible to identify relevant sub-components of the main concept. Only once identified, selection criteria can be applied in order to select the underlying indicators. Good selection criteria allow you to clearly distinguish input, process and output measures of the phenomenon. According to Nardo et al. (2008) this is a task which is neglected too often.

The problems due to the absence of a theoretical framework are reinforced by that what Brunel and Levinson (2013) identify as the "multidimensionality" problem. Without defining what environmental policy is, it remains ambiguous what those indicators actually intend to quantify. Environmental policy and environmental policy stringency are rather vague concepts which could cover a wide range of policies. They might include policies as diverse as the protection of a flower, the regulation of hunting or the reduction of CO_2. Hence, as Nardo et al. (2008, p. 22) put it: "What is badly defined is likely to be badly measured."

To overcome those obstacles, I develop a coherent methodological framework. Based on an explicit definition, the framework allows to measure specific types of environmental policies, while making a clear distinction between input, process and output measures. To mitigate the multidimensionality problem I focus on a specific type of environmental policy: pollutant policies; and on a particular case: anthropogenic CO_2 emissions.

3.2 What we should measure: input, process and output indexes

A policy can be defined as a set of government made decisions which have been implemented and which aim to solve a particular problem. The particular problem pollutant policies are dealing with is the reduction of anthropogenic emissions of the pollutant in question. Based on this general definition, one can define a CO_2 policy as a set of government made decisions which have been implemented and which aim to reduce anthropogenic CO_2 emissions.

Defined as such one can look at pollutant policies in three complementary ways by measuring the input, process or output side of the phenomenon. As economists we work every day with variables constructed on this trinity. Take our measures quantifying the phenomenon "production": to analyze the input side we use measures like the quantity of labor or capital. To analyze the process dimension we develop measures which quantify how those inputs are put together. Technology indexes and efficiency measures are examples of such process indicators. And we quantify the output dimension using indicators like GDP. Imagine for a second the mess applied research would face if we would have only one measure of production mixing the above mentioned. So why not apply the same structure to develop measures quantifying the phenomenon pollutant policy?

Failing to properly separate input, process and output indicators, as advocated by many (e.g. Nardo et al. (2008)), poses a risk. Take for instance the proposed index by Botta and Kozluk (2014), which is supposed to reflect the price of pollution and other environmentally harmful behavior. As such, their approach suggests that this price - supposedly formed as a result of environmental laws which have somehow been implemented, and can thus be seen as a combined input and process index - is faced by all agents within an economy and thereby alters their behavior. This is certainly appealing. But given for instance the possibility that in two countries, the same de-jure tax might be subject to completely different tax bases, tax-evasion strategies, sizes of shadow economies etc., this might not be true. Therefore, mixing several dimensions in one single index, could promise a false accuracy and lead to biased results if applied in an empirical analysis. By properly separating input and process indexes, one can however avoid this problem, and would dispose of two variables which can be jointly used in an analysis, and which capture both dimensions separately.

Given the definition of pollutant policies and the need to carefully separate input, process and output measures, I propose to proceed as follows (see next section for implementation issues): To develop an *input* index we have to quantify all different decisions taken by government entities which aim to reduce the pollutant. The more decisions have been taken and the more important they were, the higher the input dimension policy stringency. To develop a *process* index of the phenomenon one has to capture how those inputs are implemented. The stronger the implementation (the less exceptions, the more inspections etc.) the higher the process dimension policy stringency. To develop an *output* index we have to quantify by how much the particular problem has been solved by the policies. The better it has been solved, the higher the output dimension stringency.

3.3 What we will measure here: input and performance indexes

Apart from space constraints, the implementation of the methodological framework is conditional on data availability. Even in the widely-studied cases of CO_2 emissions, reliable and comparable country-specific data is difficult to obtain. This has led to two restrictions with respect to the ideal case.

On the one hand, I do not report any process index results. This is due to the absence of the relevant information at the level of a specific pollutant. On the other hand, developing a proper output index of CO_2 policies is out of the scope of the present chapter because it would mean, apart from measuring performance (e.g. CO_2 emissions per capita), estimating which part of that performance is specifically attributable to government policies (and not, say, to climate or industrial structure). Hence, I limit my objective to measuring a *performance* index, which includes the influence of other factors, and is a first step towards a real output index of pollutant policies.

With these important caveats in mind, the next two sections describe the construction of a general greenhouse gas policy input index, a CO_2 policy input index and a CO_2 performance index. The same methodology is used on two other pollutants: CH_4, a second direct greenhouse gas, and SO_2, an acidifying (cooling) gas. Results for SO_2 can be found in appendix A, while results for CH_4 are presented in appendix B.

4 Implementation of a pollutant policy input index

A CO_2 policy stringency input measure is a metric that captures the decisions taken to reduce CO_2 quantitatively. The proposed indicator captures the huge variety of CO_2 policy inputs. As such the indicator has to be seen as a so-called “de jure” indicator (or in the terminology of Kaufmann and Kraay (2008) a “rule based indicator”) which captures statutory laws “on the book”. In that sense, the indicator follows partially the work of Knill et al. (2012).

4.1 Approach and data sources

I use two different databases to construct two input indicators a "narrow" and a "broad" one.

Taking the definition of pollutant policies literally one can classify a policy as a CO_2 policy only if the law explicitly refers to the goal of reducing CO_2. The ECOLEX database (FAO et al., 2013) allows the extraction of such CO_2 policies. After selecting all laws in ECOLEX which contain the words CO_2 (or any derivative like carbon dioxide in any language) I had to drop some. There are laws which contain the right keywords but which cannot be classified as CO_2 policies. For example, laws on the minimum quantity of CO_2 in bottled water have been dropped. Across the 55 countries covered I identified a total of 379 narrow CO_2 measures which are (or have been) enacted, those measures are country specific. Out of those 379 measures, 35 apply on a sub-national level. Besides those sub-national measures, there are some which have been enacted by the European Union. Those supra-national measures have been attributed to the EU member countries[2]. Based on the ECOLEX data an input index is developed which is labeled "Narrow CO_2 Input Index".

Interpreting the definition in a broader sense, one can classify a policy as a CO_2 policy if the law implicitly refers to the goal of reducing CO_2. Taxes on fuels (although not necessarily containing a paragraph specifying the goal of CO_2 reduction) can in this sense be classified as CO_2 policies. The Database for instruments of environmental policy and natural resource management published by the OECD and EEA (2012) allows to select such policies. This is a major advantage. Across the 52 covered countries, I identified a total of 1109 country-specific greenhouse gas measures which are (or have been) enacted. Out of those 1109 measures, 435 measures apply on a sub-national level. I completed the database by finding several hundreds of missing dates of enactment entries in the national legislation of the concerned countries. The major advantage of this database (the possibility to include laws which can be classified in a broad sense as pollutant policies) comes at a cost. The database does not allow to make a clear distinction between pollutants. Hence the resulting input index

[2]If a country has already been a member of the EU at the time the EU adopted the measure then the national date of enactment of the measure corresponds to the one of the EU. If a country hasn't been a member at the time the EU adopted the measure, then the national date of enactment of the measure corresponds to the date where the country joined the EU (provided that the measure was still in place at that time).

has to be seen as a general greenhouse gas input index which is labeled "Broad GHG Input Index".

4.2 Codification, weighting and normalization of the input indicator

Given that it is difficult to quantify juridical information, I proceed as others did in constructing "de jure" indicators[3]. In order to capture this information quantitatively I generate dummy variables. Each dummy reflects the answer to the question "Does measure j exist in country i in year t?". A dummy variable takes the value of 1 if a measure exists in a certain country and in a given year and the value of 0 otherwise. This procedure has been applied twice using the two different databases.

I follow the "usual" equal weighting approach to construct the two input indexes. At the same time I also account for the fact that some measures are only applied on a sub-national level. The dummies are summed up by country and by year. This has been done separately for both databases leading to the following two input indicators:

$$\textit{Narrow Input Index}_{i,t} = \sum_j w_{j,i,t} \textit{EcolexDummy}_{j,i,t} \tag{1}$$

$$\textit{Broad Input Index}_{i,t} = \sum_j w_{j,i,t} \textit{OECD/EEA Dummy}_{j,i,t} \tag{2}$$

where j indexes the instruments, i the countries and t the time. The weight $w_{j,i,t}$ takes the value of 1 if the measure j is applied on a national scale. If the measure j is only applied in a part of the country i, then $w_{j,i,t} = \frac{n_{i,t}^{part}}{n_{i,t}}$, where $n_{i,t}$ is the population of country i at time t and $n_{i,t}^{part}$ is the population of the area of country i in which the measures is applied at time t. Proceeding in this way gives each instrument which is applied on a national scale exactly the same weight in the final index. As a further step an informed weighting approach could improve the indexes. If theoretical work will be able to rank different categories of instruments, one could use those ranks to refine the weighting of the dummies. Using such an informed weighting approach, the index could be calculated as follows: $I_{i,t} = \sum_c \gamma_c \sum_j w_{j,i,t} \textit{Dummy}_{j,i,t,c}$, where i indexes

[3]See for instance the work on the Global Integrity Index (Global Integrity, 2011) or on the Doing Business indicator (World Bank, 2012).

the countries, t the time, c the different categories, j the instruments within a given category, γ_c indicates the weights for each of the categories and $w_{j,i,t}$ the weight which accounts for federal measures as defined before. The indexes have subsequently been normalized to range between zero and one.

5 Implementation of a pollutant performance index

According to the definition of pollutant policies, CO_2 policies aim to solve the particular problem of reducing anthropogenic CO_2. A CO_2 performance indicator captures this particular problem. It is therefore also the first step in the construction of an output index of pollutant policies: if you want to know by how much the policies solved the problem you first need to quantify the problem.

5.1 Approach and data sources

To implement the indexes I use the World Input Output Tables database (Timmer et al., 2015), an extension of the National Accounting Matrix including Environmental Accounts project of Eurostat (2009)[4] . This dataset combines the conventional national accounting framework with socioeconomic as well as environmental satellite accounts. For a total of 40 major countries, and 35 sectors, input-output tables, complemented with sectoral labor and capital input data as well as sectoral emission data are available for the time span between 1995 and 2009[5].

Using this database, I develop, for each sector, a CO_2 performance indicator which is constructed on two dimensions: CO_2 intensity and CO_2 efficiency. Then I aggregate those sectoral indexes to obtain an index covering the whole economy. Conceptually, the proposed performance indicator follows and extends the work of the Yale Center for Environmental Law and Policy (YCELP)

[4] Although the project which led to the elaboration of this dataset has been completed in 2012, prospects are good that the dataset will be extended in geographical and time coverage. The Statistical Division of the UN has launched the System of Environmental-Economic Accounts (SEEA) (see United Nations, 2012), which - once completed - would correspond to an extension of WIOT. Conditional on the successful implementation of SEEA, the proposed indicators could be extended, in time and in country coverage.

[5] Those 40 countries accounted for over 70% of global anthropogenic CO_2 emissions during the 00's.

which develops an Environmental Performance Indicator (EPI)[6] (Emerson et al., 2012). There are three main differences between the climate change part of the EPI and the proposed CO_2-performance indicator: Firstly, instead of trying to quantify overall climate change performance, the CO_2-performance indicator focuses only on the performance of CO_2. Secondly, alongside CO_2 intensity, CO_2 efficiency is integrated as an additional dimension of CO_2 performance. And thirdly, the proposed CO_2-performance indicator is constructed on a sectoral scale.

5.2 The construction of sectoral CO_2 performance indexes

Capturing sectoral CO_2 intensity In accordance with the work of the YCELP I capture the sectoral CO_2 intensity dimension with two different relative measures: Sectoral CO_2 emissions per unit of sectoral GDP and sectoral CO_2 emissions per sectoral workers. Those two are common metrics used to asses the intensity in the use of carbon dioxide emissions in an economy (Emerson et al., 2012).

Capturing sectoral CO_2 efficiency I capture the sectoral CO_2 efficiency dimension by estimating CO_2 efficiency scores. CO_2 efficiency is defined as the ratio of minimal feasible to observed use of CO_2, conditional on observed output levels and conventional inputs. CO_2-efficiency scores are therefore estimates describing how far a sectoral production process is away from the contemporary best practice. There are two different approaches in the literature on environmental efficiency. The first one treats emissions as inputs in the production function while the second one considers emissions as bad outputs of the production process. Both approaches can be implemented using either Stochastic Frontier Analysis (SFA) or Data Envelopment Analysis (DEA). Treating emissions as inputs has however several theoretical shortcomings. For a review on both approaches refer to Mandal and Madheswaran (2010). I follow the second approach using DEA and treat emissions as a bad output.

[6] This indicator intends to track national environmental results on a quantitative basis. The EPI is divided into several parts, one of them measuring “climate change and energy” performance. To quantify the climate change and energy part of this index four sub-indicators are used by the YCELP: CO_2 emissions per capita, CO_2 emissions per dollar, CO_2 emissions per kWh and the percentage of renewable energy in total energy production. All those sub-indicators are constructed using aggregated data (i.e. not sectoral data). Those sub-indicators are then aggregated using weights determined by YCELP experts.

The following presentation of the methodology used to estimate CO_2 efficiency scores follows closely the paper of Färe (2012). First some notation, assume that a decision making unit[7] produces L bad outputs $(b_1, ..., b_L) \in \mathbb{R}_+^L$, M good outputs $(y_1, ..., y_M) \in \mathbb{R}_+^M$, while using N inputs $(x_1, ..., x_N) \in \mathbb{R}_+^N$. The technology set is given by $T = \{(x, y, b) : x \textit{ can produce (y,b)}\}$. Färe (2012) imposes structure on the technology set by assuming that the set is closed with bounded output sets. Inputs are assumed to be strongly disposable. Good outputs (y) and bad outputs (b) are assumed null-joint: if $(x, y, b) \in T, b = 0 \Rightarrow y = 0$. Bad and good outputs are assumed being together weakly disposable: if $(x, y, b) \in T, \textit{and } 0 \leq \alpha \leq 1 \Rightarrow (x, \alpha y, \alpha b) \in T$. Finally, Färe (2012) assumes that good outputs are strongly disposable: if $(x, y, b) \in T, \textit{and } y' \leq y \Rightarrow (x, y', b) \in T$.

Assuming that there are I observations for a given year, (x^i, y^i, b^i) for $i = 1, .., I$, Färe (2012) models T in a DEA setting as follows: The pollution generating technology is given by:

$$\begin{aligned} T = \{(x, y, b) : \quad & \textstyle\sum_{i=1}^{I} \quad z_i y_{im} \geq y_m, \ m = 1, ..., M \\ & \textstyle\sum_{i=1}^{I} \quad z_i b_{il} = b_l, \ l = 1, ..., L \\ & \textstyle\sum_{i=1}^{I} \quad z_i x_{in} \leq x_n, \ n = 1, ..., N \\ & z_i \geq 0 \quad , \ i = 1, ...I\} \end{aligned} \tag{3}$$

The intensity variables z_i in (3) are constrained to be non-negative, imposing thereby constant returns to scale. In addition the following constraints are imposed:

$$\textstyle\sum_{i=1}^{I} \quad y_{im} > 0, \ m = 1, ..., M \tag{4}$$
$$\textstyle\sum_{m=1}^{M} \quad y_{im} > 0, \ i = 1, ..., I \tag{5}$$
$$\textstyle\sum_{i=1}^{I} \quad x_{in} > 0, \ n = 1, ..., N \tag{6}$$
$$\textstyle\sum_{n=1}^{N} \quad x_{in} > 0, \ i = 1, ..., I \tag{7}$$
$$\textstyle\sum_{i=1}^{I} \quad b_{il} > 0, \ l = 1, ..., L \tag{8}$$
$$\textstyle\sum_{l=1}^{L} \quad b_{il} > 0, \ i = 1, ..., I \tag{9}$$
$$\tag{10}$$

[7] A decision making unit (DMU) may refer to an individual worker, a subsection of a firm, a firm but also - as in this chapter - to a sector.

Constraints (4)-(7), introduced by Kemeny (1956) generalize the Von Neumann (1945) assumptions (for a discussion see (Färe, 2012)). Constraints (4), (5), (7) and (8) constrain good and bad outputs to be null-joint.

To obtain CO_2 efficiency scores (EEs) the following linear programming problem will be solved for each observation. Note that for a given DMU the target values (y_m^*, b_l^*, x_n^*) are set equal to the observed values:

$$EE = min\ \beta \tag{11}$$

Subject to:

$$\begin{aligned} \textstyle\sum_{i=1}^{I} \quad & z_i y_{im} \geq y_m^*,\ m = 1, ..., M && (12) \\ \textstyle\sum_{i=1}^{I} \quad & z_i b_{il} = \beta b_l^*,\ l = 1, ..., L && (13) \\ \textstyle\sum_{i=1}^{I} \quad & z_i x_{in} \leq x_n^*,\ n = 1, ..., N && (14) \\ z_i \geq \quad & 0,\ i = 1, ...I && (15) \end{aligned}$$

Note that the intensity variables z_i are jointly constrained by (12) and (14) which allows the computation of the βs. This linear programming model is separately estimated for each year and each sector. I use a sequential frontier approach assuming that all current and past observations are feasible[8]. I thereby follow Mukherjee (2008) and Mandal and Madheswaran (2010). Constructed as such, I obtain one β for each country, each sector and each year. By construction, β takes values between zero and one. A β equal to one indicates full efficiency while a β equal to zero indicates full inefficiency of the DMU.

I estimate two different models using this framework: one based on a profit function and the other based on a revenue function. In both models there is one bad output: CO_2. The profit function model uses value added as the good output, hours worked and the size of the capital stock are used as classical inputs. The model which is based on a revenue function uses gross output as good output, hours worked, the size of the capital stock and intermediate inputs are used as classical inputs. Those two models yield the two subindicators EE_t and EE_t^* used to quantify the efficiency dimension of the sectoral CO_2 performance index.

[8]So, to estimate the βs of the first year only data from the first year has been used. To estimate the βs of the second year, data from the first and the second year has been used, etc.

Table 1: Sectoral CO_2 performance sub-indicators

Indicator	Description	Mean weight	Dimension
$\frac{\text{sectoral } CO_2 \text{ emissions}}{\text{sectoral GDP}}$ [9]	Sectoral CO_2 per sectoral GDP	0.446	CO_2 intensity
$\frac{\text{sectoral } CO_2 \text{ emissions}}{\text{sectoral work force}}$ [10]	Sectoral CO_2 per sectoral workforce	0.226	
EE_t	CO_2 efficiency score (profit function)	0.592	CO_2 efficiency
EE_t^*	CO_2 efficiency score (revenue function)	0.589	

Computing the sectoral CO_2 performance indicators by weighting the four sub-indicators The four sub-indicators listed in Table (1) - each of them standardized between zero and one - quantify the sectoral CO_2 performance. They are weighted and aggregated to obtain the sectoral CO_2 performance indicator $SPI_{i,s,t}$, where i indexes the countries, s the sectors and t the time. To weight the sub-indicators I use Principal Component Analysis (PCA). And I take the first principal component as sectoral performance index. PCA has become one of the major approaches in the construction of composite indicators. It is now also used in social sciences in a variety of fields ranging from the computation of socio-economic well-being indexes (for an overview on weighting of such indexes see for instance Decancq and Lugo (2013)), technology and science indexes (see for instance NISTEP (1995)) and sustainability indexes (see for instance Singh et al. (2012)) to name only a few. PCA is generally preferred to equal weighting approaches because it doesn't impose the strong assumption that all sub-indicators are "worth" the same in the composite indicator. Even if PCA based weighting does not (necessarily) reveal the theoretical importance of the different sub-indicators, it is able to account for overlapping information

[9] Note that this variable has been re-scaled. Each observed value is subtracted from the observed maximum (max) of the variable, then the minimum (min) of the variable is added: (max-observation)+min. With this transformation higher values now indicate a better performance. Subsequently values have been standardized between zero and one.

[10] See: footnote 9.

between the (correlated) sub-indicators (Nardo et al., 2008), thereby avoiding the problem of "double accounting" (Decancq and Lugo (2013), p. 20). The (rounded) means over all sectors of the weights per sub-indicator obtained using PCA are listed in Table (1). Note that the weights of CO_2 per capita and CO_2 per dollar are both positive. This is because those variables have been transformed as described in the footnotes in Table (1).

5.3 Computing the economy-wide CO_2 performance index by aggregating the sectoral performance indicators

The aggregation of the sectoral performance indicators is the last step in the construction of the economy-wide CO_2 performance indicator. I use a linear weighting approach to construct this final economy-wide CO_2 performance index:

$$CO_2PerformanceIndex_{i,t} = \sum_{s=1}^{S} \frac{(ES_{i,s,t=0} + SS_{i,s,t})}{2} SPI_{i,s,t} \tag{16}$$

Where $SS_{i,s,t}$ is country i's share of sector s in total GDP at time t, $ES_{i,s,t=0}$ is country i's share of sector s in total country emissions at time $t = 0$ and $SPI_{i,s,t}$ is country i's sectoral CO_2-performance index of sector s at time t.

I choose this weighting approach because it gives the final index several desired properties. First it respects the fact that the CO_2 performance of a country can be improved in two ways. Either by improving the within sector CO_2-performance which is captured by the SPI's. Or by reducing the share of relatively polluting sectors, a property which is respected by integrating sectoral GDP shares as a part of the weight. Second it attributes a bigger weight to a sectoral performance index the more polluting a sector is, hence the integration of the sectoral emissions share as a part of the weight. And third it allows to keep track of the history of the CO_2 performance of a country by using always the time 0 sectoral emission share.[11] The country CO_2 performance

[11] Other sectoral data based indexes, as for instance trade barrier indexes, encounter often the same problem in the aggregation phase. As an example: suppose a country improves the CO_2-performance within a given sector (and obtains a score of 1 for this sectoral CO_2 performance indicator), and in turn sectoral emissions approach zero (as an extreme case). If one now simply weights the sectoral CO_2-performance indicator (which is supposed to be one) by the corresponding contemporary sectoral emission share (which is here supposed to be zero), then the final effect on the country index would be zero. Hence the improvement in the CO_2-performance would not be reflected in the final indicator. This would be clearly undesirable.

index has subsequently been normalized to range between zero and one, where one indicates the best performance and zero the worst.

6 Results

To obtain an overview, Figure (1) displays the evolution of the narrow CO_2 input index, the broad GHG input index and the CO_2 performance index by country. Note that due to the different data-sources, not all indexes are available for all countries. And note as well that each of the displayed indexes has been bounded to range between zero and one. In general one can observe that the CO_2 input indexes increase over time. This indicates an increase in the stringency of CO_2 policies over time in the sample. The magnitude of this increase varies however considerably among the different countries. The CO_2 performance index doesn't show such a clear pattern.

To empirically assess whether the constructed indexes measure what they are supposed to measure, one should ideally compare them to a sound benchmark. Given the absence of such a measure (i.e. given the reason why this chapter has been written) I pursue two complementary evaluation strategies. First I compare the constructed input (performance) indexes to existing input (performance) indexes as well as to the WEF survey index which is a measure of perceived environmental policy stringency. Second I compare the constructed CO_2 input index to the constructed performance index and verify whether the expected relationship holds, after all a higher stringency should go hand in hand with a better performance[12]. Table (2) reports the pairwise correlations of the country-means[13] of the indexes.

First look at the input indexes. The first set of benchmark indexes are the two input indexes measuring air policy stringency constructed by Knill et al. (2012). Both air policy indexes show a strongly positive and highly significant correlation with the narrow CO_2 input index. The higher CO_2 input policy stringency, the higher air policy input stringency, a result which has been expected. While the correlations of both air policy index with the broad GHG input index are positive, they are not significant. The latter is probably due

[12]Note that as I did not construct a general GHG performance index, this second step will only be carried out for gas specific indexes.

[13]I use country means and not each observation available to avoid that the pairwise correlations capture trends. In the single observation case (not displayed) the correlations are stronger and more significant but the same overall tendencies hold.

Figure 1: The CO_2 input indexes and the CO_2 performance index by country

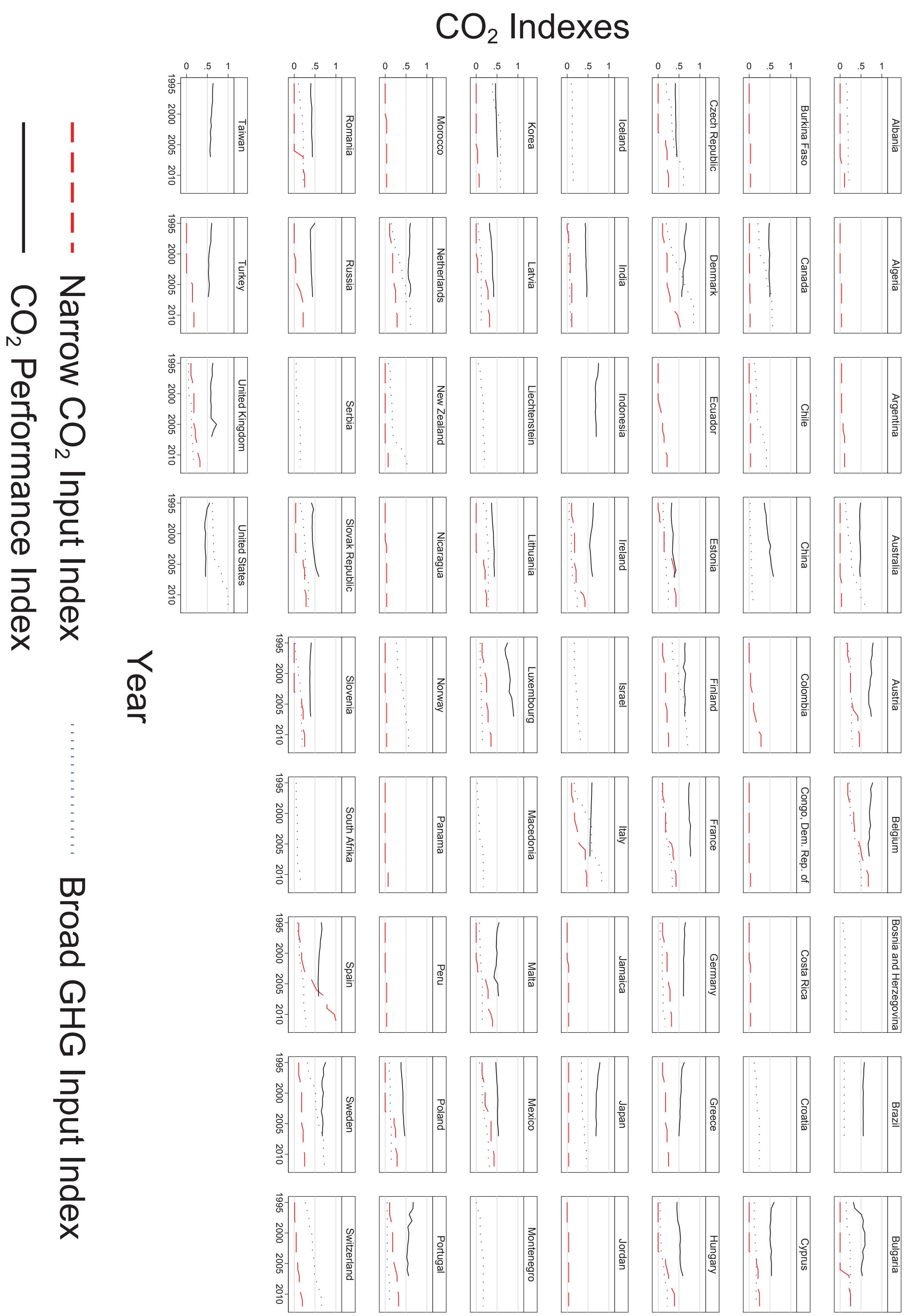


Table 2: Pairwise correlations of the means of the variables

	Narrow CO_2 II	Broad GHG II	Air Policy II 1	Air Policy II 2	WEF	CO_2 PI	EPI	Lead
Narrow CO_2 II	1							
Broad GHG II	-.0913	1						
Air Policy II 1	.633**	.166	1					
Air Policy II 2	.687***	.231	.905***	1				
WEF	.422**	.484***	-.139	.0466	1			
CO_2 PI	.540***	.197	-.00243	.165	.469**	1		
EPI	.267	.493***	.144	.273	.660***	.403*	1	
Lead	-.291	-.490**	-.0938	-.235	-.544***	-.380*	-.553***	1

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

II stands for Input Index, PI for Performance Index. The Narrow CO_2 Input Index, the Broad GHG Input Index and the CO_2 Performance Index have been constructed by the above outlined methodology. The Air Policy Input Index 1 and 2 are taken from Knill et al. (2012). The WEF survey index is taken from Browne et al. (2012). The Environmental Performance Index (EPI) is taken from Emerson et al. (2012) and the lead content of gasoline (Lead) index is taken from Grether et al. (2012a).

to relatively few overlapping data points between the two indexes. As an additional benchmark the WEF survey index, measuring perceived environmental policy stringency, is used (Browne et al., 2012). I expect that the opinion of the survey respondents on environmental policy stringency should be positively correlated with the CO_2 input index and with the broad GHG input index. This is the case, the correlation is positive and strongly significant for both the narrow CO_2 index and the broad GHG input index. The benchmark comparisons seem to indicate that both input indexes do actually measure what they should.

The CO_2 performance index is compared to two widely used performance indexes. The Environmental Performance Index of Yale (Emerson et al., 2012) is positively and significantly correlated with the constructed CO_2 performance index. A better overall environmental performance parallels a better CO_2 performance. As an additional benchmark a second performance index - the index of the lead content of gasoline - is used. A negative and significant correlation is observed. Again this result is anticipated, a better CO_2 performance goes hand in hand with lower lead contents in gasoline. Overall the benchmark comparisons seem to indicate that the CO_2 performance indicator measures what it is supposed to.

Finally let's look at the relation between the narrow CO_2 input index and the CO_2 performance index. A priori, I expect that a more stringent CO_2 input policy should coincide with a better CO_2 performance. Looking simply at the correlation this seems to be the case: a positive and strongly significant correlation exists between the two indicators. Figure (2) plots the mean value of the two indexes by country, including a linear fit and the corresponding confidence interval for the mean value of the performance index given the different input index values. One can observe a rather clear tendency: the higher the mean value of the CO_2 input index, the higher the mean CO_2 performance by country. Figure (3) shows the difference between the last and the first year of the performance index on the y-axis and of the input index on the x-axis. Again a simple linear fit and the corresponding confidence interval is displayed. The results go in the expected direction, but are not strong[14]. Overall, and without making any causal statement, it seems that higher CO_2 input stringency is positively associated with a better CO_2 performance, a result which is expected.

Two remarks have to be made in order to illustrate both the limits and the importance of these results. First, policy unrelated factors might influence the CO_2 performance of a country. Most of the countries which show a strong increase in the CO_2 performance but only a slight increase in the policy stringency are countries from the former Soviet Union. Their position in Figure (3) might be explained by the dismantling and relocation of the heavy industry in those countries after 1991. Hence, taking performance indicators as proxies of environmental policy stringency might be quite dangerous. Second, Figure (3) underlines the importance of having clearly separated input, process and output indexes. This can be illustrated by the example of countries showing relatively big improvements of their input indexes which go hand in hand with a decline in their performance indexes. As an example take Greece. It is possible that the relatively high corruption in Greece (see for instance Transparency International (2012)) might indicate a low implementation stringency. If this is the case, this could explain Greece's position in Figure (3). Ideally, a researcher should have all three types of indicators available and use them according to his specific research question.

[14] In appendix A and B, the same analysis has been done for SO_2 and CH_4. Note that, for SO_2, the results go even more in the expected direction.

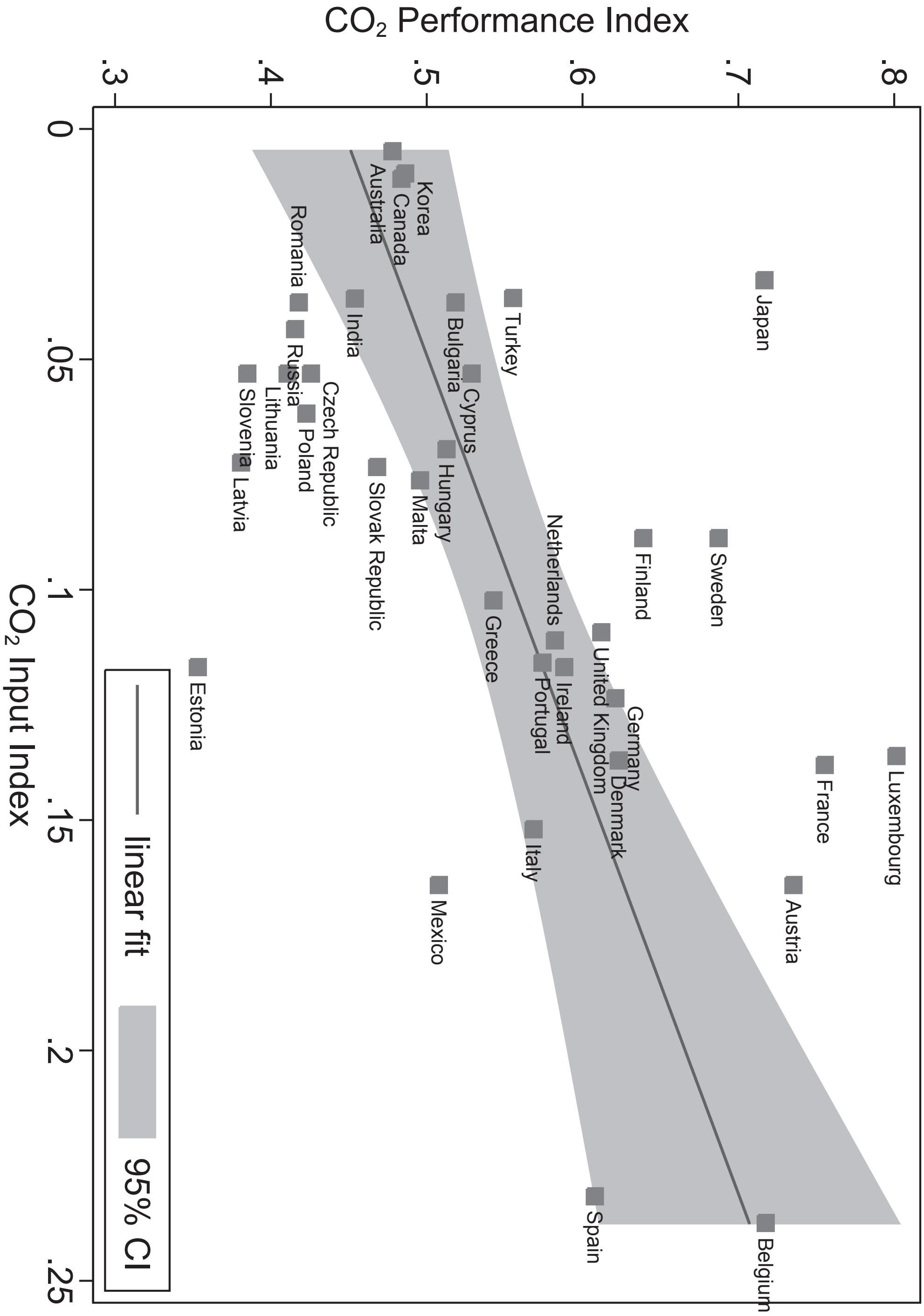
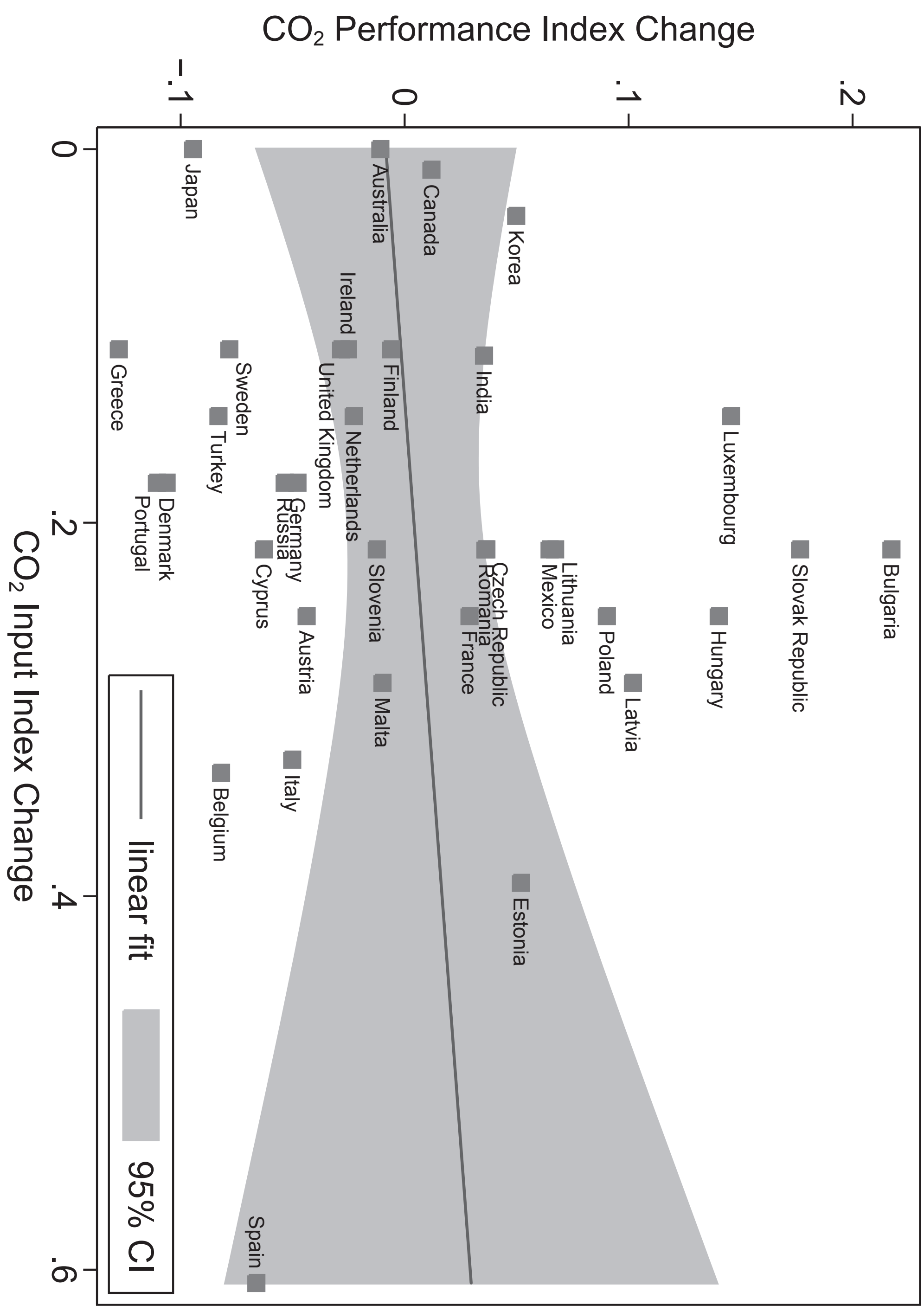


Figure 2: Means of the Narrow CO_2 input index and the CO_2 performance index by country

Figure 3: Change of the Narrow CO_2 input index and of the CO_2 performance index from the first to the last year in the sample



7 Conclusion

In this chapter I identify what I think to be the main obstacle currently limiting the development of indicators measuring environmental policy stringency: the absence of an explicitly stated methodological framework. Previous attempts violate one of the most fundamental rules found in the literature on index construction by not defining the concept they intend to quantify. What is badly defined is likely to be badly measured. The solution I propose allows to separately quantify the input, process and output dimension of various specific - hence well definable - types of environmental policies. I applied the general methodology to measure the stringency of pollutant policies, implementing a broad GHG policy input index, a CO_2 input index and a corresponding CO_2 performance index. Additional results for SO_2 and CH_4 input and performance indicators can be found in appendix A and B. Comparisons with available benchmark indicators suggest that the obtained indexes measure what they are supposed to.

The implemented indexes can and will be extended trough time and space. Improvements, especially concerning the equal weighting approach of the input indicators, should be readily implementable as soon as priors are becoming available in the literature. In a next step it will be possible to assess to what extent policy efforts actually solved the problem they intend to solve.[15] Using the developed input and performance indexes as well as a proxy for policy implementation stringency, it will be possible to estimate by how much policy efforts improved the CO_2 performance of a country over time. Or, in other words, it will be possible to calculate a real output index of CO_2 policy.

[15]Note that Chapter 4 provides a first application - using the broad GHG input index - which investigates this important question empirically.

Appendix A: SO_2 indexes

The SO_2 input policy stringency index and the SO_2 performance index rely on the same methodology as outlined in the above chapter at the example of CO_2 input policy stringency and CO_2 performance. In case of SO_2, two important comments have to be made:

1) For the construction of the narrow SO_2 input index, a total of 240 SO_2 policies have been identified using ECOLEX. Out of those 240 policies, 14 are only applied on a sub-national level.

2) For the construction of the SO_2 performance indicator I used the same approach as in the CO_2 case described in the main part of the chapter. The database used doesn't report sulphur dioxide but sulphur oxide (SO_X), hence the constructed performance index has to be interpreted as a SO_X performance index. The variables used to construct the sectoral performance indicator and the mean of the pca weights used to construct it are summarized in Table (A.1):

Table A.1: Sectoral SO_X performance sub-indicators

Indicator	Description	Mean weight	Dimension
$\frac{\text{sectoral } SO_X \text{ emissions}}{\text{sectoral GDP}}$ [16]	Sectoral SO_X per sectoral GDP	0.443	SO_X intensity
$\frac{\text{sectoral } SO_X \text{ emissions}}{\text{sectoral work force}}$ [17]	Sectoral SO_X per sectoral workforce	0.411	
EE_t	SO_X efficiency score (profit function)	0.545	SO_X efficiency
EE_t^*	SO_X efficiency score (revenue function)	0.551	

[16] Note that this variable has been re-scaled. Each observed value is subtracted from the observed maximum (max) of the variable, then the minimum (min) of the variable is added: (max-observation)+min. With this transformation higher values now indicate a better performance. Subsequently values have been standardized between zero and one.

[17] See: footnote 16.

SO_2 results

To obtain an overview, Figure (A.1) displays the evolution of the narrow SO_2 input index and the SO_X performance index by country. Note that due to the different data-sources, not all indexes are available for all countries.

To empirically assess whether the constructed indexes measure what they are supposed to I pursue the same strategy as in the main part of the chapter. First I compare the input (performance) index to existing input (performance) indexes and second I compare the input index to the performance index and verify that the expected relation holds. Table (A.2) reports the pairwise correlations of the country-means[18] of the indexes.

The first set of benchmark indexes are the two input indexes measuring Air Policy Stringency constructed by Knill et al. (2012). Both air policy indexes show a strongly positive and highly significant correlation with the narrow SO_2 input index. The higher SO_2 input policy stringency the higher air policy input stringency, a result which has been expected. As a second benchmark the WEF survey index[19] is used (Browne et al., 2012). I expect that the opinion of the survey respondents on environmental policy stringency should be positively correlated with the SO_2 input index. This is the case, the correlation is positive and significant. Looking at the performance index, we observe again a positive and significant correlation with the EPI, the overall environmental performance index of Yale. As a second benchmark for the performance index the lead content of gasoline index has been taken. Here we observe a negative and significant correlation. Indicating that a better SO_X performance is paralleled by a lower lead content in gasoline concentration, a result which has been expected.

Looking at the relationship between input and performance index, the strong and highly significant correlation is in accordance with the expectations: a higher SO_2 input stringency goes hand in hand with a higher SO_X performance. Figure (A.2) plots the mean value of the two indexes by country, including a linear fit and the corresponding confidence interval for the mean value of the performance index given the different input index values. One can observe a

[18]I use country means and not each observation available to avoid that the pairwise correlations capture trends. In the single observation case (not displayed) the correlations are stronger and more significant but the same overall tendencies hold.

[19]Even if the WEF survey index is not an input index, I use this index as a benchmark due to it's wide usage in the literature.

clear tendency: the higher the mean value of the SO_2 input index, the higher the mean SO_X performance by country. Figure (A.3) shows the difference between the last and the first year of the performance index on the y-axis and of the input index on the x-axis. Again a simple linear fit and the corresponding confidence interval is displayed. The result goes in the expected direction and is even stronger than in the CO_2 case displayed in the main part of the chapter.

As in the CO_2 case discussed in the chapter, results seem to indicate that the indexes measure what they are supposed to.

Table A.2: Pairwise correlations of the means of the variables

	Narrow SO2 II	Air Policy II 1	Air Policy II 2	WEF	SOX PI	EPI	lead
Narrow SO2 II	1						
Air Policy II 1	.691**	1					
Air Policy II 2	.661**	.905***	1				
WEF	.411**	-.139	.0466	1			
SOX PI	.605***	.108	.274	.478**	1		
EPI	.298*	.144	.273	.660***	.419**	1	
lead	-.320	-.0938	-.235	-.544***	-.530**	-.553***	1

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

II stands for Input Index, PI for Performance Index. The Narrow SO_2 Input Index and the SO_2 Performance Index have been constructed by the above outlined methodology. The Air Policy Input Index 1 and 2 are taken from Knill et al. (2012). The WEF survey index is taken from Browne et al. (2012). The Environmental Performance Index (EPI) is taken from Emerson et al. (2012) and the lead content of gasoline (Lead) index is taken from Grether et al. (2012a).

Figure A.1: The SO_2 input indexes and the SO_X performance index by country

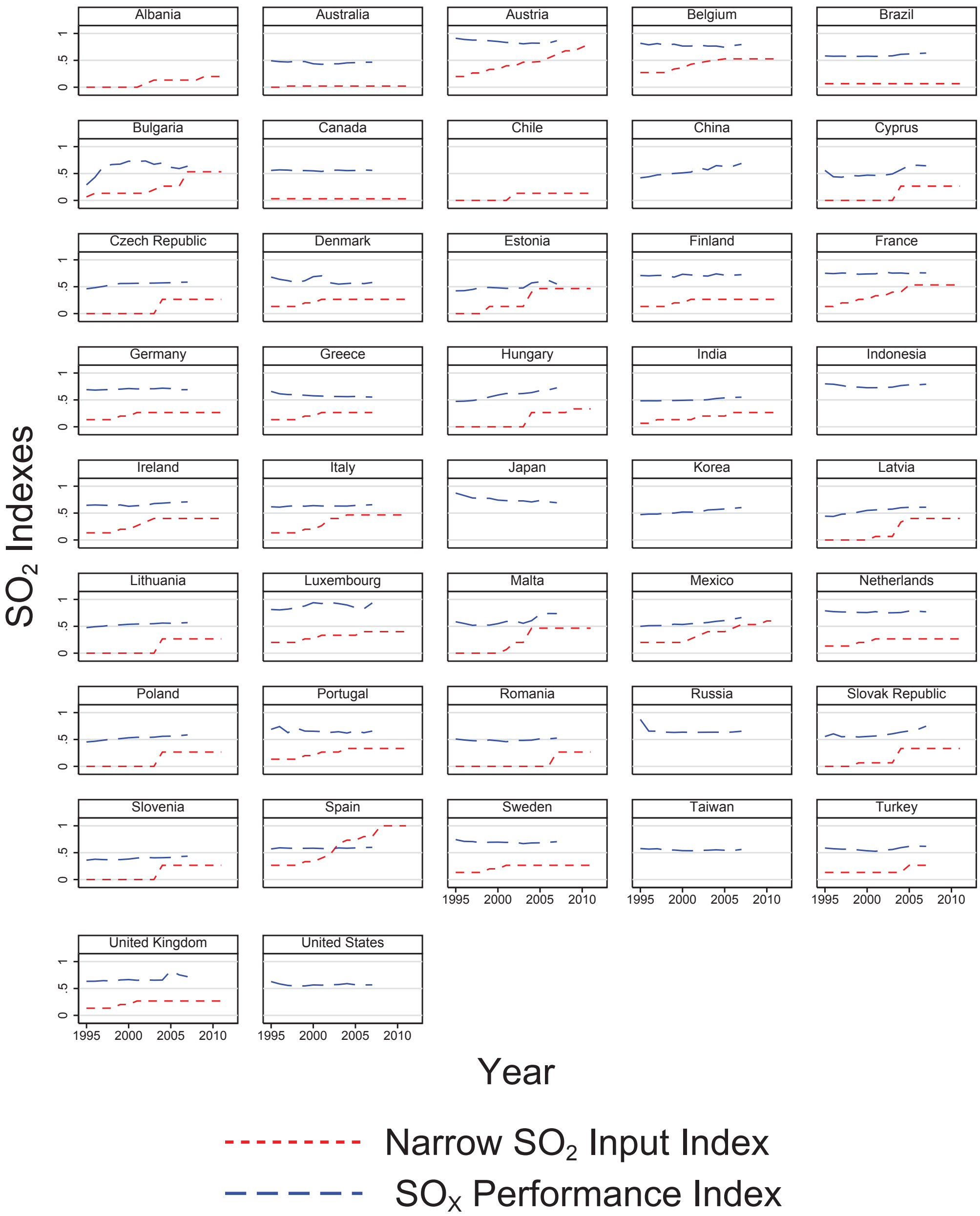


Figure A.2: Mean of the narrow SO_2 input index and the SO_X performance index by country

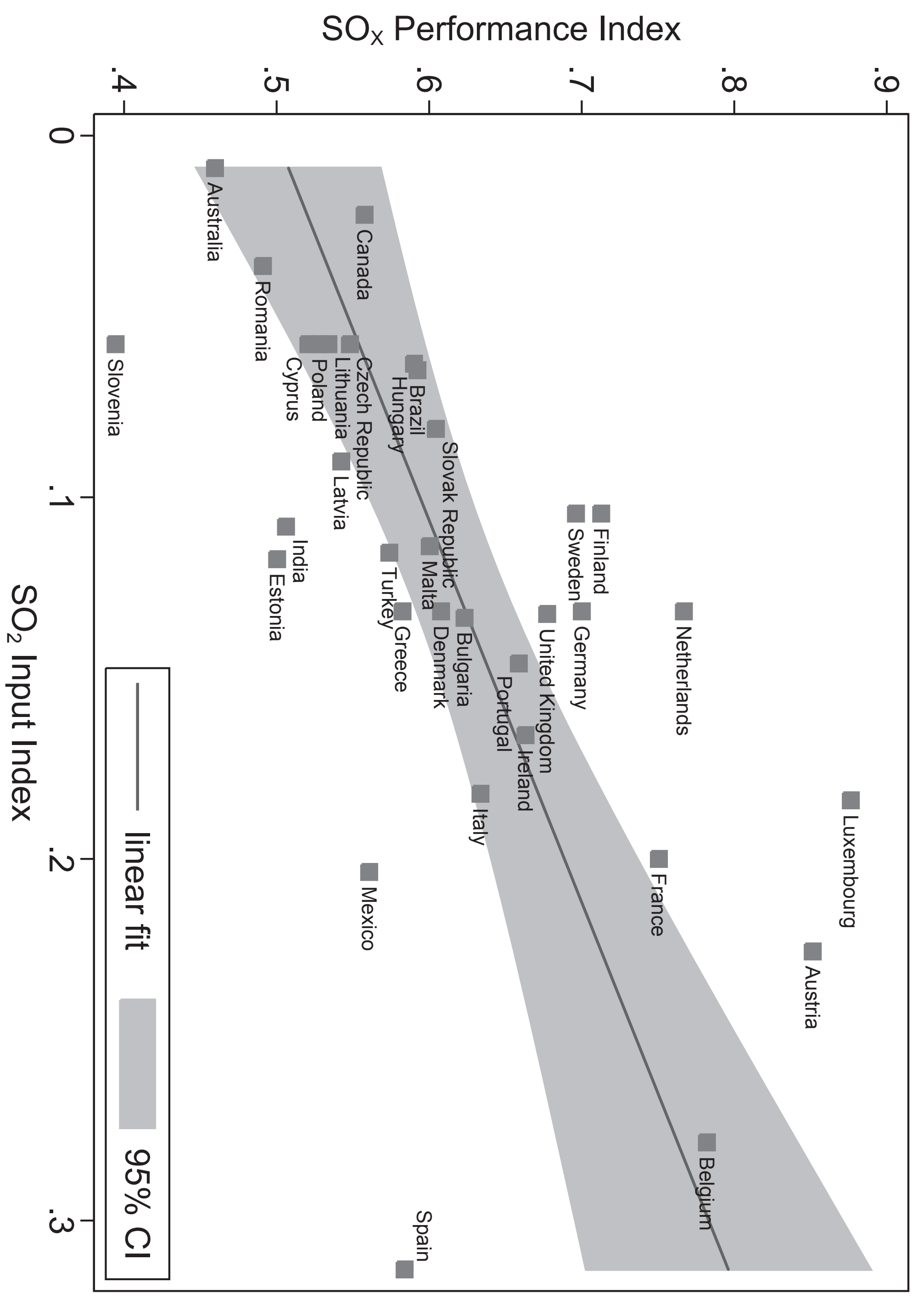
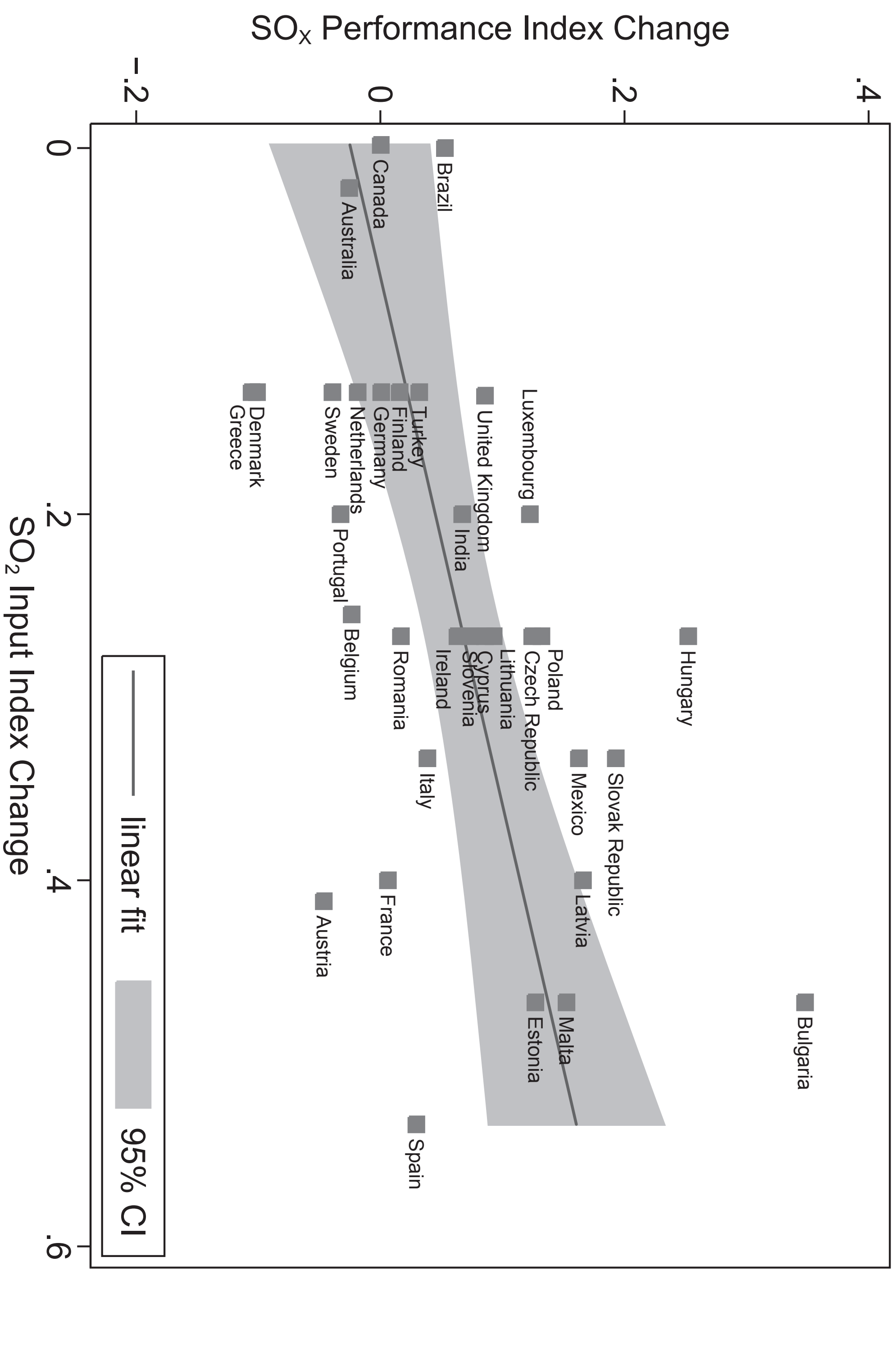


Figure A.3: Change of the Narrow SO_2 input index and of the SO_X performance index from the first to the last year in the sample



Appendix B: CH_4 Indexes

The CH_4 input policy stringency index and the CH_4 performance index rely on the same methodology as outlined in the above chapter at the example of CO_2 input policy stringency and CO_2 performance. In case of CH_4 two important comments have to be made:

1) For the construction of the CH_4 input index, a total of only 53 CH_4 policies have been identified using ECOLEX. Out of those 53 policies, 6 are applied on a sub-national level. This really limited number of CH_4 policies and therefore the small variation in the CH_4 input index limit the use of the narrow methane input index considerably.

2) For the construction of the CH_4 performance indicator I used the same approach as in the CO_2 case described in the chapter. The variables used to construct the sectoral performance indicator and the weights used to construct it are summarized in Table (B.1):

Table B.1: Sectoral CH_4 performance sub-indicators

Indicator	Description	Mean weight	Dimension
$\frac{\text{sectoral } CH_4 \text{ emissions}}{\text{sectoral GDP}}$ [20]	Sectoral CH_4 per sectoral GDP	0.453	CH_4 intensity
$\frac{\text{sectoral } CH_4 \text{ emissions}}{\text{sectoral work force}}$ [21]	Sectoral CH_4 per sectoral workforce	0.449	
EE_t	CH_4 efficiency score (profit function)	0.529	CH_4 efficiency
EE_t^*	CH_4 efficiency score (revenue function)	0.538	

[20] Note that this variable has been re-scaled. Each observed value is subtracted from the observed maximum (max) of the variable, then the minimum (min) of the variable is added: (max-observation)+min. With this transformation higher values now indicate a better performance. Subsequently values have been standardized between zero and one.

[21] See: footnote 20.

CH_4 results

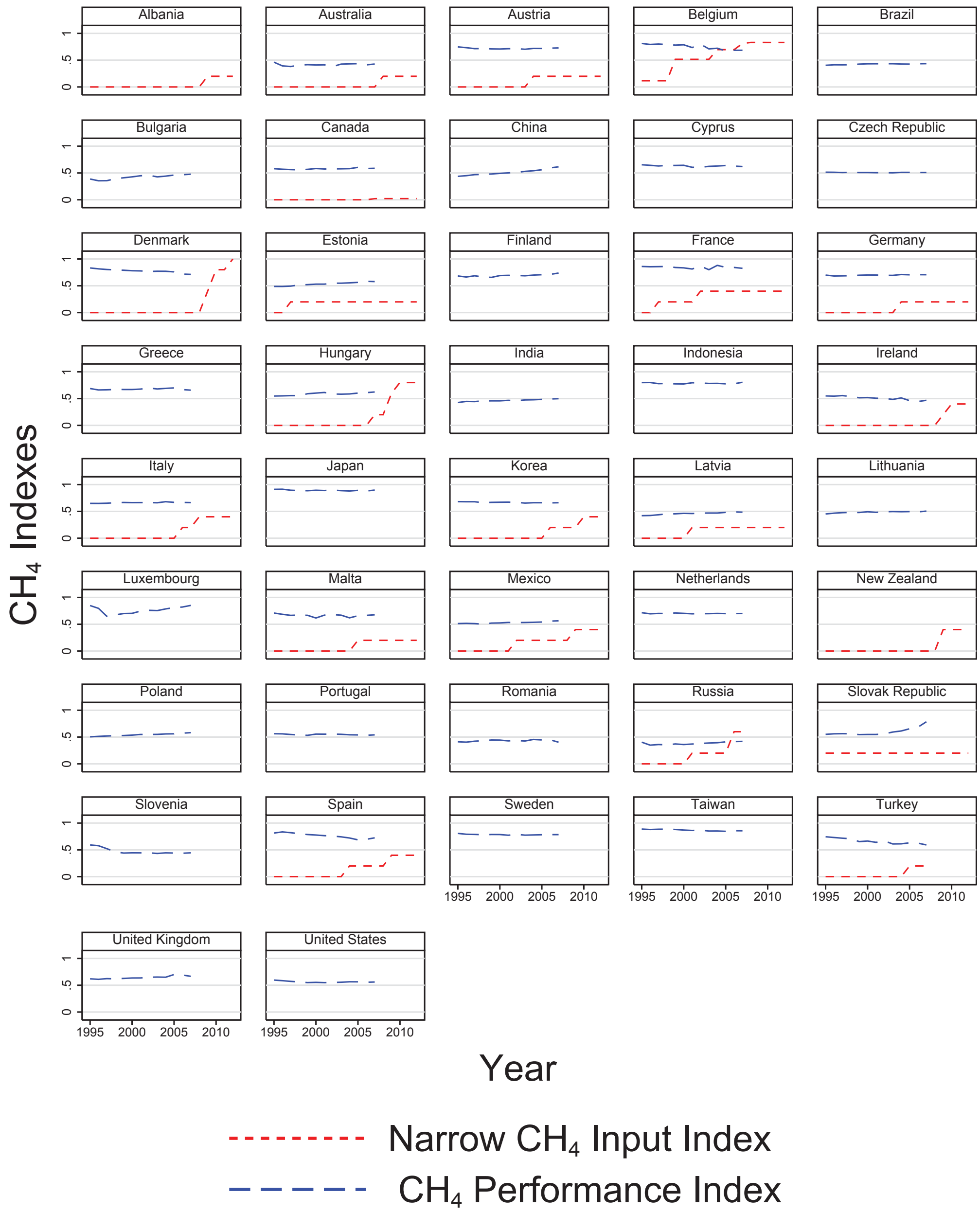
Figure B.1 displays the evolution of the CH_4 input and performance indicator by country. Given the absence of a lot of methane specific laws, the input index displays a very limited variability over time and space.

Table B.1 displays the pairwise correlation of the means of the variables. The narrow CH_4 index is positively and significantly correlated with the Air Policy indexes of Knill et al. (2012). There is no significant correlation between the CH_4 input indicator and the WEF index. The small number of explicit CH_4 laws seems to limit the input indicator approach considerably. Looking at the performance indicator, there is a positive and significant correlation between the CH_4 performance indicator and the EPI of Yale. And a negative and significant correlation between the performance index and the lead content of gasoline. Both results suggest that the performance index is measuring what he is supposed to.

For the sake of completeness I included Figure B.2 and B.3 despite the fact that comparisons between the performance and input index make only limited sense, given the small numbers of explicit CH_4 laws. The correlation between the two is positive but not significant and Figure B.2 displays a relationship which goes in the expected direction. Figure B.3 however displays a result which is not in accordance with the expectation.

Overall, the CH_4 performance indicator seem to work as intended. However, the small number of explicit CH_4 laws clearly exemplifies one of the limits of the proposed input index approach.

Figure B.1: The CH_4 input indexes and the CH_4 performance index by country



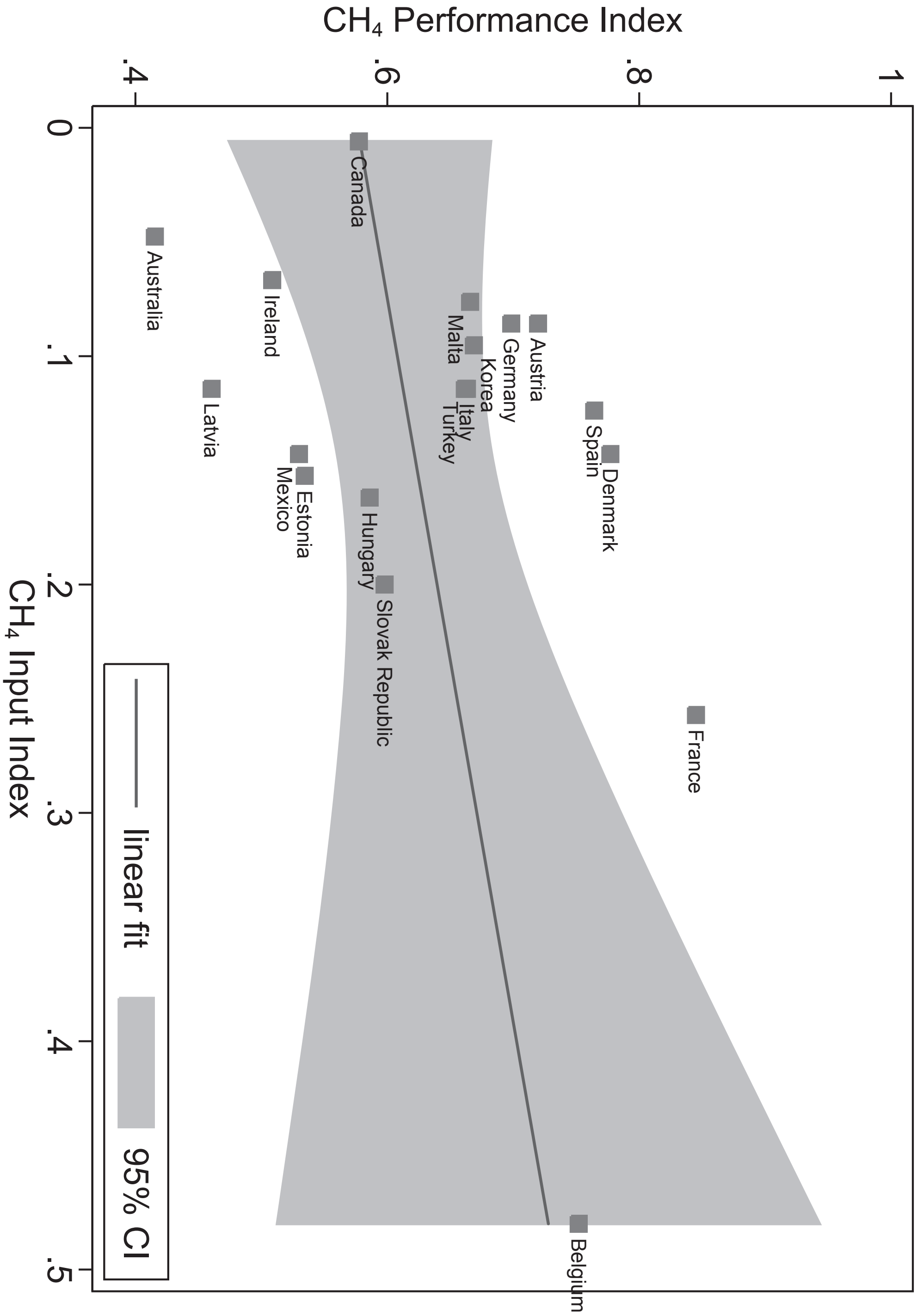


Figure B.2: Mean of the Narrow CH$_4$ input index and of the CH$_4$ performance index by country

Figure B.3: Change of the Narrow CH_4 input index and of the CH_4 performance index from the first to the last year in the sample

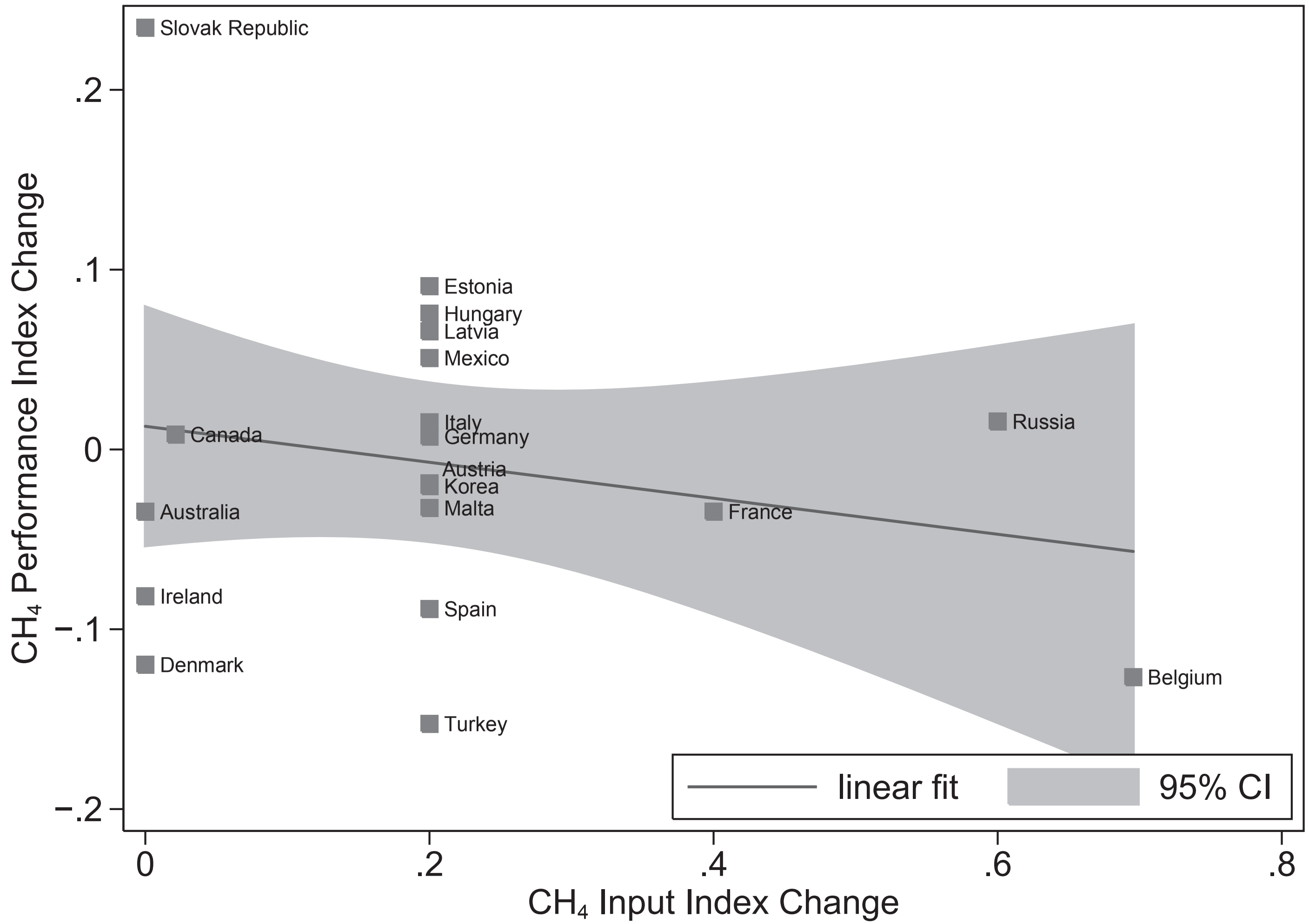


Table B.2: Pairwise correlations of the means of the variables

	Narrow CH4 II	Air Policy II 1	Air Policy II 2	WEF	CH4 PI	EPI	lead
Narrow CH4 II	1						
Air Policy II 1	.710**	1					
Air Policy II 2	.769**	.905***	1				
WEF	.0778	-.139	.0466	1			
CH4 PI	.255	-.00817	.139	.430**	1		
EPI	.0264	.144	.273	.660***	.409*	1	
lead	-.161	-.0938	-.235	-.544***	-.355*	-.553***	1

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

II stands for Input Index, PI for Performance Index. The Narrow SO_2 Input Index and the SO_2 Performance Index have been constructed by the above outlined methodology. The Air Policy Input Index 1 and 2 are taken from Knill et al. (2012). The WEF survey index is taken from Browne et al. (2012). The Environmental Performance Index (EPI) is taken from Emerson et al. (2012) and the lead content of gasoline (Lead) index is taken from Grether et al. (2012a).

Chapter 4

CO_2 Emissions and Greenhouse Gas Policy Stringency *

1 Introduction

An accelerated warming of the climate system increases the likelihood of "severe, pervasive and irreversible" impacts. Those risks can be mitigated by limiting the rate and magnitude of climate change (IPCC, 2014a). To do so, anthropogenic greenhouse-gas (GHG) emissions have to be reduced as they are "extremely likely" to be the dominant cause of the observed global warming (IPCC, 2013). This calls for a tightening of GHG policy regimes and raises a set of questions regarding their effects. Does an increase in the stringency of a country's GHG policy regime reduce anthropogenic GHG emissions? What are the opportunity costs of a policy induced CO_2 emission reduction? And if CO_2 can be reduced, do stricter GHG policies increase the GHG efficiency of sectors or alter the composition of dirty and clean sectors of an economy? The latter question is important when taking a global perspective, as the impact on global emissions depends on how a reduction in country emissions has been achieved. This chapter attempts to answer those questions by empirically investigating the relationship between GHG policy stringency and anthropogenic carbon dioxide

*This paper is co-authored by Marcel Probst, University of Lausanne, Faculty of Business and Economics.

emissions.

The literature on environmental policy evaluation contains assessments focusing on a single country or a specific industry (e.g., Cole et al. (2005) or Gamper-Rabindran and Finger (2013)), qualitative assessments of environmental policies (e.g., Aldy et al. (2003), or Taylor et al. (2012)), quantitative assessments of single policy measures (e.g., Anderson and Maria (2011)), as well as model-based ex-ante assessments of environmental policies (e.g., Manne et al. (1995), Tol (1999), Barker et al. (2007) or Clarke et al. (2009)). But, to the best of our knowledge, few papers empirically evaluate the impact of environmental policy stringency on anthropogenic GHG emissions using either panel or country cross-sectional data. In the following review, we exclusively focus on those contributions.

Most of them originate from the literature analyzing the links between economic development and pollution, as well as the links between trade and pollution. Panayotou (1997) finds a significantly negative relation between ambient SO_2 levels and a general policy index reflecting the degree of enforcement of contracts in different political systems. De Bruyn (1997) provides evidence that per capita GDP and environmental policy stringency (proxied by abatement targets from the Convention on Long Range Transboundary Air Pollution) are positively correlated. He points out that this could partly explain why pollution seems to curb downwards at high income levels. Esty and Porter (2005) wrote the first paper which puts the assessment of environmental policy impacts at the center of attention. They use a variety of environmental performance indicators (including SO_2 concentrations) and the environmental regulatory regime index (ERRI) as the policy variable. The latter is based on the World Economic Forum's Global Competitiveness Report Survey. Results indicate a significantly negative relation of SO_2 concentrations and environmental policy stringency. However, they state that their results must be seen as preliminary and that causal linkages remain unproven due to data and econometric limitations. Huang and Barker (2012) and Huang et al. (2012) investigate the impact of clean development mechanism (CDM) projects on CO_2 emissions. They provide evidence in support of a CO_2 emission reduction associated with CDM project developments. A result which can be interpreted as evidence for a negative relationship between pollution and environmental policy stringency. Gani (2012) shows that the general World Bank indicators of political stability, rule of law, and control of corruption are negatively correlated with CO_2 emissions per capita. Aichele and Felbermayr (2013) find that the ratification of binding Kyoto commitments (which could be interpreted as a proxy for increased stringency), significantly lowers domestic CO_2 emissions in committed countries. Using cross-sectional data for OECD countries, Calbick and Gunton (2014) show that environmental governance, proxied by the WEF's Global Competitiveness Report Executive Opinion Survey, is negatively correlated with per capita GHG emissions, and explains about 7% of its cross-sectional variation.

These findings provide some evidence that more stringent environmental policy is negatively associated with anthropogenic GHG emissions. However, three limitations of the current empirical literature can be identified. Firstly - as noted by Esty and Porter (2005) - it is difficult to obtain good measures of environmental policy stringency. Due to this relative scarcity of sound data, previous contributions use either general government indicators, survey based indexes or policy specific dummies. Moreover, as Sauter (2014) points out, the concepts of environmental policy and environmental policy stringency are rather broad. They potentially encompass a diverse array of measures like the regulation of hunting or the protection of a particular species. Hence, to evaluate the impact of policy stringency on GHG emissions, it is crucial to use an index quantifying GHG policy stringency rather than general environmental policy stringency or - even worse - general government indicators. Secondly, GHG policy stringency and CO_2 emissions, as well as the channels through which those variables influence one another, have not yet been subject to simultaneous analysis. Thirdly, no attention has been put to empirically disentangle the overall effect of GHG policy stringency. Besides reducing absolute production levels, a country's CO_2 emissions may be reduced through a CO_2 efficiency improvement of some or all of its sectors, or by altering the relative production shares of dirty and clean sectors. Since the contribution of Grossman and Krueger (1991), the literature labels those effects as scale, technique and composition effect, respectively.

Focusing on anthropogenic CO_2, we address those limitations by using the newly proposed indicator by Sauter (2014) which allows to quantify country GHG policy stringency. In order to deal with potential endogeneity issues, and in the absence of suitable instruments, we use a spatial structural VAR model proposed by Di Giacinto (2010). Finally, we pursue a two-fold estimation strategy. To estimate the size of the overall effect of GHG policy stringency on CO_2 emissions, we use aggregated country data. The country-wide analysis allows us as well to assess over which channels GHG policy stringency operates, and thus to estimate the policy induced scale effect. It also allows to measure opportunity costs of a CO_2 emission reduction in terms of GDP. In order to disentangle the overall country effect, we rely on industry specific country data. We assess if increased GHG policy stringency alters the sectoral composition within countries and increases CO_2 efficiency of sectors. Hence, we do not perform a classical decomposition but empirically estimate GHG policy induced scale, technique and composition effects. We subsequently perform extended robustness tests to asses the validity of our results.

The remainder of the chapter is organized as follows: Section 2 describes the data used in the estimation, section 3 outlines our methodological approach, preliminary test results are reported in section 4, results are displayed in section 5, and section 6 reports robustness tests which are followed by a discussion in section 7.

2 Data

The economy-wide and the sector-level datasets are described in subsections (2.1) and (2.2), respectively. A general overview and summary statistics of the variables is provided in Table (1). The table also contains a column listing papers supporting the variable use. Together, those variables cover the economic, socio-demographic and climatic factors the literature on anthropogenic country GHG emissions finds to be relevant. For a recent summary of this literature, refer to Calbick and Gunton (2014).

2.1 Economy-wide Dataset

The economy-wide dataset covers yearly observations for 46 developed and developing countries (see Table (A1) in the Appendix) accounting for 71% of the world's CO_2 emissions over the time range 1990-2010. Anthropogenic CO_2 emissions, GHG policy stringency, GDP, technology and energy prices are considered endogenous. In addition, we include a set of exogenous variables: corruption, cooling degree days and heating degree days, the latter two capture climatic conditions.

Anthropogenic CO_2 emissions in kilo tons and real *GDP* are taken from the World Bank. The variable quantifying *GHG policy stringency* is the "Broad GHG input index" taken from Sauter (2014). The index is a count variable of all laws which aim to reduce GHG emissions. It can therefore be seen as a de-jure indicator which captures statutory laws on the books. By using such a variable, we avoid the conceptual problems faced by previous studies using general environmental policy stringency proxies or general government indicators. Furthermore, this index is - to our best knowledge - the only GHG policy stringency measure covering our sample. The evolution of the index by country is summarized in Figure (A1) in the Appendix. This index also has some limitations. It does not incorporate changes of policy implementation stringency over time. To cope with this issue, we include *corruption* as a proxy for general policy implementation stringency. Also, due to the equal weighting approach, the introduction of each new nation-wide law is considered to correspond to an equal sized increase in GHG policy stringency. However, in the absence of theoretical work allowing to weight different policy measures in terms of GHG policy stringency, any weight approach remains an arbitrary choice. We also considered the use of two alternative measures. Firstly, the most widely used indicator of environmental policy stringency provided by the Browne et al. (2012). This index is survey based and thus measures only perceived environmental policy stringency and is only available from 2004 onward.[1] Secondly, the recently developed index of environmental policy stringency proposed by Botta and Kozluk (2014). This index has, however, a considerably smaller coverage in terms of world CO_2 emissions, excludes developing countries and does not solely focus on GHG policies. The country specific level of *technology* is approximated by the count of filed patents. A patent is taken as an observation the year the patent is filed in a national patent authority. We use the IEA indicator of energy end use prices including taxes as our *energy price* variable. Approximately 20 % of the countries from our dataset are not included in the IEA database. The missing data are computed with the World Bank's two-years interval country specific data on pump gasoline prices. We then linearly interpolate the country specific World Bank data on the world crude oil price index from the IMF Primary Commodity Prices dataset to fill the two year gaps. After verifying that the within country correlation between the interpolated World Bank pump gasoline price data and the IEA data is sufficiently high, we use the interpolated data on pump gasoline prices as proxy for energy prices for the countries which are not in the IEA dataset.

In addition to the endogenous variables, three exogenous variables are included in our model: The variable *corruption* is used as a proxy for country differences in the implementation stringency of policies. *Climatic conditions* that directly influence the CO_2 emissions are approximated by cooling degree days (CDD) and heating degree days (HDD). The former quantifies the cooling

[1] Nevertheless, we use this index to assess the robustness of our results and obtain qualitatively similar results.

sufficient to neutralize the deviation of surface temperature from a standard comfort level. The latter quantifies the heating sufficient to neutralize the deviation of surface temperature from a standard comfort level.

2.2 Sector-level Dataset

The sector level dataset covers yearly observations for the time range 1995-2009 for 34 sectors and 35 countries (see Table (A1) in the Appendix). The countries in the sector-level dataset account for roughly 57% of world CO_2 emission over the covered period. We keep the same variables as in the economy wide specification but use sectoral data where it is available and appropriate.

Sectoral anthropogenic CO_2 and *sectoral value added* are taken from the World Input Output Database. Given that the *GHG policy stringency* index measures overall country GHG policy stringency, all sectors may, to a greater or lesser extent, be affected. We thus use the country wide policy stringency variable as described in section (2.1). The *energy price* level is also identical to the one in the country-wide specification. For the sector-level estimation, we use the per cent of sector-specific high-skilled working hours as compared to total sector-specific working hours as our measure of *sectoral technology.* A relative increase in working hours of highly skilled is considered to be equivalent to an improvement in the sector-specific technology.

All exogenous variables are identical to the ones described in section (2.1). The climatic and socio-demographic factors influencing country CO_2 emissions stay the same independently of the level of analysis (economy-wide or sectoral). Note that as part of the robustness analysis, we aggregate the sector level dataset in order to dispose of a second economy-wide dataset.

Table 1: Data: Description, Sources, Support and Descriptive Statistics

Variable Name	Variable Description	Specification	Data Source	Selected Papers supporting Variable Use	Descriptive Statistics	
Country CO2 emissions	Anthropogenic CO2 emissions in kilotons.	Endogenous, economy-wide	World Bank (2014c)	-	Mean	407664.1
					Min/Max	1543.81/8286892
					Sd	1045659
Sectoral CO2 emissions	Sectoral emissions of CO2 in kilotons.	Endogenous, sector-level	World Input-Output Database (2012)	-	Mean	13285.04
					Min/Max	0/3326279
					Sd	94337.46
GHG Policy Stringency	GHG policy stringency index, bound between 0 and 1. Higher values indicate higher stringency.	Endogenous, economy & sector-level	Sauter (2014)	Panayotou (1997), De Bruyn (1997), Hettige et al. (2000), Esty and Porter (2005) Huang and Barker (2012), Huang et al. (2012), Gani (2012) , Calbick and Gunton (2014)	Mean	0.21
					Min/Max	0/0.99
					Sd	0.18
Country GDP	GDP, constant USD, 2005.	Endogenous, economy-wide	World Bank (2014c)	Neumayer (2002), Stern (2004), Copeland and Taylor (2004), Esty and Porter (2005), Raupach et al. (2007), Rosa and Dietz (2012), Gani (2012), Calbick and Gunton (2014)	Mean	7.63E+11
					Min/Max	3.52e+08/1.37e+13
					Sd	1.79E+12
Sectoral Value Added	Sectoral value added, constant 1995 USD.	Endogenous, sector-level	World Input-Output Database (2012)	Neumayer (2002), Stern (2004), Copeland and Taylor (2004),Esty and Porter (2005), Raupach et al. (2007), Rosa and Dietz (2012), Gani (2012), Calbick and Gunton (2014)	Mean	25883.51
					Min/Max	0/1360052
					Sd	84965.64
Country Technology	Patent application data based proxy. Higher values indicated higher country technology levels.	Endogenous, economy-wide	World Bank (2014c)	Dietz and Rosa (1997), Lindmark (2002), Bruvoll and Medin (2003), Fan et al. (2006), Lantz and Feng (2006), Rosa and Dietz (2012)	Mean	88.92
					Min/Max	32.05/201.19
					Sd	23.69
Sectoral Technology	Sectoral high skilled hours in total hours, percentage points, higher values indicated higher sectoral technology levels.	Endogenous, sector-level	World Input-Output Database (2012)	Dietz and Rosa (1997), Lindmark (2002), Bruvoll and Medin (2003), Fan et al. (2006), Lantz and Feng (2006), Rosa and Dietz (2012)	Mean	21.81
					Min/Max	3.9/61.3
					Sd	12
Energy price index	IEA energy price index, completed with WB and IMF data (c.f. section). Higher values indicate higher energy price levels.	Endogenous, economy & sector-level	IEA (2014), IMF (2014), World Bank (2014c)	Burgess (1990), Moomaw and Unruh (1997), Olsthoorn (2001), Lindmark (2002), Calbick and Gunton (2014)	Mean	18388.33
					Min/Max	2/384201
					Sd	60785.35
Corruption	6 point corruption index, bound between 7 and 1. Where 7 indicates no corruption and 1 indicates a high degree of corruption.	Exogenous, economy & sector-level	International Country Risk Guide (2014)	Robbins (2000), Damania (2002), Fredriksson and Svensson (2003), Welsch (2004), Sauter (2014)	Mean	3.97
					Min/Max	01.06.1967
					Sd	1.32
CDD	Cooling Degree Day, measured as the annual sum of negative deviations of daily mean surface temperatures from a reference standard of 18.3 degree Celsius.	Exogenous, economy & sector-level	Wheeler (2012)	Considine (2000), Neumayer (2002), York et al. (2003), Isaac and van Vuuren (2009), Calbick and Gunton (2014)	Mean	591.84
					Min/Max	1/3449
					Sd	783.32
HDD	Heating Degree Day, measured as the annual sum of positive deviations of daily mean surface temperatures from a reference standard of 18.3 degree Celsius.	Exogenous, economy & sector-level	Wheeler (2012)	Considine (2000), Neumayer (2002), York et al. (2003), Isaac and van Vuuren (2009), Calbick and Gunton (2014)	Mean	5318.88
					Min/Max	134/10654
					Sd	2530.37

3 Methodology

In order to analyze the direct and indirect effect of policy stringency on CO_2 emissions, we use a spatial VAR. This is because GHG policy stringency, the technology level, energy prices, GDP and CO_2 emissions are interdependent variables. Estimating each individual effect on CO_2 emissions within such an endogenous system would require a series of instrumental variables. Those are either difficult to define, or come with a high cost in terms of data loss. A VAR, however, is suitable to take into account the dynamic structure of our data generating process and allows the use the full dataset. In addition, by embedding all individual linkages into one global estimation, it allows for a subsequent simulation analysis via impulse response functions.
Hence within our VAR, anthropogenic CO_2 emissions, GHG policy stringency and the transmission channels are treated both as endogenous and predetermined variables. In addition, to take into account changes in the external demand for input factors or intermediate goods, we allow the variables to affect one another across national borders by including a spatial lag.

Following Di Giacinto (2010), our empirical model with the number of temporal lags P looks as follows:

$$\Gamma_0 Y_t = \sum_{p=1}^{P} \Gamma_{1p} Y_{t-p} + \sum_{p=0}^{P} \Gamma_{2p} X_{t-p} + \Psi_i + \Lambda_t + U_t \tag{1}$$

with $Y_t = [I_t, T_t, E_t, \Omega_t, H_t]'$, the vector of the endogenous variables: GHG policy stringency index, technology, energy prices, GDP and CO_2 emissions, respectively. $I_t = [\iota_{1t}, \iota_{2t}, ..., \iota_{Nt}]'$, $T_t = [\tau_{1t}, \tau_{2t}, ..., \tau_{Nt}]'$, $E_t = [\epsilon_{1t}, \epsilon_{2t}, ..., \epsilon_{Nt}]'$, $\Omega_t = [\omega_{1t}, \omega_{2t}, ..., \omega_{Nt}]'$ and $H_t = [\eta_{1t}, \eta_{2t}, ..., \eta_{Nt}]'$ where I_t, T_t, E_t, Ω_t and H_t are vectors of the panel units $1, ..., N$ (countries or sectors). Ψ_i and Λ_t include a set of dummies to account for panel specific fixed effect and period-specific common shocks, respectively. U_t is a vector of structural error terms where $\sum_{U_t}$ is diagonal, and contains a heterogeneous set of variances. Γ_{1p} and Γ_{2p} assume the following form:

$$\Gamma_p = \begin{pmatrix} A_p^{\iota\iota} & A_p^{\iota\tau} & A_p^{\iota\epsilon} & A_p^{\iota\omega} & A_p^{\iota\eta} \\ A_p^{\tau\iota} & A_p^{\tau\tau} & A_p^{\tau\epsilon} & A_p^{\tau\omega} & A_p^{\tau\eta} \\ A_p^{\epsilon\iota} & A_p^{\epsilon\tau} & A_p^{\epsilon\epsilon} & A_p^{\epsilon\omega} & A_p^{\epsilon\eta} \\ A_p^{\omega\iota} & A_p^{\omega\tau} & A_p^{\omega\epsilon} & A_p^{\omega\omega} & A_p^{\omega\eta} \\ A_p^{\eta\iota} & A_p^{\eta\tau} & A_p^{\eta\epsilon} & A_p^{\eta\omega} & A_p^{\eta\eta} \end{pmatrix}$$

$$p = 1, ...P$$

where $A_p^{rk} = \sum_{s=0}^{S} \tilde{\Gamma}_{ps}^{rk} W_s$ and $\tilde{\Gamma}_{ps}^{rk} = diag\{[\gamma_{1ps}^{rk}, \gamma_{2ps}^{rk}, ..., \gamma_{Nps}^{rk}]\}$, with γ^{rk} the coefficient for endogenous variable $k = 1, ..., K$ and sub-equation $r = 1, ..., K$. Also, $s = 1, ..., S$, with s the spatial lag, and the function $diag\{\}$ indicating that the off-diagonal elements are zero. W is a NxN matrix that selects and weighs the neighboring variables. We use an aspatial approach as our baseline model where we set $S = 0$. W_0 then selects the within unit values of each country or sector. Subsequently, we set $S = 1$ in a robustness analysis, where W_1 selects and summarizes the neighboring values. We choose to weigh each neighboring value equally, such that a weight $w_{ij} = \frac{1}{N_j}$ with N_j the number of neighbors. The definition of a neighbor is treated in section 6. Γ_0 is constructed similarly. As in a standard VAR, exclusion restrictions are imposed such that it becomes lower triangular.[2]
In a homogeneous specification, the following constraints are imposed: $\gamma_{ips}^{rk} = \gamma_{jps}^{rk} = \gamma_{ps}^{rk} I_N$. We use this constraint in our country-specific analysis. In order to analyse the composition effect on the one hand, and to see how different sectors or countries react to policy stringency on the other, we can relax this restriction by allowing for heterogeneous effects among some subgroups of countries or sectors. A group-heterogeneous model where we assume a set of coefficients to be homogeneous within a group z is defined as follows: $\tilde{\Gamma}_{ps}^{rk} = diag\{[\gamma_{1ps}^{rk}, ..., \gamma_{zps}^{rk}, ..., \gamma_{Zps}^{rk}]\}$ where $z = 1, 2, .., Z < N$.

In order to identify our model, we impose a series of exclusion restrictions which set some contemporaneous effects in Γ_0 to zero. The ordering of the variables determine these exclusion restrictions. GHG policy stringency is taken first in the ordering. None of our endogenous variables are assumed to impact GHG policy stringency contemporaneously. This is more so the case when considering that the elaboration of a policy may take some time. Technology is also relatively exogenous, in that it is most likely not affected through contemporane-

[2] Moreover, on the diagonal, we have $A_p^{rk} = I_N - \sum_{s=1}^{S} \tilde{\Gamma}_{ps}^{rk} W_s$.

ous changes in the remaining endogenous variables. This is because technology is approximated through filed patents, which implies that they have been sufficiently developed in order to qualify for the filing process. In the sector-specific estimation, we argue that the relative number of high-skilled workers may be the result of previously determined capital and R&D investments. It is thus put second in the ordering. Energy prices is put third, as it may directly impact on GDP levels as well as CO_2 emissions. GDP is the fourth variable, because it is likely to be contemporaneously impacted through all the previous variables and exerts a direct influence on GHG emissions. CO_2 emissions, however, are directly impacted by policy stringency, the technological level, energy prices as well as GDP. We thus perform the analysis using the ordering of the variables as described in (1). Note that the results prove to be robust against a series of alternative orderings (see discussion in section 6).

In order to analyze the pass-through effect on a variable given an exogenous change of another variable, we estimate impulse response functions. These impulse response functions portray the reaction function of a given variable as a consequence of a one unit orthogonal shock on another endogenous variable. It allows us, in addition to the direct effect of GHG policy stringengy, to see the accumulated overall effect of such a policy stringency change, which also includes the effect on CO_2 via the transmission channels. The corresponding confidence intervals are computed using a bootstrap procedure with 100 iterations.

3.1 Country-specific Analysis: Methodological Approach

The country-specific analysis allows to measure the overall country-specific effect of the stringency of GHG policy. To illustrate the group-heterogeneous aspatial version of (1), the sub-equation with the CO_2 emissions as the endogenous variable writes as follows:

$$\Delta\eta_{it} = \sum_{p=0}^{P} \gamma_{zp}^{\eta\iota} \Delta\iota_{i,t-p} + \sum_{p=0}^{P} \gamma_{zp}^{\eta\tau} \Delta\tau_{i,t-p} + \sum_{p=0}^{P} \gamma_{zp}^{\eta\epsilon} \Delta\epsilon_{i,t-p} + \sum_{p=0}^{P} \gamma_{zp}^{\eta\omega} \Delta\omega_{i,t-p} + \sum_{p=1}^{P} \gamma_{zp}^{\eta\eta} \Delta\eta_{i,t-p} + \sum_{p=0}^{P} X'_{i,t-p}\tilde{\Gamma}_{p}^{\eta x} + \psi_i^{\eta} + \lambda_t^{\eta} + u_t^{\eta} \quad (2)$$

where the indexes i and z denote the country and the group specific coefficient values, respectively. The Δ's indicate that the variables are first-differenced. A similar equation is formulated for all remaining endogenous variables and the system of equation is estimated simultaneously through a full information maximum likelihood.

3.2 Sector-level Analysis: Methodological Approach

We use a sectoral analysis to disentangle the overall effect of environmental policy stringency on CO_2 emissions. This approach allows to assess to what extent the country-wide change in CO_2 emissions is due to sectoral CO_2 efficiency changes, and to what extent it stems from changes in value added of dirty and clean sectors. In the sectoral analysis, the index i in (2) denotes a country-sector. The policy stringency index as well as energy prices remain the same as in the country-specific analysis and are assumed to be identical across all sectors within a country. In addition, neighboring effects are added to (2) to account for possible externalities for a given sector. Value added, technology as well as CO_2 emissions are measured at the sector-country level. The matrix of controls X remains the same as in the country-wide specification. Groups z are defined over 4 different levels of CO_2 emission intensity per country. Each group contains approximatively 290 country-sector units.

4 Integration Properties and Lag Length Selection

A Harris and Tzavalis (1999) panel unit root test (HT test) is used to test for non-stationarity of each of the variables. This test is based on pooled ADF statistics and is consistent with a panel dimension $N \rightarrow \infty$ and a fixed time dimension T.[3] The test is carried out with demeaned cross-sections to account for panel fixed effects, and a common time trend. Results are reported in Table (B1) in the Appendix. For most of the variables in our economy-wide dataset, the null hypothesis of all panels containing a unit root cannot be rejected. We conclude that the GHG policy stringency index as well as the log of technology, GDP, CO_2, corruption, cooling day degrees and heating day degrees have a unit root and proceed by first differencing those variables. Even though the test rejects the null for energy prices, we still proceed by first differencing this vari-

[3] Simulation results of Harris and Tzavalis (1999) indicate that the test has good size and power properties for N greater than 25, a condition which is satisfied in our sample.

able. This is because the nature of the test is such that it remains silent about the proportion of panels that do contain unit roots. In addition, treating all endogenous variables identically facilitates the interpretation of the IRFs. Rerunning a Harris and Tzavalis (1999) test on the differentiated variables confirms the stationarity of the variables with unit roots. We apply the same transformations of the counterparts of those variables in the sector-wide dataset, even though there the HT test rejects the null hypothesis in all variables. This is again justified by the limited information that such tests reveal, and because the country-wide tests hinge towards non-stationarity. Note that we include, for every sub-equation, a panel-specific dummy variable after first differencing, which controls for different average growth rates of all our endogenous variables.

In order to select the panel VAR specifications which achieves the best performance in terms of log likelihood score, a number of alternative temporal lag structures are estimated for each model and the preferred specification is selected on the basis of the evidence provided by the AIC and BIC criteria. Results are reported in Table (B2) in the Appendix. Note that due to the limited time series lengths, the more parsimonious suggestion of AIC and BIC is taken. For all specifications (with one only exception), AIC and BIC criteria both indicate the use of a specification with one temporal lag, for all sub-equations.

5 Results

5.1 Countrywide Semi-elasticity of CO_2 to GHG Policy Stringency

All coefficients of our country-wide baseline specification are displayed in Table (2). We observe a significantly negative direct contemporaneous semi-elasticity of CO_2 with respect to GHG policy stringency of 16.6%. This direct effect on CO_2 reflects, for example, the impact of new or stricter command and control instruments. Given that an increase in stringency is in general preceded by a political debate, such an increase may be anticipated in advance. It is hence little surprising that the effect can be observed contemporaneously.[4] In addition, the direct effect of both GDP and technology on CO_2 are significantly positive. Previous contributions find mixed results on the CO_2-technology relation (for a summary, see Lantz and Feng (2006)). We use a general proxy for technology

[4]We also run an alternative estimation with a forward lag for the GHG policy stringency index to allow for a larger forward looking horizon. See discussion in section 6.

and do not specifically consider green technology. The qualitative results on technology may be justified by the possibility that new technologies might not be less emission intensive than older ones, which would explain why technological development impacts positively on CO_2 emissions.

Table 2: Country Specification with 1 Lag

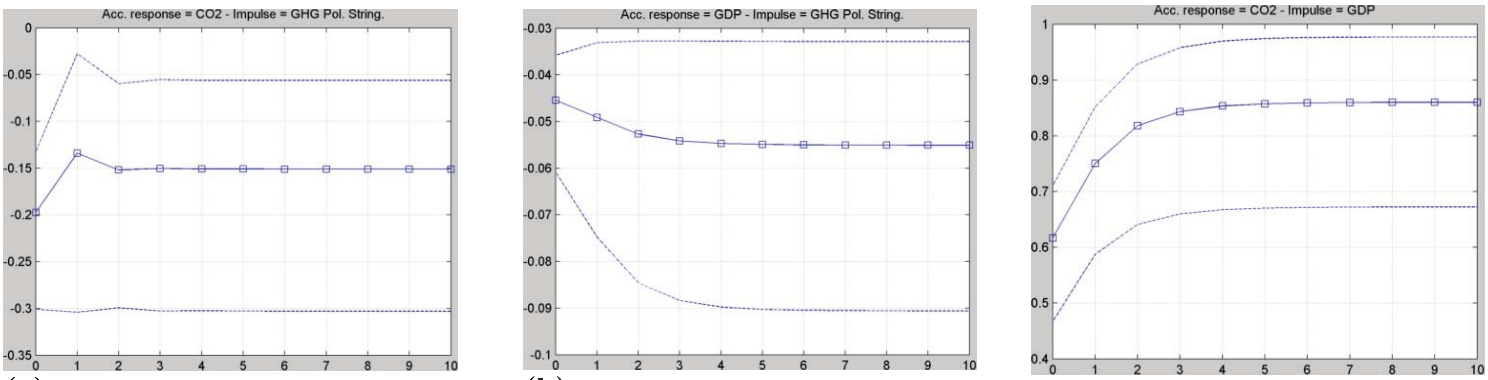
Variable and Statistics	CO2		GDP		Energy Price		Technology		GHG Pol. String.	
	L0	L1	L0	L1	L0	L1	L0	L1	L0	L1
GHG Pol. String.	-0.166***	0.039	-0.044**	0.015	0.045	-0.159***	-0.086	-0.188*	-	-0.019
	(0.004)	(0.511)	(0.012)	(0.370)	(0.352)	(0.001)	(0.444)	(0.093)	-	(0.576)
ln(Technology)	0.027**	0.013	0.012***	0.007*	-0.015	0.010	-	0.020	-	0.003
	(0.014)	(0.235)	(0.004)	(0.077)	(0.160)	(0.353)	-	(0.561)	-	(0.272)
ln(Energy prices)	-0.019	0.033	-0.014	0.007	-	0.034	-	-0.091	-	0.004
	(0.386)	(0.133)	(0.103)	(0.390)	-	(0.312)	-	(0.102)	-	(0.373)
ln(GDP)	0.617***	-0.036	-	0.386***	-	0.050	-	0.069	-	-0.008
	(0.000)	(0.517)	-	(0.000)	-	(0.291)	-	(0.531)	-	(0.466)
ln(CO2)	-	-0.129***	-	0.008	-	-0.060***	-	0.173***	-	0.003
	-	(0.000)	-	(0.381)	-	(0.009)	-	(0.000)	-	(0.642)
ln(Corruption)	-0.003	0.003	0.006	0.003	-0.004	0.006	0.001	-0.013	0.001	-0.001
	(0.795)	(0.787)	(0.206)	(0.531)	(0.722)	(0.592)	(0.950)	(0.453)	(0.695)	(0.788)
ln(CDD)	-0.001	-0.003	0.003***	0.000	-0.004	0.002	-0.007	-0.007	-0.003**	-0.001
	(0.856)	(0.304)	(0.004)	(0.798)	(0.106)	(0.365)	(0.228)	(0.261)	(0.014)	(0.355)
ln(HDD)	0.088***	-0.062***	0.001	0.008	0.054***	-0.020	0.087*	-0.094*	0.001	-0.007**
	(0.000)	(0.005)	(0.950)	(0.373)	(0.002)	(0.260)	(0.061)	(0.053)	(0.688)	(0.044)
Time FE/Country FE	Yes/Yes		Yes/Yes		Yes/Yes		Yes/Yes		Yes/Yes	
Obs.	920		920		920		920		920	
AIC	-4278.15		-5858.61		-4176.63		-2954.85		-6097.26	
BIC	-3907.56		-5492.77		-3815.55		-2598.52		-5745.68	
R2	0.22		0.57		0.10		0.13		0.18	

Column titles indicate the sub-equations. L0: contemporaneous effect, L1: effect from one time lag. * $p<0.1$, ** $p<0.05$, *** $p<0.01$, p-values in parenthesis

Furthermore, we identify the main channels which amplify or curb the observed direct effect of stringency on emissions. As main channel is defined a variable that is both significantly affected by the policy stringency and which significantly affects CO_2 emissions.

We observe a significant negative contemporaneous reaction of GDP to GHG policy stringency and a positive reaction of CO_2 to GDP. GDP can therefore be considered a channel which amplifies the negative effect of policy stringency on CO_2 emissions. This result shows that policy stringency operates partly over a scale effect. In addition, we find evidence for an amplifying technology channel, although less strong than GDP, as policy stringency impacts negatively on technological development and technological development positively affects CO_2 emissions. Thus, a higher GHG policy stringency might slow down overall technological advancement by inhibiting the development of emission intensive technologies, which in turn would explain the decrease in CO_2 emissions.

Figure 1: Impulse Response Functions: Country-wide Specification with 1 Lag, 10% Confidence Interval



(a) Response of CO_2 to a Unit Shock of GHG Pol. String.

(b) Response of GDP to a Unit Shock of GHG Pol. String.

(c) Response of CO_2 to a Unit Shock of GDP

We further compute IRFs to capture the overall effect of an exogenous shock of policy stringency on CO_2.[5] A shock corresponds to a one unit increase in the policy stringency - i.e., passing from zero stringency to the highest observed stringency. Figure (1a) displays the IRF of a positive stringency shock on CO_2. Increasing GHG policy stringency by one unit reduces country CO_2 emissions on average by 15 % in the long run.

In addition, Figure (1b) displays the cumulative pass-through effect of a positive policy stringency shock on GDP and Figure (1c) the cumulative pass-through effect of a positive GDP shock on CO_2. Both Figures illustrate the presence of a scale effect: On the one hand, the effect of a positive stringency shock on *GDP* is significantly negative. And on the other hand, the effect of a positive GDP shock on CO_2 is significantly positive.

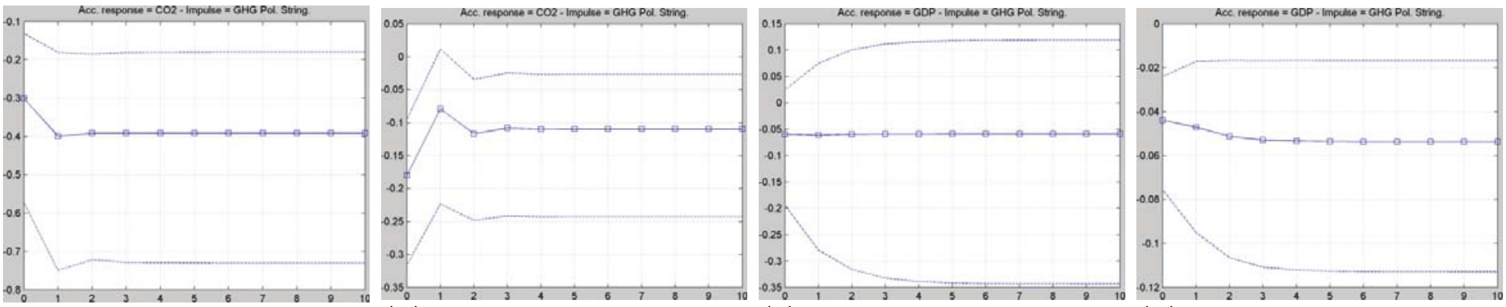
[5]Figure (C1) in Appendix C displays the complete set of IRFs from the CO_2 equation as well all IRFs with GHG policy stringency shocks.

Opportunity Costs of Policy Induced CO_2 Emission Reductions

Figure (1a) and (1b) allow to compare the overall reaction of CO_2 and GDP to a unit shock in GHG policy stringency. Thus, they reveal information about the ex-post average opportunity cost of a tightening of GHG policy stringency. Results suggest that a policy induced CO_2 emissions reduction of 1%, cost on average 0.35% of GDP in the long run. Those opportunity costs are rather high, especially when compared to the numerous ex-ante estimations of the costs of greenhouse gas emission reductions (e.g., Barker et al. (2007), Clarke et al. (2009) or Tavoni and Tol (2010)). Most of those ex-ante modeling approaches assume, however, a cost-effective implementation of greenhouse gas mitigation policies. But, as Leahy and Tol (2012) state: "There is no reason to assume that climate policy would be designed as recommended in an economics textbook. As a result, emission abatement may be considerably more expensive than typically assumed". Some papers assess the cost of specific greenhouse gas policies ex-post and suggest that some existing GHG policies do cost considerably more compared to least cost solutions (e.g., Jenkins (2010) or Leahy and Tol (2012)). Our results confirm this.

We subsequently assess whether there is a difference in the opportunity costs of GHG policies for developing and developed countries. As a developed country, we define those countries whose GDP per capita at the beginning of our measurement period, in 1990, is among the 50% highest. The developing countries are defined to be the remaining ones. For developing countries, Figure (2a) and (2c) reveal that a policy induced CO_2 emission reduction of 1%, costs on average 0.13% of GDP. The opportunity costs are almost 4 times higher for developed countries, as a GHG policy induced 1% CO_2 emission reduction costs on average 0.5% of GDP for those countries as displayed in Figure (2b) and (2d). A result which confirms the frequently advanced argument of relatively cheap abatement opportunities in developing countries. Moreover, the difference in opportunity costs is mostly driven by the significantly stronger negative reaction of CO_2 emissions to a policy shock in developing compared to developed countries. A finding which is consistent with the "low-hanging fruit" argument invoked during the preparation phase of the Kyoto Protocols' Clean Development Mechanism (see for instance Narain and Van't Veld (2008)).

Figure 2: IRFs for a GHG Policy Stringency Shock, Developed vs. developing Countries, 10% Confidence Interval



(a) Response of CO_2: Developing Country

(b) Response of CO_2: Developed Country

(c) Response of GDP: Developing Country

(d) Response of GDP: Developed Country

5.2 Disentangling the Overall Effect: Composition and Technique Effect

There are three potential ways to achieve a country-wide reduction in CO_2 emissions: by reducing the overall scale of production, by increasing the CO_2 efficiency within all or some of the sectors, or by increasing the share of the clean sectors. Our economy-wide results suggest that increased policy stringency reduces the overall scale of production, but remains silent about the two other potential effects. Working with sectoral data and defining group-heterogeneity allows us to separate potential policy induced technique and composition effects. To do so, we define the groups z based on country-specific emission intensity, which is defined by sectoral CO_2 emissions per sectoral value added. The first group contains the cleanest sectors and is labeled "very clean". This group includes sectors whose emission intensities at the beginning of our time period in 1995 are among the lowest 25% in a country. Similarly, the second group (labeled "clean"), third group (labeled "dirty") and fourth group (labeled "very dirty") contain sectors with CO_2 emission intensities between the 25^{th} and 50^{th} percentile, between the 50^{th} and 75^{th} percentile, and amongst the top 25%, respectively. Because this categorization of sectors is performed using a within-country criterium, the labelling of a given sector may differ across countries.
Coefficients from all sub-equations are displayed in Table (C1) and (C1) in the Appendix.

Composition Effect

If GHG policy stringency operates over a composition effect, we expect to observe a significantly different reaction of sectoral value added to GHG policy stringency across the sectoral groups z: The dirty sectors' value added should decrease significantly more than the clean sectors' value added. This is confirmed by the results. We find a significant negative cumulative effect over both time lags of GHG policy stringency on sectoral value added for the very dirty sector group (see Table (3)). The cumulative effects over both lags for the dirty, clean and very clean sector groups are not significant.

Table 3: Composition Effect: Sector Specification

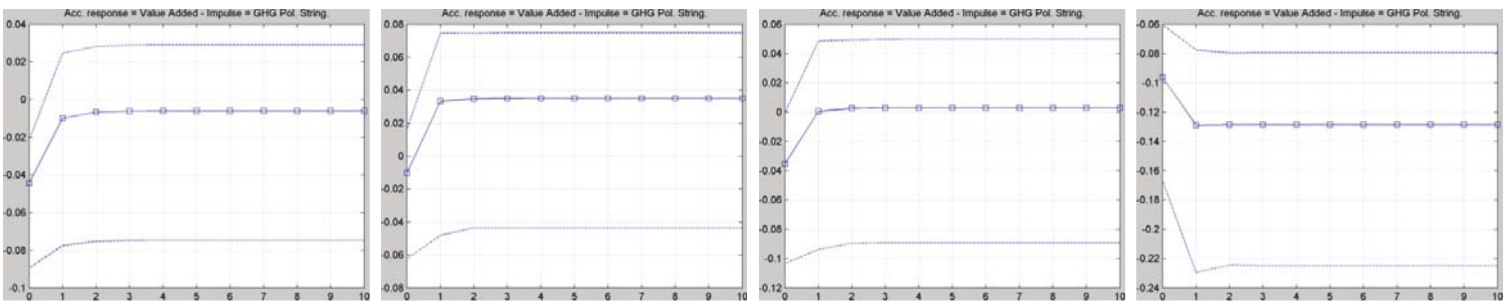
Variable and Statistics	Value Added Equation							
	Very Clean		Clean		Dirty		Very Dirty	
	L0	L1	L0	L1	L0	L1	L0	L1
GHG Pol. String.	-0.043**	0.036*	-0.010	0.044*	-0.035	0.038	-0.099***	-0.025
	(0.041)	(0.094)	(0.682)	(0.082)	(0.262)	(0.249)	(0.007)	(0.504)
ln(Technology)	0.004	0.004	0.005	-0.001	0.002	-0.003	0.007	-0.005
	(0.186)	(0.175)	(0.172)	(0.764)	(0.626)	(0.512)	(0.226)	(0.443)
ln(Energy prices)	-0.041***	-0.000	-0.037***	-0.009	-0.022**	-0.011	0.030**	-0.013
	(0.000)	(0.955)	(0.000)	(0.371)	(0.038)	(0.330)	(0.028)	(0.393)
ln(Value Added)	-	0.149***	-	0.071***	-	0.094***	-	0.028
	-	(0.000)	-	(0.000)	-	(0.000)	-	(0.103)
ln(CO2)	-	0.003	-	0.008**	-	0.013**	-	0.036***
	-	(0.333)	-	(0.023)	-	(0.020)	-	(0.000)
ln(Corruption)	0.002	0.003	0.002	0.003	0.002	0.003	0.002	0.003
	(0.352)	(0.172)	(0.352)	(0.172)	(0.352)	(0.172)	(0.352)	(0.172)
ln(CDD)	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001
	(0.163)	(0.151)	(0.163)	(0.151)	(0.163)	(0.151)	(0.163)	(0.151)
ln(HDD)	-0.003	0.004	-0.003	0.004	-0.003	0.004	-0.003	0.004
	(0.515)	(0.387)	(0.515)	(0.387)	(0.515)	(0.387)	(0.515)	(0.387)
Time FE/Country FE	Yes/Yes							
Obs.	920							
Pseudo R2	0.04							

Column titles indicate the sector groups. L0: contemporaneous effect, L1: effect from one time lag. * $p<0.1$, ** $p<0.05$, *** $p<0.01$, p-values in parenthesis

Furthermore, Table (3) and Table (C1) (Appendix) show that no main channel can be identified as contributing to a differentiated reaction of value added to GHG policy stringency depending on the cleanness of the sectors. However, an interesting result concerns the potential energy price channel. Although GHG policy stringency has no significant cumulative impact on energy prices[6], value added reacts as expected significantly negatively to higher energy prices for the very clean, the clean and the dirty sector group. Higher energy prices, however, increase the value added of the very dirty sector group, a finding which can be related to the presence of energy producing sectors in this group.

The pass-through effects - which are for each group mostly driven by the direct effect of stringency on sectoral value added - confirm the existence of a policy induced composition effect. The IRFs relevant for this discussion are displayed in Figure (3). The complete set of IRFs from the CO_2 equation as well all IRFs with GHG policy stringency shocks are shown in Figures (C2), (C3), (C4) and (C5) in the Appendix. The long run pass-through effect of a unit shock of GHG policy stringency on value added for the very clean, the clean and the dirty group are not significantly different from zero. But the one for the very dirty group is significantly negative and different from the very clean and clean sector groups.

Figure 3: IRF's for a GHG Policy Stringency Shock on Sectoral Value Added, 10% Confidence Interval



(a) Very clean sectors **(b)** Clean sectors **(c)** Dirty sectors **(d)** Very dirty sectors

Results provide therefore evidence pointing towards the existence of a policy induced composition effect: a stricter GHG policy regime does alter the composition of clean and dirty sectors. It does so by reducing the value added of very dirty sectors, while not significantly affecting the value added of the other groups.

[6]See section 7 for a discussion of this result

Technique Effect

If increased GHG policy stringency raises CO_2 efficiency of sectors, we expect to find a negative effect of stringency on the sectoral CO_2 coefficients. As Table (4) suggests, a policy induced technique effect is present for all sectors. Those direct effects of stricter policies - potentially operating over stricter command and control instruments - lower CO_2 intensity in all sector groups and can thus be interpreted as classical technique effects, i.e., all other things - including sectoral value added - equal, an increase in stringency lowers sectoral CO_2. This effect presents a lower bound of the technique effect, as we also hold constant the technology and energy channel, two channels which potentially contribute to the technique effect.

Table 4: Technique Effect: Sector Specification

Variable and Statistics	CO_2 Equation							
	Very Clean		Clean		Dirty		Very Dirty	
	L0	L1	L0	L1	L0	L1	L0	L1
GHG Pol. String.	-0.271***	0.023	-0.197***	0.030	-0.082*	0.017	-0.176***	-0.017
	(0.000)	(0.653)	(0.000)	(0.543)	(0.088)	(0.736)	(0.000)	(0.722)
ln(Technology)	0.001	0.008	0.011*	0.014**	0.010*	-0.002	0.004	-0.005
	(0.842)	(0.271)	(0.079)	(0.023)	(0.090)	(0.703)	(0.419)	(0.366)
ln(Energy prices)	-0.111***	-0.059***	-0.073***	-0.057***	-0.087***	-0.063***	-0.009	-0.012
	(0.000)	(0.003)	(0.000)	(0.002)	(0.000)	(0.001)	(0.600)	(0.503)
ln(Value Added)	0.102***	0.036**	0.110***	0.068***	0.079***	0.002	0.064***	0.042***
	(0.000)	(0.025)	(0.000)	(0.000)	(0.000)	(0.810)	(0.000)	(0.000)
ln(CO2)	-	-0.079***	-	-0.097***	-	-0.080***	-	-0.051***
	-	(0.000)	-	(0.000)	-	(0.000)	-	(0.003)
ln(Corruption)	-0.019***	-0.017***	-0.019***	-0.017***	-0.019***	-0.017***	-0.019***	-0.017***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
ln(CDD)	0.006***	-0.005***	0.006***	-0.005***	0.006***	-0.005***	0.006***	-0.005***
	(0.000)	(0.001)	(0.000)	(0.001)	(0.000)	(0.001)	(0.000)	(0.001)
ln(HDD)	0.011	-0.008	0.011	-0.008	0.011	-0.008	0.011	-0.008
	(0.205)	(0.349)	(0.205)	(0.349)	(0.205)	(0.349)	(0.205)	(0.349)
Time FE/Country FE	Yes/Yes							
Obs.	920							
Pseudo R2	0.09							

Column titles indicate the sector groups. L0: contemporaneous effect, L1: effect from one time lag. * $p<0.1$, ** $p<0.05$, *** $p<0.01$, p-values in parenthesis

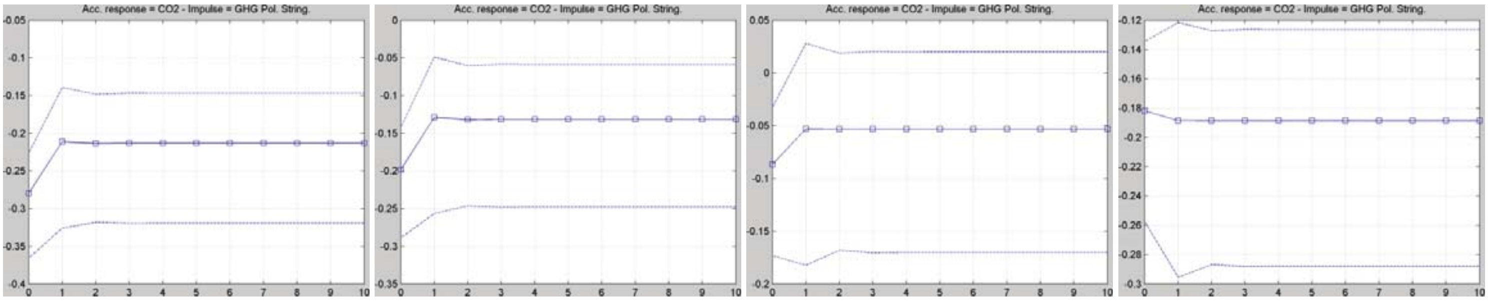
Moreover, we can identify some tendency: the cleaner a sector group, the stronger the negative effect of GHG policy stringency on CO_2 emissions (with the exception of the dirty sector group). Note that this result does not imply that absolute average abatement due to the technique effect is highest in the clean sector groups. On the contrary, given that average group CO_2 emissions are considerably higher in the very dirty sector group, absolute abatement due to the direct effect is highest in this group despite the fact that cleaner sectors display a stronger negative reaction. The latter result can be explained by two complementary arguments. It may be very costly and technically difficult to increase CO_2 efficiency in heavily CO_2 intensive sectors such as energy producing sectors. If technical difficulties and costs are high enough, firms in dirty sectors may prefer to relocate production instead of complying with regulation. Our results from the composition effect analysis supports this argument. On the other hand, firms in cleaner sectors may not need to change central parts of their production technology but can substitute inputs (such as non-renewable energy) more readily to comply with regulations. Additionally, a second - policy related - argument can be made. The regulation of GHGs started well before 1995 targeting initially CO_2 intensive sectors, only later in time regulation included also rather clean sectors. Thus, as our sectoral sample starts only in 1995, it is possible that we do not capture initial policy induced technique effects in very dirty sectors.

5.3 The Sectoral Overall Effect: A Combination of Composition and Technique Effect

Given that an increase in GHG policy stringency alters the composition of sectors and increases the CO_2 efficiency of all sectors, it is interesting to analyze the overall effect of policy stringency on sectoral CO_2 emissions. Figure (4) displays the pass-through effects capturing the joint impact of direct and indirect effects of GHG policy stringency on emissions. For the very clean group, the pass-through effect is roughly -2.1% and significant. The one for the second group is about -1.4% and significant. The one for the third group is roughly -0.5 % but not significant. At last, the pass-through effect for very dirty sectors is approximately -1.9% and also significant.

Given that CO_2 reacts positively to value added for all groups, the composition effect acts as an important channel in the very dirty sector group, which amplifies the impact from the technique effect on CO_2 emissions considerably.

Figure 4: IRF's for a GHG Policy Stringency Shock on CO2, 10% Confidence Intervals



(a) Very clean sectors **(b)** Clean sectors **(c)** Dirty sectors **(d)** Very dirty sectors

6 Robustness

We conduct an extensive robustness check including different specifications, using a different dataset, a different environmental policy stringency index, as well as using a spatial variant of the DiGiacinto model.

6.1 Countrywide Robustness Results: Alternative Data, Forward Lag and Spatial Specification

In a first step, we assess the robustness of our results to different data. Firstly, we use the baseline dataset and replace the GHG policy stringency variable by the one provided by the WEF (see Browne et al. (2012)). Our main results - the negative impact of GHG policy stringency on CO_2 and GDP - stay qualitatively the same (cf. Table (D1) in Appendix D). Secondly, we aggregate our sector-specific dataset to produce an alternative economy-wide dataset and re-estimate the baseline model. Again, our two main results are robust (c.f. Table (D2) in Appendix D.).

In a second step, we estimate a spatial version of the baseline model. By doing so, we additionally control for externalties such as changes in the demand from trading partners. We rely upon aggregated trade data from the UN Comtrade Database (2015) to construct the W matrix. This matrix essentially defines which countries are considered as neighbors. For each country, we define as a neighbor one of the 5 countries which have the highest import share with respect to the country under consideration. An import share is defined as being total imports by a foreign country over total value added of the country under consideration. The results are robust when controlling for such externalities (c.f. Table (D3) in Appendix D.).

Finally, a VAR estimation may typically be criticized for its dependence on the variable ordering. Hence, we estimate specifications with our baseline lag length using different orderings of the endogenous variables. Besides the ordering described in equation (1), we test all five alternative orderings one obtains by varying the positions of gdp, technology and energy prices. All results remain robust both qualitatively and quantitatively (c.f. Tables (E1)-(E5) in Appendix E). Lastly, we introduce a forward lag for GHG policy stringency to allow for a larger potential forward looking horizon. Results indicate that no significant changes happen to all variables at the lead of a GHG policy stringency change, and that results for the lags are qualitatively identical, and quantitatively similar as in the baseline model (c.f. Table (E6) in Appendix E).

6.2 Sectoral Robustness Results: Different Group Definitions and Spatial Specification

Not only the country-wide but also the sectoral results are robust to any specification. First, we estimate a spatial version of the sectoral baseline model. By doing so, we additionally control for externalities such as changes in the demand for input goods of trade partners. We use trade flow data from the input output matrix provided by the World Input-Output Database (2012) to define the W matrix. For each sector in a given country, we define as a neighbor one of the 20 sectors from any other country which have the highest import share with respect to the sector under consideration. Note that sectors within the same country are not considered neighbors. This is because we use country-wide policy stringency measures and energy price levels. An import share is defined as being total imports by a sector in a foreign country over total value added of the sector under consideration. Coefficients of all sub-equations are displayed in Table (D4) in Appendix D. We find again strong evidence for the existence of a policy induced composition effect, as value added of very dirty sectors reacts significantly negatively to stringency while the one from the other groups does not show a significant reaction. Evidence suggests as well that more stringent GHG policy regimes increase CO_2 efficiency in all sector groups.

In addition, we test the use of a different grouping structure with two and three groups instead of four. Again, the main results stay qualitatively the same: as a reaction to a policy shock, value added of rather dirty sectors decreases significantly while the value added of rather clean sectors does not react significantly differently from zero. In addition, we also find consistent evidence for the existence of a technique effect, and this effect is stronger the cleaner the sector group (c.f. Tables (E7) and (E8) in Appendix E). Finally, using the same grouping structure, we test specifications with the 5 alternative orderings as we did for the country-wide specification, results remain robust (c.f. Tables (E9)-(E13) in Appendix E).

7 Discussion

By using a relatively large panel dataset including countries responsible for roughly 71 % of the world's CO_2 emissions over the sample period, a new GHG policy stringency indicator and a structural spatial panel VAR approach, we are able to avoid several limitations of earlier contributions attempting to measure policy induced CO_2 emission reductions. Our results from the country-wide analysis show that increasing the stringency of a country's GHG policy regime does reduce its CO_2 emissions, which is good news from a national environmental policy perspective. In addition, a country with no GHG regulations could achieve a 15% reduction of its' CO_2 emissions by adopting the stringency level of the most stringent country in the sample. Our results also reveal the existence of a policy induced scale effect, as national GHG policy stringency impacts negatively on a country's GDP. Opportunity costs of policy induced CO_2 reductions in terms of GDP are relatively high, but 4 times lower for developing countries compared to developed countries. Being robust to alternative specifications, a different environmental policy stringency variable, as well as to a different dataset, those results confirm and extend the fragmented evidence of earlier contributions (cf. Esty and Porter (2005)).

A sectoral analysis then allows to disentangle the overall effect of GHG policy stringency and shows the existence of a policy induced composition and technique effect. Increasing the stringency of a GHG policy regime alters the composition of dirty and clean sectors in an economy. It does so by decreasing the size of the dirtiest 25% of sectors while not significantly impacting on the production scale of cleaner sectors. Moreover, increasing GHG policy stringency improves CO_2 efficiency in sectors. This technique effect is present for all sector groups. Those results are also robust to different specifications and when controlling for externalities, such as changes in a trade partners' demand for input goods. From a global perspective, the existence of a policy induced technique effect is desirable, as reducing CO_2 intensities of dirty sectors is beneficial for the climate. A more nuanced statement has to be made when it comes to the policy induced composition effect. If the composition effect is mainly due to absolute reduction of the production in highly CO_2 intensive sectors, it would be beneficial for the global climate system. If, however, production relocation accounts for the main bulk of the composition effect, then it is unclear to which extent this effect of a stricter policy regime decreases global GHG emissions, if at all. Additional research is needed to analyze how exactly the composition effect is achieved. Should further research confirm that the policy induced composition effect is mainly due to production relocation, a global - instead of national - policy response is indispensable. The latter argument would additionally reinforce the frequently advanced call for a global policy response due to the inherent global public good nature of the problem at hand (see for instance: IPCC (2001)).

An interesting additional result concerns the energy price channel, one out of several channels over which GHG policies could potentially operate. Country-wide results show that GDP and CO_2 both react negatively to a change in energy prices. Sector-level results suggest that the same holds for all except the dirtiest sector group in the sample. GHG policy stringency, on the other hand, does not seem to raise energy prices. A possible explanation is that international competitiveness concerns dominate policy makers' decisions and lead them to not or only sparely design policies operating over increased energy prices.

In short, our results indicate that by increasing the stringency of GHG policy regimes, policy efforts can reduce national CO_2 emissions up to a certain extent. Prospects are therefore encouraging that one can limit the rate and magnitude of climate change and thereby reduce climate change induced risks as advocated by IPCC (2014a). However, the presence of a policy induced composition effect might limit the extent to which global emissions are reduced by national policies. This would be especially true if emission outsourcing is found to be the main driver of this composition effect. On the other hand, it seems as if policy makers have so far been reluctant to design policies operating over increased energy prices. A finding which suggests that by using this channel more extensively, there might still be scope for further CO_2 emission reductions in the future. Such policies would, however, have to be carefully designed and should take into account the heterogeneous response of sector value added and CO_2.

Appendix A: Policy Stringency Index, Country Coverage and Sector Coverage

Figure A1: GHG Policy Stringency Index

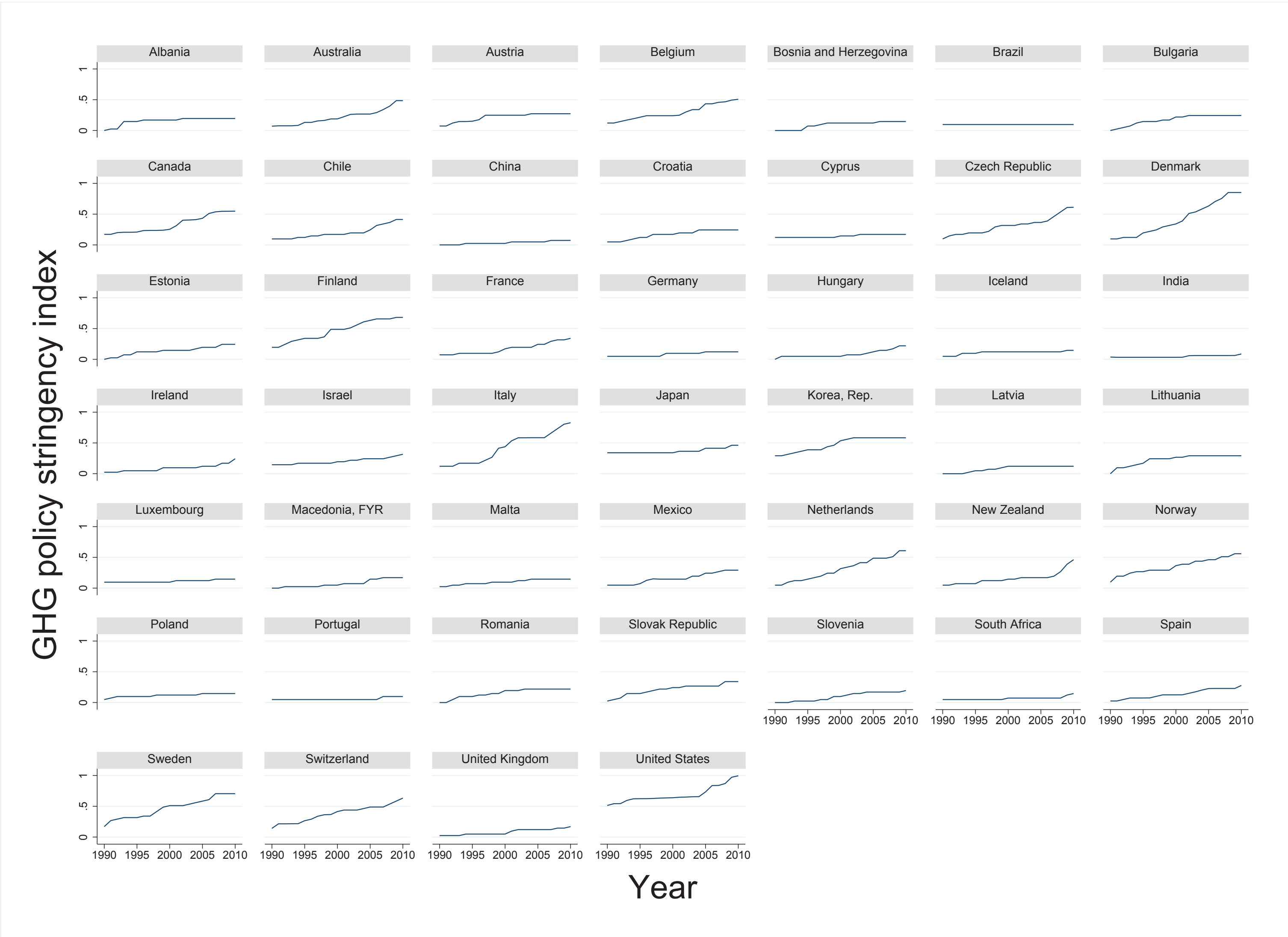


Table A1: Countries and Sectors

Country-wide Specification	**Sector Specification**		
Countries	**Countries**	**Sectorcode**	**Sector description**
Albania	Australia	15t16	Food, beverages and tobacco
Australia	Austria	17t18	Textiles and textile
Austria	Belgium	19	Leather, leather and footwear
Belgium	Brazil	20	Wood and Cork
Bosnia and Herzegovina	Bulgaria	21t22	Pulp, paper, printing and publishing
Brazil	Canada	23	Coke, refined petroleum and nuclear fuel
Bulgaria	China	24	Chemicals and chemical
Canada	Cyprus	25	Rubber and plastics
Chile	Czech Republic	26	Other non-metallic minerals
China	Denmark	27t28	Basic metals and fabricated metals
Croatia	Estonia	29	Machinery, NEC
Cyprus	Finland	30t33	Electrical and optical equipment
Czech Republic	France	34t35	Transport equipment
Denmark	Germany	36t37	Manufactruing NEC, Recycling
Estonia	Hungary	50	Sale, maintenance and repair of motor vehicles and motorcycles; retail sale of fuel
Finland	India	51	Wholesale trade and commission trade, except of motor vehicles and motorcycles
France	Ireland	52	Retail trade, except of motor vehicles and motorcycles; repair of household goods
Germany	Italy	60	Other Inland transport
Hungary	Japan	61	Other Water transport
Iceland	Korea	62	Other Air transport
India	Latvia	63	Other Supporting and auxiliary transport activities; activities of travel agencies
Ireland	Lithuania	64	Post and telecommunications
Israel	Luxembourg	70	Real estate activities
Italy	Malta	71t74	Renting of m&eq and other business activities
Japan	Mexico	AtB	Agriculture, hunting, forestry and fishing
Korea, Rep.	Netherlands	C	Mining and quarrying
Latvia	Poland	E	Electricity, gas and water supply
Lithuania	Portugal	F	Construction
Luxembourg	Romania	H	Hotels and restaurants
Macedonia, FYR	Slovak Republic	J	Financial intermediation
Malta	Slovenia	L	Public admin and defence, compulsory social security
Mexico	Spain	M	Education
Netherlands	Sweden	N	Health and social work
New Zealand	United Kingdom	O	Other community, social and personal services
Norway			
Poland			
Portugal			
Romania			
Slovak Republic			
Slovenia			
South Africa			
Spain			
Sweden			
Switzerland			
United Kingdom			
United States			

Appendix B: Preliminary Test Results

Table B1: Harris Tzavalis Test Statistics:

Variable	P-value
ln(CO2)	0.4842
ln(Sectoral CO2)	0.000
ln(GDP)	0.9868
ln(Sectoral GDP)	0.0000
ln(Technology)	0.9955
ln(Sectoral Technology)	0.0000
ln(Energy price)	0.0000
GHG Pol. String.	0.9871
ln(Corruption)	0.3528
ln(CDD)	0.000
ln(HDD)	0.000
H0: All panels contain a unit root	

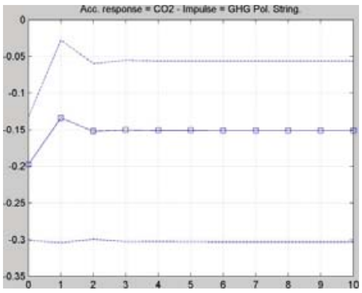
Table B2: Lag Length Selection: AIC BIC by Equation

Country-wide Analysis										
Nb. of Lags	CO2 Equ.		GDP Equ.		Energy Price Equ.		Technology Equ.		GHG Pol. String. Equ.	
	AIC	BIC	AIC	BIC	AIC	BIC	AIC	BIC	AIC	BIC
1 Lag	-4278.15	-3907.56*	-5858.61*	-5492.77*	-4176.63*	-3815.55*	-2954.85*	-2598.52*	-6097.26*	-5745.68*
2 Lags	-4192.1	-3788.16	-5611.34	-5212.09	-3936.09	-3541.54	-2978.8	-2588.95	-5787.15	-5401.99
3 Lags	-4286.53*	-3850.39	-5343.87	-4912.36	-4148.87	-3722	-2887.38	-2465.15	-5686.48	-5268.89
1 Lead/1 Lag	-4211.12	-3807.17	-5609.64	-5210.39	-3936.76	-3542.21	-2980.65	-2590.79	-5757.65	-5372.49
Sector Analysis										
Nb. of Lags	CO2 Equ.		GDP Equ.		Energy Price Equ.		Technology Equ.		GHG Pol. String. Equ.	
	AIC	BIC	AIC	BIC	AIC	BIC	AIC	BIC	AIC	BIC
1 Lag	-52183.79*	-42923.08*	-66561.19*	-57330.96*	-79661.74*	-70462*	-49621.22*	-40451.97*	-117878.4*	-108739.63*
2 Lags	-50976.3	-38943.62	-61282.9	-52876.31	-76255.6	-68122	-48792.7	-39763.11	-112967.19	-107242.95
1 Lead/1 Lag	-48671.26	-39334.33	-61779.3	-52472.52	-73764.3	-64487.7	-47236	-39219.23	-110506.37	-101290.12

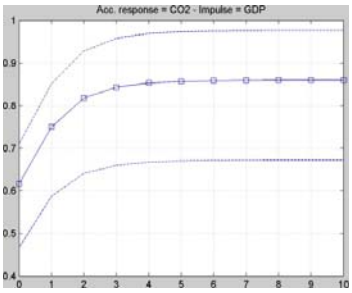
* Indicates the preferred specification by AIC or BIC

Appendix C: Main Results - IRFs and Coefficients

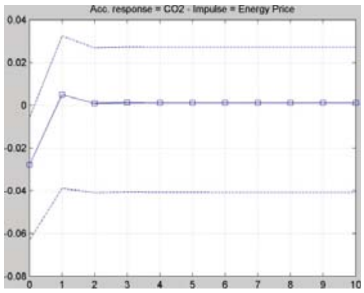
Figure C1: Impulse Response Functions: Homogeneous Country-wide Specification with 1 Lag



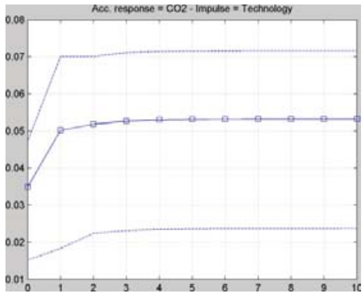
(a) CO_2 - GHG Pol. String.



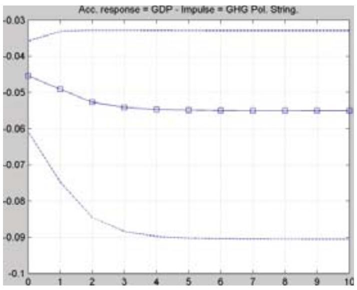
(b) CO_2 - Value Added



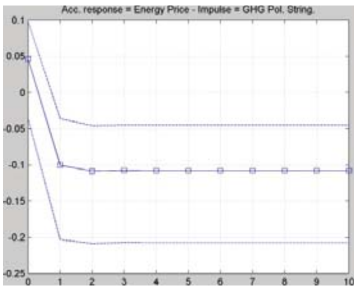
(c) CO_2 - Energy Prices



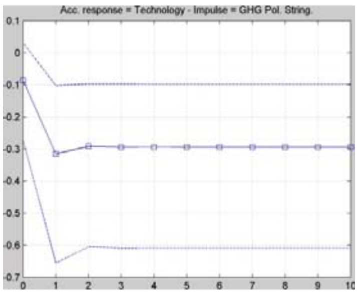
(d) CO_2 - Technology



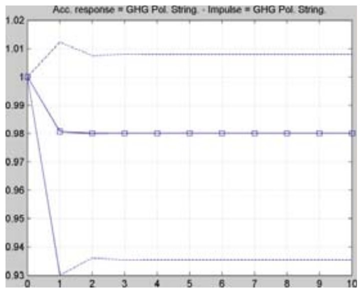
(e) Value Added - GHG Stringency



(f) Energy Prices - GHG Stringency



(g) Technology - GHG Stringency



(h) GHG Stringency - GHG Stringency

Note: The first variable in the caption corresponds to the response variable, whereas the second variable corresponds to the impulse variable. 10 % confidence intervals.

Table C1: Sector Specification with 1 Lag (Continued on Next Page)

Variable and Statistics	CO2 Equation							
	Very Clean		Clean		Dirty		Very Dirty	
	L0	L1	L0	L1	L0	L1	L0	L1
GHG Pol. String.	-0.271***	0.023	-0.197***	0.030	-0.082*	0.017	-0.176***	-0.017
	(0.000)	(0.653)	(0.000)	(0.543)	(0.088)	(0.736)	(0.000)	(0.722)
ln(Technology)	0.001	0.008	0.011*	0.014**	0.010*	-0.002	0.004	-0.005
	(0.842)	(0.271)	(0.079)	(0.023)	(0.090)	(0.703)	(0.419)	(0.366)
ln(Energy prices)	-0.111***	-0.059***	-0.073***	-0.057***	-0.087***	-0.063***	-0.009	-0.012
	(0.000)	(0.003)	(0.000)	(0.002)	(0.000)	(0.001)	(0.600)	(0.503)
ln(Value Added)	0.102***	0.036**	0.110***	0.068***	0.079***	0.002	0.064***	0.042***
	(0.000)	(0.025)	(0.000)	(0.000)	(0.000)	(0.810)	(0.000)	(0.000)
ln(CO2)	-	-0.079***	-	-0.097***	-	-0.080***	-	-0.051***
	-	(0.000)	-	(0.000)	-	(0.000)	-	(0.003)
ln(Corruption)	-0.019***	-0.017***	-0.019***	-0.017***	-0.019***	-0.017***	-0.019***	-0.017***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
ln(CDD)	0.006***	-0.005***	0.006***	-0.005***	0.006***	-0.005***	0.006***	-0.005***
	(0.000)	(0.001)	(0.000)	(0.001)	(0.000)	(0.001)	(0.000)	(0.001)
ln(HDD)	0.011	-0.008	0.011	-0.008	0.011	-0.008	0.011	-0.008
	(0.205)	(0.349)	(0.205)	(0.349)	(0.205)	(0.349)	(0.205)	(0.349)
Time FE/Country FE	Yes/Yes							
Obs.	920							
Pseudo R2	0.09							

Variable and Statistics	Value Added Equation							
	Very Clean		Clean		Dirty		Very Dirty	
	L0	L1	L0	L1	L0	L1	L0	L1
GHG Pol. String.	-0.043**	0.036*	-0.010	0.044*	-0.035	0.038	-0.099***	-0.025
	(0.041)	(0.094)	(0.682)	(0.082)	(0.262)	(0.249)	(0.007)	(0.504)
ln(Technology)	0.004	0.004	0.005	-0.001	0.002	-0.003	0.007	-0.005
	(0.186)	(0.175)	(0.172)	(0.764)	(0.626)	(0.512)	(0.226)	(0.443)
ln(Energy prices)	-0.041***	-0.000	-0.037***	-0.009	-0.022**	-0.011	0.030**	-0.013
	(0.000)	(0.955)	(0.000)	(0.371)	(0.038)	(0.330)	(0.028)	(0.393)
ln(Value Added)	-	0.149***	-	0.071***	-	0.094***	-	0.028
	-	(0.000)	-	(0.000)	-	(0.000)	-	(0.103)
ln(CO2)	-	0.003	-	0.008**	-	0.013**	-	0.036***
	-	(0.333)	-	(0.023)	-	(0.020)	-	(0.000)
ln(Corruption)	0.002	0.003	0.002	0.003	0.002	0.003	0.002	0.003
	(0.352)	(0.172)	(0.352)	(0.172)	(0.352)	(0.172)	(0.352)	(0.172)
ln(CDD)	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001
	(0.163)	(0.151)	(0.163)	(0.151)	(0.163)	(0.151)	(0.163)	(0.151)
ln(HDD)	-0.003	0.004	-0.003	0.004	-0.003	0.004	-0.003	0.004
	(0.515)	(0.387)	(0.515)	(0.387)	(0.515)	(0.387)	(0.515)	(0.387)
Time FE/Country FE	Yes/Yes							
Obs.	920							
Pseudo R2	0.04							

Variable and Statistics	Energy Price Equation							
	Very Clean		Clean		Dirty		Very Dirty	
	L0	L1	L0	L1	L0	L1	L0	L1
GHG Pol. String.	0.035*	-0.063***	0.035**	-0.061***	0.034*	-0.061***	0.040**	-0.051***
	(0.057)	(0.001)	(0.043)	(0.001)	(0.064)	(0.001)	(0.025)	(0.005)
ln(Technology)	0.007**	0.024***	0.007**	0.024***	0.007**	0.025***	0.007**	0.025***
	(0.023)	(0.000)	(0.015)	(0.000)	(0.026)	(0.000)	(0.028)	(0.000)
ln(Energy prices)	-	0.058***	-	0.057***	-	0.056***	-	0.055***
	-	(0.000)	-	(0.000)	-	(0.000)	-	(0.000)
ln(Value Added)	-	0.002	-	0.003	-	0.011**	-	0.003
	-	(0.705)	-	(0.673)	-	(0.027)	-	(0.185)
ln(CO2)	-	-0.004*	-	0.001	-	-0.001	-	-0.004
	-	(0.090)	-	(0.833)	-	(0.769)	-	(0.331)
ln(Corruption)	-0.002	0.027***	-0.002	0.027***	-0.002	0.027***	-0.002	0.027***
	(0.275)	(0.000)	(0.275)	(0.000)	(0.275)	(0.000)	(0.275)	(0.000)
ln(CDD)	-0.002***	0.006***	-0.002***	0.006***	-0.002***	0.006***	-0.002***	0.006***
	(0.002)	(0.000)	(0.002)	(0.000)	(0.002)	(0.000)	(0.002)	(0.000)
ln(HDD)	0.071***	0.008	0.071***	0.008	0.071***	0.008	0.071***	0.008
	(0.000)	(0.110)	(0.000)	(0.110)	(0.000)	(0.110)	(0.000)	(0.110)
Time FE/Country FE	Yes/Yes							
Obs.	920							
Pseudo R2	0.17							

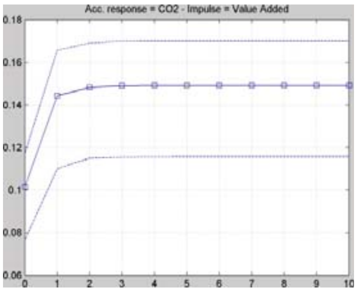
Column titles indicate the sector groups. L0: contemporaneous effect, L1: effect from one time lag. * $p<0.1$, ** $p<0.05$, *** $p<0.01$, p-values in parenthesis

Table C1: Sector Specification with 1 Lag (Continued)

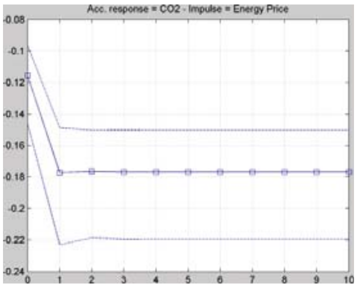
Variable and Statistics	Technology Equation							
	Very Clean		Clean		Dirty		Very Dirty	
	L0	L1	L0	L1	L0	L1	L0	L1
GHG Pol. String.	0.126***	0.047	0.163***	0.012	0.159***	0.033	0.126***	0.043
	(0.009)	(0.372)	(0.000)	(0.815)	(0.001)	(0.522)	(0.005)	(0.384)
ln(Technology)	-	-0.082***	-	-0.086***	-	-0.086***	-	-0.090***
	-	(0.000)	-	(0.000)	-	(0.000)	-	(0.000)
ln(Energy prices)	-	-0.016	-	-0.013	-	-0.018	-	-0.012
	-	(0.220)	-	(0.283)	-	(0.174)	-	(0.329)
ln(Value Added)	-	-0.026**	-	-0.060***	-	-0.032**	-	-0.003
	-	(0.030)	-	(0.000)	-	(0.012)	-	(0.657)
ln(CO2)	-	0.010*	-	-0.004	-	-0.022***	-	0.006
	-	(0.093)	-	(0.517)	-	(0.006)	-	(0.329)
ln(Corruption)	-0.017***	0.012***	-0.017***	0.012***	-0.017***	0.012***	-0.017***	0.012***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
ln(CDD)	0.022***	0.015***	0.022***	0.015***	0.022***	0.015***	0.022***	0.015***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
ln(HDD)	-0.035***	0.030***	-0.035***	0.030***	-0.035***	0.030***	-0.035***	0.030***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Time FE/Country FE	Yes/Yes							
Obs.	920							
Pseudo R2	0.08							
Variable and Statistics	GHG Policy Stringency Equation							
	Very Clean		Clean		Dirty		Very Dirty	
	L0	L1	L0	L1	L0	L1	L0	L1
GHG Pol. String.	-	-0.060***	-	-0.060***	-	-0.058***	-	-0.042***
	-	(0.000)	-	(0.000)	-	(0.000)	-	(0.007)
ln(Technology)	-	-0.004***	-	-0.004***	-	-0.004***	-	-0.004***
	-	(0.000)	-	(0.000)	-	(0.000)	-	(0.000)
ln(Energy prices)	-	0.010***	-	0.010***	-	0.010***	-	0.010***
	-	(0.000)	-	(0.000)	-	(0.000)	-	(0.000)
ln(Value Added)	-	0.000	-	-0.000	-	-0.000	-	-0.000
	-	(0.956)	-	(0.968)	-	(0.746)	-	(0.938)
ln(CO2)	-	-0.000	-	-0.000	-	0.000	-	0.000
	-	(0.787)	-	(0.793)	-	(0.730)	-	(0.995)
ln(Corruption)	0.002***	0.000	0.002***	0.000	0.002***	0.000	0.002***	0.000
	(0.000)	(0.271)	(0.000)	(0.271)	(0.000)	(0.271)	(0.000)	(0.271)
ln(CDD)	-0.002***	0.000	-0.002***	0.000	-0.002***	0.000	-0.002***	0.000
	(0.000)	(0.410)	(0.000)	(0.410)	(0.000)	(0.410)	(0.000)	(0.410)
ln(HDD)	0.003***	-0.001*	0.003***	-0.001*	0.003***	-0.001*	0.003***	-0.001*
	(0.000)	(0.054)	(0.000)	(0.054)	(0.000)	(0.054)	(0.000)	(0.054)
Time FE/Country FE	Yes/Yes							
Obs.	920							
Pseudo R2	0.25							

Column titles indicate the sector groups. L0: contemporaneous effect, L1: effect from one time lag. * p<0.1, ** p<0.05, *** p<0.01, p-values in parenthesis

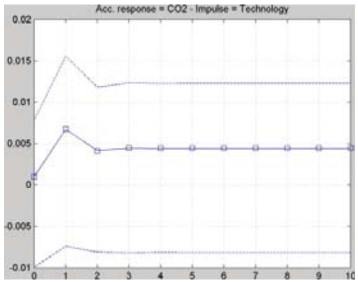
Figure C2: Impulse Response Functions Very Clean Sector



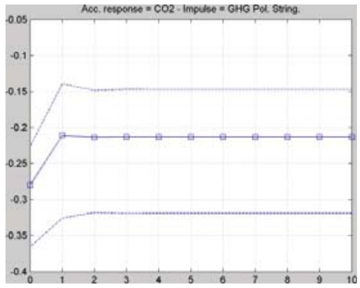
(a) CO_2 - Value Added



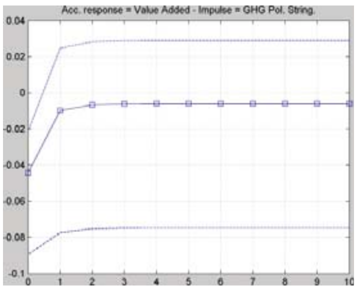
(b) CO_2 - Energy Prices



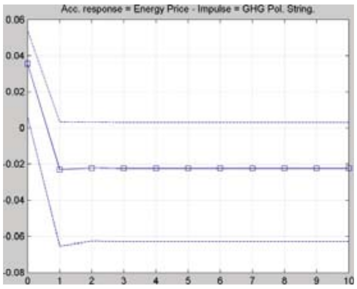
(c) CO_2 - Technology



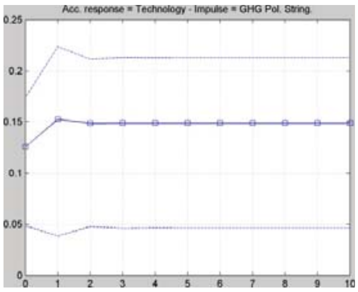
(d) CO_2 - GHG Stringency



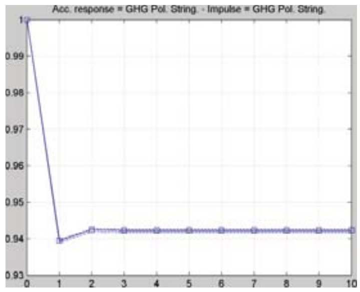
(e) Value Added - GHG Stringency



(f) Energy Prices - GHG Stringency



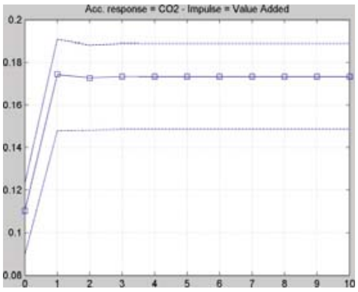
(g) Technology - GHG Stringency



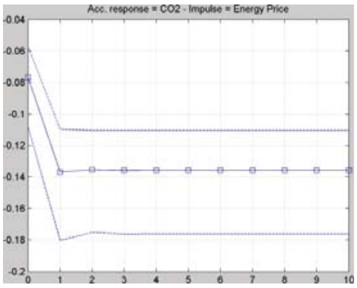
(h) GHG Stringency - GHG Stringency

Note: The first variable in the caption corresponds to the response variable, whereas the second variable corresponds to the impulse variable. 10% confidence intervals.

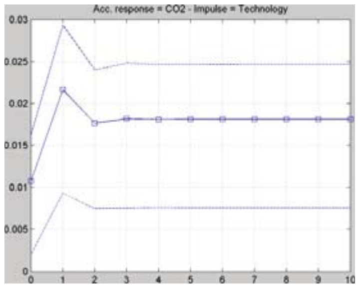
Figure C3: Impulse Response Functions Clean Sector



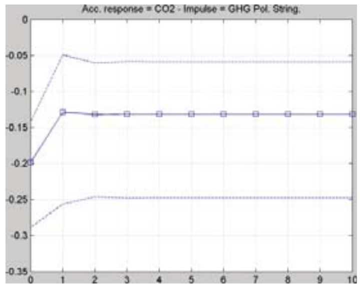
(a) CO_2 - Value Added



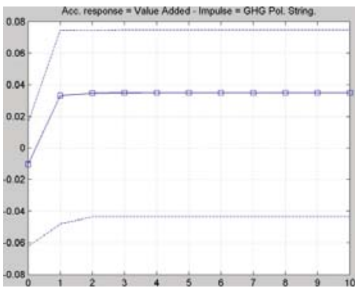
(b) CO_2 - Energy Prices



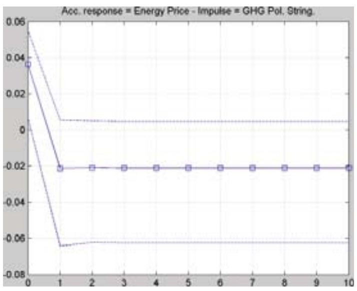
(c) CO_2 - Technology



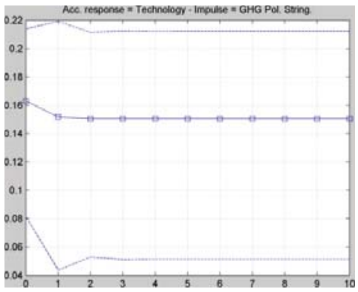
(d) CO_2 - GHG Stringency



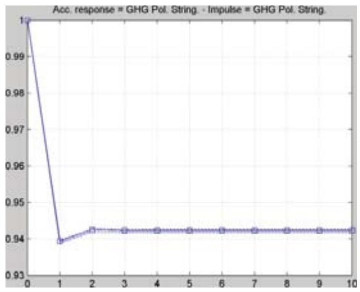
(e) Value Added - GHG Stringency



(f) Energy Prices - GHG Stringency



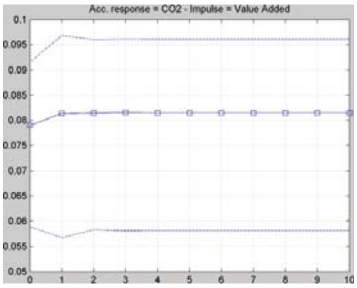
(g) Technology - GHG Stringency



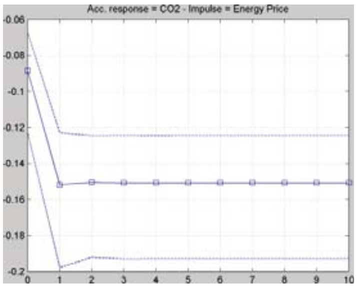
(h) GHG Stringency - GHG Stringency

Note: The first variable in the caption corresponds to the response variable, whereas the second variable corresponds to the impulse variable. 10% confidence intervals.

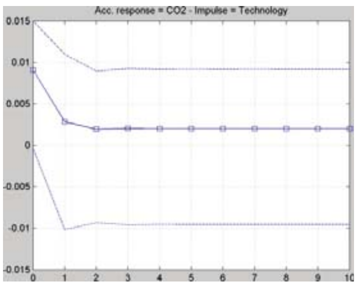
Figure C4: Impulse Response Functions Dirty Sector



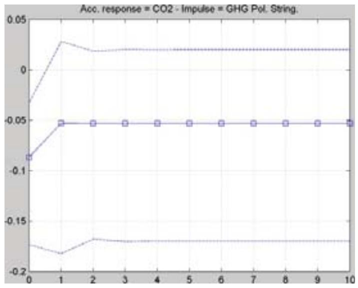
(a) CO_2 - Value Added



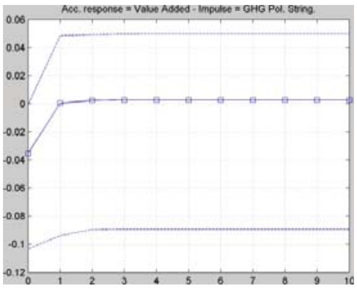
(b) CO_2 - Energy Prices



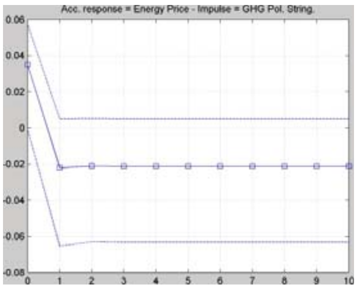
(c) CO_2 - Technology



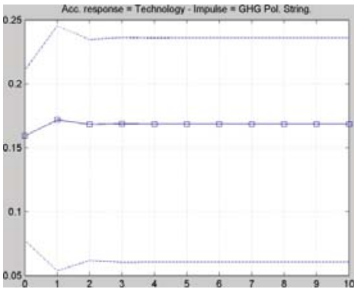
(d) CO_2 - GHG Stringency



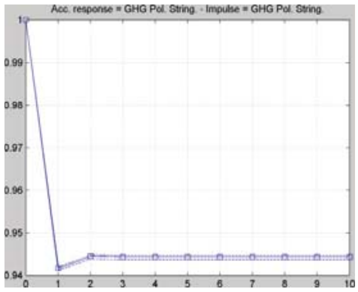
(e) Value Added - GHG Stringency



(f) Energy Prices - GHG Stringency



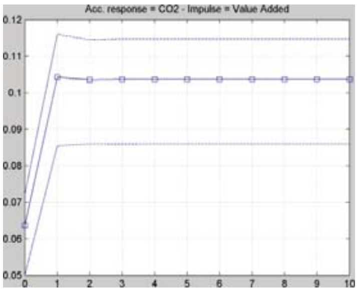
(g) Technology - GHG Stringency



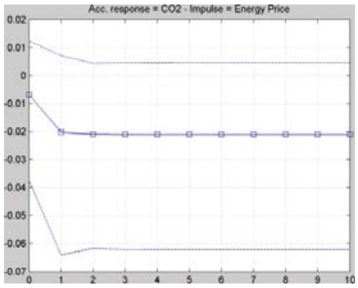
(h) GHG Stringency - GHG Stringency

Note: The first variable in the caption corresponds to the response variable, whereas the second variable corresponds to the impulse variable. 10% confidence intervals.

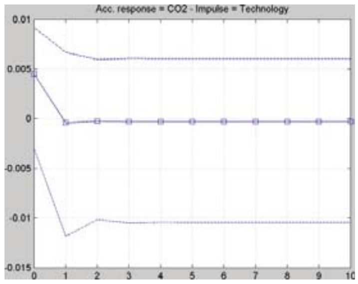
Figure C5: Impulse Response Functions Very Dirty Sector



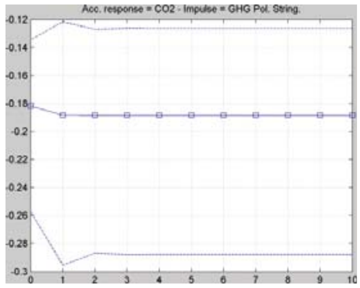
(a) CO_2 - Value Added



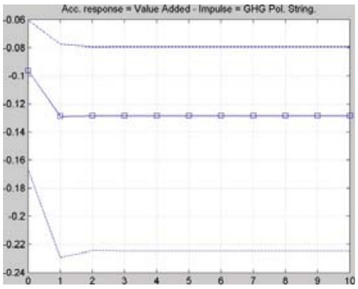
(b) CO_2 - Energy Prices



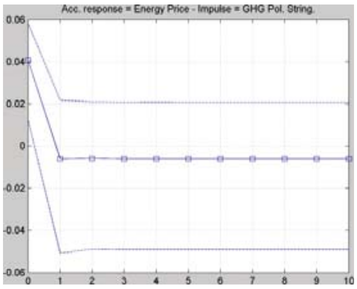
(c) CO_2 - Technology



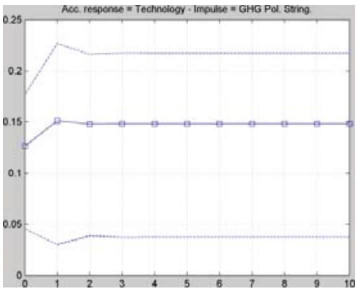
(d) CO_2 - GHG Stringency



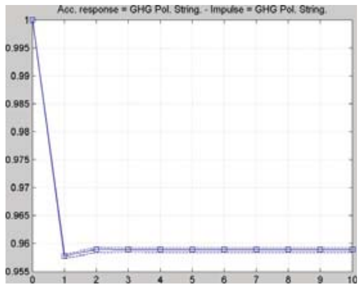
(e) Value Added - GHG Stringency



(f) Energy Prices - GHG Stringency



(g) Technology - GHG Stringency



(h) GHG Stringency - GHG Stringency

Note: The first variable in the caption corresponds to the response variable, whereas the second variable corresponds to the impulse variable. 10% confidence intervals.

Appendix D: Main Robustness Results: Different Data, Spatial Specification

Table D1: Country Specification with 1 Lag, WEF Environmental Policy Stringency Index

Variable and Statistics	CO2		GDP		Energy Price		Technology		WEF Pol. String.	
	L0	L1	L0	L1	L0	L1	L0	L1	L0	L1
WEF Pol. String.	-0.102***	-0.144***	0.023***	-0.068***	0.189***	-0.727***	0.033***	0.802***	-	-0.004
	(0.005)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	-	(0.224)
ln(Technology)	0.021***	-0.019***	-0.008***	-0.006***	0.020***	-0.031***	-	-0.474***	-	-0.000
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	-	(0.000)	-	(0.860)
ln(Energy prices)	0.060***	0.004	-0.045***	-0.035***	-	-0.345***	-	0.184***	-	-0.000
	(0.000)	(0.477)	(0.000)	(0.000)	-	(0.000)	-	(0.000)	-	(0.393)
ln(GDP)	0.626***	-0.406***	-	0.304***	-	-0.558***	-	0.668***	-	-0.000
	(0.000)	(0.000)	-	(0.000)	-	(0.000)	-	(0.000)	-	(0.640)
ln(CO2)	-	-0.174***	-	-0.038***	-	0.023***	-	0.216***	-	-0.000
	-	(0.000)	-	(0.000)	-	(0.000)	-	(0.000)	-	(0.658)
ln(Corruption)	0.030	0.043*	0.014	-0.008	0.007	-0.007	0.149	-0.191***	0.000	0.000
	(0.186)	(0.067)	(0.193)	(0.396)	(0.852)	(0.823)	(0.000)	(0.000)	(0.380)	(0.759)
ln(CDD)	0.005*	0.005***	0.013***	0.008***	-0.002***	0.016***	-0.025***	-0.009***	0.000	0.000
	(0.066)	(0.001)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.405)	(0.989)
ln(HDD)	0.072***	0.105***	-0.002***	0.064*	0.036***	-0.282***	0.311***	0.192***	0.000	0.000
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.335)	(0.834)
Time FE/Country FE	Yes/Yes		Yes/Yes		Yes/Yes		Yes/Yes		Yes/Yes	
Obs.	322		322		322		322		322	
Pseudo R2	0.386		0.675		0.053		0.132		0.497	

Column titles indicate the sub-equations. L0: contemporaneous effect, L1: effect from one time lag. * $p<0.1$, ** $p<0.05$, *** $p<0.01$, p-values in parenthesis

Table D2: Country Specification with 1 Lag, aggregated Sector Dataset

Variable and Statistics	CO2		GDP		Energy Price		Technology		GHG Pol. String.	
	L0	L1	L0	L1	L0	L1	L0	L1	L0	L1
GHG Pol. String.	-0.109**	-0.015	-0.046**	0.040**	0.037	-0.066	0.272***	0.167	-	-0.064
	(0.042)	(0.796)	(0.015)	(0.049)	(0.501)	(0.248)	(0.000)	(0.131)	-	(0.154)
ln(Technology)	-0.004	0.004	0.003	0.003	0.006	0.024***	-	-0.112***	-	-0.002
	(0.668)	(0.679)	(0.369)	(0.268)	(0.480)	(0.009)	-	(0.000)	-	(0.357)
ln(Energy prices)	-0.019	-0.003	-0.015	-0.004	-	0.049	-	-0.017	-	0.009
	(0.474)	(0.921)	(0.177)	(0.752)	-	(0.305)	-	(0.708)	-	(0.119)
ln(GDP)	0.453***	0.172*	-	0.404***	-	-0.083	-	-0.493**	-	-0.028
	(0.000)	(0.066)	-	(0.000)	-	(0.375)	-	(0.037)	-	(0.296)
ln(CO2)	-	-0.106**	-	0.011	-	-0.014	-	0.184	-	-0.021**
	-	(0.027)	-	(0.254)	-	(0.603)	-	(0.269)	-	(0.011)
ln(Corruption)	0.001	-0.014	0.003	0.011**	-0.003	0.027**	-0.027	-0.013	0.004	-0.001
	(0.954)	(0.198)	(0.515)	(0.031)	(0.815)	(0.029)	(0.135)	(0.453)	(0.143)	(0.821)
ln(CDD)	0.009**	0.003	0.002	0.003**	-0.002	0.006*	0.019	-0.007	-0.001	0.001
	(0.013)	(0.369)	(0.210)	(0.037)	(0.627)	(0.065)	(0.537)	(0.261)	(0.500)	(0.654)
ln(HDD)	0.010	-0.067***	-0.010	0.027***	0.067**	0.004	-0.055**	-0.094*	0.002	0.002
	(0.684)	(0.005)	(0.314)	(0.007)	(0.020)	(0.899)	(0.020)	(0.053)	(0.704)	(0.662)
Time FE/Country FE	Yes/Yes		Yes/Yes		Yes/Yes		Yes/Yes		Yes/Yes	
Obs.	490		490		490		490		490	
Pseudo R2	0.26		0.60		0.17		0.07		0.26	

Column titles indicate the sub-equations. L0: contemporaneous effect, L1: effect from one time lag. * $p<0.1$, ** $p<0.05$, *** $p<0.01$, p-values in parenthesis

Table D3: Country Specification with 1 Lag, spatial

Variable and Statistics	CO2				GDP			
	L0	L1	N0	N1	L0	L1	N0	N1
GHG Pol. String.	-0.223***	0.114*	0.040	-0.541**	-0.044**	0.018	0.047	-0.140*
	(0.000)	(0.057)	(0.855)	(0.013)	(0.019)	(0.337)	(0.583)	(0.100)
ln(Technology)	-0.000	-0.002	0.019	-0.012	-0.002	-0.004	0.005	0.004
	(0.989)	(0.814)	(0.227)	(0.392)	(0.382)	(0.148)	(0.369)	(0.481)
ln(Energy prices)	-0.007	0.018	-0.035	-0.059	-0.015*	0.008	-0.011	0.006
	(0.748)	(0.440)	(0.580)	(0.335)	(0.094)	(0.379)	(0.586)	(0.767)
ln(GDP)	0.567***	-0.118**	0.041	0.317***	-	0.375***	0.155***	-0.068*
	(0.000)	(0.016)	(0.736)	(0.003)	-	(0.000)	(0.000)	(0.091)
ln(CO2)	-	-0.129***	0.178***	-0.027	-	0.013	-	0.023
	-	(0.000)	(0.001)	(0.669)	-	(0.130)	-	(0.304)
ln(Corruption)	-0.006	-0.002	-	-	0.004	0.002	-	-
	(0.555)	(0.853)	-	-	(0.355)	(0.579)	-	-
ln(CDD)	-0.002	-0.006**	-	-	0.003***	-0.001	-	-
	(0.465)	(0.031)	-	-	(0.005)	(0.646)	-	-
ln(HDD)	0.098***	-0.110***	-	-	-0.001	0.009	-	-
	(0.000)	(0.000)	-	-	(0.903)	(0.361)	-	-
Time FE/Country FE	Yes/Yes				Yes/Yes			
Obs.	920				920			
R2	0.21				0.59			

Variable and Statistics	Energy Price				Technology			
	L0	L1	N0	N1	L0	L1	N0	N1
GHG Pol. String.	0.085*	-0.123**	-0.197	-0.289**	-0.057	0.021	0.763*	-0.626
	(0.080)	(0.011)	(0.152)	(0.046)	(0.670)	(0.877)	(0.096)	(0.157)
ln(Technology)	0.006	0.006	0.000	0.009	-	0.182***	-0.032	-0.029
	(0.467)	(0.407)	(0.971)	(0.440)	-	(0.000)	(0.347)	(0.348)
ln(Energy prices)	-	0.025	0.103**	-0.066	-	-0.078	-	-0.328**
	-	(0.447)	(0.011)	(0.122)	-	(0.239)	-	(0.011)
ln(GDP)	-	0.064	-	0.020	-	-0.008	-	0.166
	-	(0.181)	-	(0.791)	-	(0.943)	-	(0.423)
ln(CO2)	-	-0.044*	-	-0.062	-	0.039	-	0.155
	-	(0.058)	-	(0.167)	-	(0.496)	-	(0.228)
ln(Corruption)	-0.003	-0.014	-	-	0.015	-0.001	-	-
	(0.767)	(0.198)	-	-	(0.299)	(0.959)	-	-
ln(CDD)	-0.004	0.003	-	-	-0.008	-0.010	-	-
	(0.147)	(0.369)	-	-	(0.234)	(0.168)	-	-
ln(HDD)	0.050***	-0.067***	-	-	0.012	-0.025	-	-
	(0.003)	(0.005)	-	-	(0.794)	(0.607)	-	-
Time FE/Country FE	Yes/Yes				Yes/Yes			
Obs.	920				920			
R2	0.11				0.29			

Variable and Statistics	GHG Pol. String.			
	L0	L1	N0	N1
GHG Pol. String.	-	-0.026	0.027	0.240***
	-	(0.441)	(0.661)	(0.001)
ln(Technology)	-	-0.001	-	-0.003
	-	(0.724)	-	(0.313)
ln(Energy prices)	-	-0.003	-	0.033*
	-	(0.684)	-	(0.052)
ln(GDP)	-	0.009	-	-0.064*
	-	(0.470)	-	(0.061)
ln(CO2)	-	0.002	-	0.000
	-	(0.799)	-	(0.986)
ln(Corruption)	0.000	-0.001	-	-
	(0.984)	(0.723)	-	-
ln(CDD)	-0.003**	-0.001	-	-
	(0.027)	(0.296)	-	-
ln(HDD)	0.002	-0.006	-	-
	(0.768)	(0.436)	-	-
Time FE/Country FE	Yes/Yes			
Obs.	920			
R2	0.18			

Column titles indicate the sub-equations. L0: contemporaneous effect, L1: effect from one time lag, N0: contemporaneous effect from one spatial lag, N1: effect from one time and one spatial lag. * $p<0.1$, ** $p<0.05$, *** $p<0.01$, p-values in parenthesis

Table D4: Sector Specification with 1 Lag, spatial (Continued on Next Page)

Variables and Statistics	CO2 Equation															
	Very clean				Clean				Dirty				Very dirty			
	L0	L1	NL0	NL1	L0	L1	NL0	NL1	L0	L1	NL0	NL1	L0	L1	NL0	NL1
GHG Pol. String.	-0.265*** (0.000)	0.007 (0.885)	0.154 (0.288)	0.066 (0.657)	-0.195*** (0.000)	-0.004 (0.938)	0.040 (0.762)	-0.069 (0.613)	-0.088* (0.073)	-0.001 (0.991)	0.008 (0.951)	-0.012 (0.935)	-0.162*** (0.000)	-0.029 (0.547)	0.059 (0.660)	-0.222 (0.114)
ln(Technology)	0.004 (0.598)	0.006 (0.433)	-0.029* (0.061)	0.009 (0.537)	0.009 (0.138)	0.012** (0.048)	-0.004 (0.752)	0.002 (0.861)	0.009 (0.132)	-0.001 (0.894)	0.010 (0.507)	-0.020 (0.156)	0.001 (0.813)	-0.006 (0.245)	-0.010 (0.482)	-0.036** (0.010)
ln(Energy prices)	-0.153*** (0.000)	-0.138*** (0.000)	0.076* (0.088)	-0.013 (0.780)	-0.093*** (0.000)	-0.114*** (0.000)	0.060 (0.132)	-0.056 (0.175)	-0.114*** (0.000)	-0.136*** (0.000)	0.059 (0.167)	-0.036 (0.418)	-0.034 (0.105)	-0.069*** (0.002)	0.084** (0.042)	0.026 (0.558)
ln(Value Added)	0.090*** (0.000)	0.036** (0.024)	0.013 (0.495)	0.007 (0.726)	0.093*** (0.000)	0.065*** (0.000)	0.018 (0.399)	-0.030 (0.175)	0.081*** (0.000)	0.007 (0.534)	-0.005 (0.718)	0.019 (0.225)	0.043*** (0.000)	0.034*** (0.000)	-0.004 (0.734)	0.023* (0.068)
ln(CO2)	- -	-0.079*** (0.000)	0.035** (0.035)	-0.009 (0.625)	- -	-0.099*** (0.000)	-0.012 (0.424)	-0.021 (0.174)	- -	-0.084*** (0.000)	-0.014 (0.453)	-0.018 (0.371)	- -	-0.058*** (0.002)	-0.026 (0.127)	0.009 (0.659)
ln(Corruption)	-0.014*** (0.002)	-0.026*** (0.000)	- -	- -	-0.014*** (0.002)	-0.026*** (0.000)	- -	- -	-0.014*** (0.002)	-0.026*** (0.000)	- -	- -	-0.014*** (0.002)	-0.026*** (0.000)	- -	- -
ln(CDD)	0.004*** (0.009)	-0.007*** (0.000)	- -	- -	0.004*** (0.009)	-0.007*** (0.000)	- -	- -	0.004*** (0.009)	-0.007*** (0.000)	- -	- -	0.004*** (0.009)	-0.007*** (0.000)	- -	- -
ln(HDD)	-0.020* (0.063)	-0.040*** (0.000)	- -	- -	-0.020* (0.063)	-0.040*** (0.000)	- -	- -	-0.020* (0.063)	-0.040*** (0.000)	- -	- -	-0.020* (0.063)	-0.040*** (0.000)	- -	- -
Time FE/Country FE	yes/yes															
Pseudo R2	0.093															
Obs.	16660															
Variables and Statistics	Value Added Equation															
	Very clean				Clean				Dirty				Very dirty			
	L0	L1	NL0	NL1	L0	L1	NL0	NL1	L0	L1	NL0	NL1	L0	L1	NL0	NL1
GHG Pol. String.	-0.047** (0.017)	0.022 (0.281)	0.015 (0.805)	0.162** (0.013)	-0.014 (0.550)	0.041* (0.092)	-0.003 (0.960)	-0.091 (0.208)	-0.043 (0.175)	0.052 (0.119)	-0.263*** (0.003)	-0.157* (0.090)	-0.082** (0.031)	-0.019 (0.615)	-0.062 (0.569)	-0.004 (0.970)
ln(Technology)	0.005 (0.143)	0.004 (0.222)	0.006 (0.366)	0.025*** (0.000)	0.006 (0.128)	-0.001 (0.858)	-0.002 (0.763)	0.009 (0.192)	0.005 (0.304)	-0.000 (0.977)	-0.007 (0.496)	-0.029*** (0.002)	0.010 (0.128)	-0.001 (0.896)	0.010 (0.412)	-0.046*** (0.000)
ln(Energy prices)	-0.035*** (0.000)	0.005 (0.583)	-0.030 (0.110)	-0.015 (0.455)	-0.042*** (0.000)	-0.009 (0.380)	-0.004 (0.832)	-0.020 (0.348)	-0.033** (0.019)	-0.016 (0.296)	0.053** (0.034)	-0.011 (0.679)	-0.001 (0.960)	-0.035* (0.082)	0.071** (0.029)	0.070** (0.044)
ln(Value Added)	- -	0.150*** (0.000)	-0.015* (0.087)	-0.010 (0.250)	- -	0.075*** (0.000)	-0.012 (0.231)	0.005 (0.640)	- -	0.090*** (0.000)	0.032*** (0.001)	0.011 (0.257)	- -	0.020 (0.261)	0.023 (0.112)	0.027* (0.078)
ln(CO2)	- -	0.005 (0.174)	- -	0.005 (0.528)	- -	0.009** (0.014)	- -	-0.010 (0.166)	- -	0.013** (0.015)	- -	0.004 (0.763)	- -	0.039*** (0.000)	- -	0.015 (0.389)
ln(Corruption)	0.005* (0.063)	0.000 (0.882)	- -	- -	0.005* (0.063)	0.000 (0.882)	- -	- -	0.005* (0.063)	0.000 (0.882)	- -	- -	0.005* (0.063)	0.000 (0.882)	- -	- -
ln(CDD)	0.001 (0.213)	0.001 (0.216)	- -	- -	0.001 (0.213)	0.001 (0.216)	- -	- -	0.001 (0.213)	0.001 (0.216)	- -	- -	0.001 (0.213)	0.001 (0.216)	- -	- -
ln(HDD)	-0.006 (0.267)	-0.002 (0.760)	- -	- -	-0.006 (0.267)	-0.002 (0.760)	- -	- -	-0.006 (0.267)	-0.002 (0.760)	- -	- -	-0.006 (0.267)	-0.002 (0.760)	- -	- -
Time FE/Country FE	yes/yes															
Pseudo R2	0.038															
Obs.	16660															

Column titles indicate the sector groups. L0: contemporaneous effect, L1: effect from one time lag, N0: contemporaneous effect from one spatial lag, N1: effect from one time and one spatial lag. * p<0.1, ** p<0.05, *** p<0.01, p-values in parenthesis

Table D4: Sector Specification with 1 Lag, spatial (Continued)

Variables and Statistics	Energy Price															
	Very clean				Clean				Dirty				Very dirty			
	L0	L1	NL0	NL1	L0	L1	NL0	NL1	L0	L1	NL0	NL1	L0	L1	NL0	NL1
GHG Pol. String.	0.026	-0.055***	-0.091	-0.161***	0.027	-0.055***	0.035	-0.071	0.026	-0.058***	0.017	-0.021	0.044**	-0.060***	-0.191***	0.067
	(0.156)	(0.003)	(0.110)	(0.007)	(0.125)	(0.002)	(0.509)	(0.200)	(0.151)	(0.002)	(0.762)	(0.723)	(0.018)	(0.002)	(0.001)	(0.282)
ln(Technology)	0.008***	0.024***	0.003	-0.004	0.008***	0.025***	0.001	-0.001	0.008**	0.026***	-0.003	-0.006	0.008**	0.025***	0.001	0.004
	(0.009)	(0.000)	(0.681)	(0.498)	(0.006)	(0.000)	(0.890)	(0.805)	(0.015)	(0.000)	(0.641)	(0.329)	(0.014)	(0.000)	(0.928)	(0.569)
ln(Energy prices)	-	0.049***	-0.003	-0.018	-	0.047***	-0.007	-0.015	-	0.038***	0.002	0.005	-	0.061***	0.019	-0.034*
	-	(0.000)	(0.839)	(0.348)	-	(0.000)	(0.626)	(0.407)	-	(0.006)	(0.913)	(0.800)	-	(0.000)	(0.248)	(0.089)
ln(Value Added)	-	0.002	-	0.002	-	0.003	-	0.012	-	0.010**	-	0.003	-	0.003	-	0.006
	-	(0.688)	-	(0.834)	-	(0.652)	-	(0.134)	-	(0.032)	-	(0.473)	-	(0.208)	-	(0.462)
ln(CO2)	-	-0.004*	-	-0.032***	-	0.001	-	-0.005	-	-0.001	-	-0.023***	-	-0.002	-	0.018**
	-	(0.079)	-	(0.000)	-	(0.684)	-	(0.382)	-	(0.896)	-	(0.005)	-	(0.644)	-	(0.043)
ln(Corruption)	-0.004*	0.028***	-	-	-0.004*	0.028***	-	-	-0.004*	0.028***	-	-	-0.004*	0.028***	-	-
	(0.054)	(0.000)	-	-	(0.054)	(0.000)	-	-	(0.054)	(0.000)	-	-	(0.054)	(0.000)	-	-
ln(CDD)	-0.002**	0.006***	-	-	-0.002**	0.006***	-	-	-0.002**	0.006***	-	-	-0.002**	0.006***	-	-
	(0.010)	(0.000)	-	-	(0.010)	(0.000)	-	-	(0.010)	(0.000)	-	-	(0.010)	(0.000)	-	-
ln(HDD)	0.066***	0.012**	-	-	0.066***	0.012**	-	-	0.066***	0.012**	-	-	0.066***	0.012**	-	-
	(0.000)	(0.016)	-	-	(0.000)	(0.016)	-	-	(0.000)	(0.016)	-	-	(0.000)	(0.016)	-	-
Time FE/Country FE	yes/yes															
Pseudo R2	0.179															
Obs.	16660															

Variables and Statistics	Technology															
	Very clean				Clean				Dirty				Very dirty			
	L0	L1	NL0	NL1	L0	L1	NL0	NL1	L0	L1	NL0	NL1	L0	L1	NL0	NL1
GHG Pol. String.	0.128***	0.158***	0.000	0.000	0.128***	0.158***	-0.000	-0.000	0.128***	0.158***	-0.000	0.000	0.128***	0.158***	-0.000	0.000
	(0.000)	(0.000)	(0.937)	(0.966)	(0.000)	(0.000)	(0.765)	(0.988)	(0.000)	(0.000)	(0.911)	(0.975)	(0.000)	(0.000)	(0.777)	(0.957)
ln(Technology)	-	-0.135***	-0.000	0.000	-	-0.135***	0.000	0.000	-	-0.135***	-0.000	0.000	-	-0.135***	-0.000	-0.000
	-	(0.000)	(0.929)	(0.984)	-	(0.000)	(0.979)	(0.935)	-	(0.000)	(0.995)	(0.998)	-	(0.000)	(0.902)	(0.895)
ln(Energy prices)	-	0.134***	-	-0.000	-	0.134***	-	0.000	-	0.134***	-	-0.000	-	0.134***	-	-0.000
	-	(0.000)	-	(0.913)	-	(0.000)	-	(0.991)	-	(0.000)	-	(0.858)	-	(0.000)	-	(0.978)
ln(Value Added)	-	-0.000	-	0.000	-	-0.000	-	0.000	-	-0.000	-	-0.000	-	-0.000	-	-0.000
	-	(0.883)	-	(0.942)	-	(0.869)	-	(0.984)	-	(0.862)	-	(0.983)	-	(0.918)	-	(0.818)
ln(CO2)	-	0.000		0.000	-	-0.000		-0.000	-	-0.000		-0.000	-	0.000		-0.000
	-	(0.971)		(0.982)	-	(0.956)		(0.907)	-	(0.860)		(0.985)	-	(0.922)		(0.805)
ln(Corruption)	-0.059***	0.022***	-	-	-0.059***	0.022***	-	-	-0.059***	0.022***	-	-	-0.059***	0.022***	-	-
	(0.000)	(0.000)	-	-	(0.000)	(0.000)	-	-	(0.000)	(0.000)	-	-	(0.000)	(0.000)	-	-
ln(CDD)	0.022***	0.014***	-	-	0.022***	0.014***	-	-	0.022***	0.014***	-	-	0.022***	0.014***	-	-
	(0.000)	(0.000)	-	-	(0.000)	(0.000)	-	-	(0.000)	(0.000)	-	-	(0.000)	(0.000)	-	-
ln(HDD)	-0.124***	0.136***	-	-	-0.124***	0.136***	-	-	-0.124***	0.136***	-	-	-0.124***	0.136***	-	-
	(0.000)	(0.000)	-	-	(0.000)	(0.000)	-	-	(0.000)	(0.000)	-	-	(0.000)	(0.000)	-	-
Time FE/Country FE	yes/yes															
Pseudo R2	0.092															
Obs.	16660															

Column titles indicate the sector groups. L0: contemporaneous effect, L1: effect from one time lag, N0: contemporaneous effect from one spatial lag, N1: effect from one time and one spatial lag. * $p<0.1$, ** $p<0.05$, *** $p<0.01$, p-values in parenthesis

Table D4: Sector Specification with 1 Lag, spatial (Continued)

Variables and Statistics	GHG Policy Stringency Equation															
	Very clean				Clean				Dirty				Very dirty			
	L0	L1	NL0	NL1	L0	L1	NL0	NL1	L0	L1	NL0	NL1	L0	L1	NL0	NL1
GHG Pol. String.	-	-0.061***	0.000	0.000	-	-0.061***	-0.000	-0.000	-	-0.061***	0.000	-0.000	-	-0.061***	-0.000	0.000
	-	(0.000)	(0.985)	(0.953)	-	(0.000)	(0.954)	(0.963)	-	(0.000)	(0.996)	(0.974)	-	(0.000)	(0.956)	(0.982)
ln(Technology)	-	-0.003***	-	0.000	-	-0.003***	-	-0.000	-	-0.003***	-	-0.000	-	-0.003***	-	-0.000
	-	(0.000)	-	(0.995)	-	(0.000)	-	(1.000)	-	(0.000)	-	(0.994)	-	(0.000)	-	(0.978)
ln(Energy prices)	-	0.011***	-	-0.000	-	0.011***	-	0.000	-	0.011***	-	-0.000	-	0.011***	-	0.000
	-	(0.000)	-	(0.961)	-	(0.000)	-	(0.968)	-	(0.000)	-	(0.991)	-	(0.000)	-	(0.995)
ln(Value Added)	-	-0.000	-	0.000	-	-0.000	-	-0.000	-	-0.000	-	-0.000	-	-0.000	-	0.000
	-	(0.933)	-	(0.950)	-	(0.952)	-	(0.994)	-	(0.908)	-	(0.997)	-	(0.924)	-	(0.957)
ln(CO2)	-	-0.000	-	-0.000	-	-0.000	-	0.000	-	0.000	-	-0.000	-	-0.000	-	0.000
	-	(0.823)	-	(0.980)	-	(0.953)	-	(0.910)	-	(1.000)	-	(0.960)	-	(0.961)	-	(0.908)
ln(Corruption)	-0.010***	-0.014***	-	-	-0.010***	-0.014***	-	-	-0.010***	-0.014***	-	-	-0.010***	-0.014***	-	-
	(0.000)	(0.000)	-	-	(0.000)	(0.000)	-	-	(0.000)	(0.000)	-	-	(0.000)	(0.000)	-	-
ln(CDD)	-0.002**	-0.001*	-	-	-0.002**	-0.001*	-	-	-0.002**	-0.001*	-	-	-0.002**	-0.001*	-	-
	(0.041)	(0.098)	-	-	(0.041)	(0.098)	-	-	(0.041)	(0.098)	-	-	(0.041)	(0.098)	-	-
ln(HDD)	-0.016***	-0.009***	-	-	-0.016***	-0.009***	-	-	-0.016***	-0.009***	-	-	-0.016***	-0.009***	-	-
	(0.000)	(0.000)	-	-	(0.000)	(0.000)	-	-	(0.000)	(0.000)	-	-	(0.000)	(0.000)	-	-
Time FE/Country FE	yes/yes															
Pseudo R2	0.218															
Obs.	16660															

Column titles indicate the sector groups. L0: contemporaneous effect, L1: effect from one time lag, N0: contemporaneous effect from one spatial lag, N1: effect from one time and one spatial lag. * $p<0.1$, ** $p<0.05$, *** $p<0.01$, p-values in parenthesis

Appendix E: Secondary Robustness Results: Forward Lag, Different Grouping and Different Ordering Structure

Table E1: Country Specification, alternative ordering 1: technology, gdp, energy price

Variable and Statistics	CO2		GDP		Energy Price		Technology		GHG Pol. String.	
	L0	L1	L0	L1	L0	L1	L0	L1	L0	L1
ln(GHG Pol. String.)	-0.166***	0.039	-0.044**	0.015	0.045	-0.159***	-0.086	-0.188*	-	-0.019
	(0.004)	(0.511)	(0.012)	(0.370)	(0.352)	(0.001)	(0.444)	(0.093)	-	(0.576)
ln(Technology)	0.027**	0.013	0.012***	0.007*	-0.015	0.010	-	0.020	-	0.003
	(0.014)	(0.235)	(0.004)	(0.077)	(0.160)	(0.353)	-	(0.561)	-	(0.272)
ln(GDP)	-0.019	0.033	-0.014	0.007	-	0.034	-	-0.091	-	0.004
	(0.386)	(0.133)	(0.103)	(0.390)	-	(0.312)	-	(0.102)	-	(0.373)
ln(Energy Price)	0.617***	-0.036	-	0.386***	-	0.050	-	0.069	-	-0.008
	(0.000)	(0.517)	-	(0.000)	-	(0.291)	-	(0.531)	-	(0.466)
ln(CO2)	-	-0.129***	-	0.008	-	-0.060***	-	0.173***	-	0.003
	-	(0.000)	-	(0.381)	-	(0.009)	-	(0.000)	-	(0.642)
ln(Corruption)	-0.003	0.003	0.006	0.003	-0.004	0.006	0.001	-0.013	0.001	-0.001
	(0.795)	(0.787)	(0.206)	(0.531)	(0.722)	(0.592)	(0.950)	(0.453)	(0.695)	(0.788)
ln(CDD)	-0.001	-0.003	0.003***	0.000	-0.004	0.002	-0.007	-0.007	-0.003**	-0.001
	(0.856)	(0.304)	(0.004)	(0.798)	(0.106)	(0.365)	(0.228)	(0.261)	(0.014)	(0.355)
ln(HDD)	0.088***	-0.062***	0.001	0.008	0.054***	-0.020	0.087*	-0.094*	0.001	-0.007**
	(0.000)	(0.005)	(0.950)	(0.373)	(0.002)	(0.260)	(0.061)	(0.053)	(0.688)	(0.044)
Time FE/Country FE	Yes/Yes		Yes/Yes		Yes/Yes		Yes/Yes		Yes/Yes	
Obs.	920		920		920		920		920	
AIC	-4278.15		-5858.61		-4176.63		-2954.85		-6097.26	
BIC	-3907.56		-5492.77		-3815.55		-2598.52		-5745.68	
R2	0.22		0.57		0.10		0.13		0.18	

Column titles indicate the sub-equations. L0: contemporaneous effect, L1: effect from one time lag. * $p<0.1$, ** $p<0.05$, *** $p<0.01$, p-values in parenthesis

Table E2: Country Specification, alternative ordering 2: energy price, technology, gdp

Variable and Statistics	CO2		GDP		Energy Price		Technology		GHG Pol. String.	
	L0	L1	L0	L1	L0	L1	L0	L1	L0	L1
ln(GHG Pol. String.)	-0.166***	0.039	-0.044**	0.015	0.045	-0.159***	-0.086	-0.188*	-	-0.019
	(0.004)	(0.511)	(0.012)	(0.370)	(0.352)	(0.001)	(0.444)	(0.093)	-	(0.576)
ln(Energy Price)	0.027**	0.013	0.012***	0.007*	-0.015	0.010	-	0.020	-	0.003
	(0.014)	(0.235)	(0.004)	(0.077)	(0.160)	(0.353)	-	(0.561)	-	(0.272)
ln(Technology)	-0.019	0.033	-0.014	0.007	-	0.034	-	-0.091	-	0.004
	(0.386)	(0.133)	(0.103)	(0.390)	-	(0.312)	-	(0.102)	-	(0.373)
ln(GDP)	0.617***	-0.036	-	0.386***	-	0.050	-	0.069	-	-0.008
	(0.000)	(0.517)	-	(0.000)	-	(0.291)	-	(0.531)	-	(0.466)
ln(CO2)	-	-0.129***	-	0.008	-	-0.060***	-	0.173***	-	0.003
	-	(0.000)	-	(0.381)	-	(0.009)	-	(0.000)	-	(0.642)
ln(Corruption)	-0.003	0.003	0.006	0.003	-0.004	0.006	0.001	-0.013	0.001	-0.001
	(0.795)	(0.787)	(0.206)	(0.531)	(0.722)	(0.592)	(0.950)	(0.453)	(0.695)	(0.788)
ln(CDD)	-0.001	-0.003	0.003***	0.000	-0.004	0.002	-0.007	-0.007	-0.003**	-0.001
	(0.856)	(0.304)	(0.004)	(0.798)	(0.106)	(0.365)	(0.228)	(0.261)	(0.014)	(0.355)
ln(HDD)	0.088***	-0.062***	0.001	0.008	0.054***	-0.020	0.087*	-0.094*	0.001	-0.007**
	(0.000)	(0.005)	(0.950)	(0.373)	(0.002)	(0.260)	(0.061)	(0.053)	(0.688)	(0.044)
Time FE/Country FE	Yes/Yes		Yes/Yes		Yes/Yes		Yes/Yes		Yes/Yes	
Obs.	920		920		920		920		920	
AIC	-4278.15		-5858.61		-4176.63		-2954.85		-6097.26	
BIC	-3907.56		-5492.77		-3815.55		-2598.52		-5745.68	
R2	0.22		0.57		0.10		0.13		0.18	

Column titles indicate the sub-equations. L0: contemporaneous effect, L1: effect from one time lag. * p<0.1, ** p<0.05, *** p<0.01, p-values in parenthesis

Table E3: Country Specification, alternative ordering 3: gdp, technology, energy price

Variable and Statistics	CO2		GDP		Energy Price		Technology		GHG Pol. String.	
	L0	L1	L0	L1	L0	L1	L0	L1	L0	L1
ln(GHG Pol. String.)	-0.166***	0.039	-0.044**	0.015	0.045	-0.159***	-0.086	-0.188*	-	-0.019
	(0.004)	(0.511)	(0.012)	(0.370)	(0.352)	(0.001)	(0.444)	(0.093)	-	(0.576)
ln(GDP)	0.027**	0.013	0.012***	0.007*	-0.015	0.010	-	0.020	-	0.003
	(0.014)	(0.235)	(0.004)	(0.077)	(0.160)	(0.353)	-	(0.561)	-	(0.272)
ln(Technology)	-0.019	0.033	-0.014	0.007	-	0.034	-	-0.091	-	0.004
	(0.386)	(0.133)	(0.103)	(0.390)	-	(0.312)	-	(0.102)	-	(0.373)
ln(Energy Price)	0.617***	-0.036	-	0.386***	-	0.050	-	0.069	-	-0.008
	(0.000)	(0.517)	-	(0.000)	-	(0.291)	-	(0.531)	-	(0.466)
ln(CO2)	-	-0.129***	-	0.008	-	-0.060***	-	0.173***	-	0.003
	-	(0.000)	-	(0.381)	-	(0.009)	-	(0.000)	-	(0.642)
ln(Corruption)	-0.003	0.003	0.006	0.003	-0.004	0.006	0.001	-0.013	0.001	-0.001
	(0.795)	(0.787)	(0.206)	(0.531)	(0.722)	(0.592)	(0.950)	(0.453)	(0.695)	(0.788)
ln(CDD)	-0.001	-0.003	0.003***	0.000	-0.004	0.002	-0.007	-0.007	-0.003**	-0.001
	(0.856)	(0.304)	(0.004)	(0.798)	(0.106)	(0.365)	(0.228)	(0.261)	(0.014)	(0.355)
ln(HDD)	0.088***	-0.062***	0.001	0.008	0.054***	-0.020	0.087*	-0.094*	0.001	-0.007**
	(0.000)	(0.005)	(0.950)	(0.373)	(0.002)	(0.260)	(0.061)	(0.053)	(0.688)	(0.044)
Time FE/Country FE	Yes/Yes		Yes/Yes		Yes/Yes		Yes/Yes		Yes/Yes	
Obs.	920		920		920		920		920	
AIC	-4278.15		-5858.61		-4176.63		-2954.85		-6097.26	
BIC	-3907.56		-5492.77		-3815.55		-2598.52		-5745.68	
R2	0.22		0.57		0.10		0.13		0.18	

Column titles indicate the sub-equations. L0: contemporaneous effect, L1: effect from one time lag. * p<0.1, ** p<0.05, *** p<0.01, p-values in parenthesis

Table E4: Country Specification, alternative ordering 4: energy price, gdp, technology

Variable and Statistics	CO2		GDP		Energy Price		Technology		GHG Pol. String.	
	L0	L1	L0	L1	L0	L1	L0	L1	L0	L1
ln(GHG Pol. String.)	-0.166***	0.039	-0.044**	0.015	0.045	-0.159***	-0.086	-0.188*	-	-0.019
	(0.004)	(0.511)	(0.012)	(0.370)	(0.352)	(0.001)	(0.444)	(0.093)	-	(0.576)
ln(Energy Price)	0.027**	0.013	0.012***	0.007*	-0.015	0.010	-	0.020	-	0.003
	(0.014)	(0.235)	(0.004)	(0.077)	(0.160)	(0.353)	-	(0.561)	-	(0.272)
ln(GDP)	-0.019	0.033	-0.014	0.007	-	0.034	-	-0.091	-	0.004
	(0.386)	(0.133)	(0.103)	(0.390)	-	(0.312)	-	(0.102)	-	(0.373)
ln(Technology)	0.617***	-0.036	-	0.386***	-	0.050	-	0.069	-	-0.008
	(0.000)	(0.517)	-	(0.000)	-	(0.291)	-	(0.531)	-	(0.466)
ln(CO2)	-	-0.129***	-	0.008	-	-0.060***	-	0.173***	-	0.003
	-	(0.000)	-	(0.381)	-	(0.009)	-	(0.000)	-	(0.642)
ln(Corruption)	-0.003	0.003	0.006	0.003	-0.004	0.006	0.001	-0.013	0.001	-0.001
	(0.795)	(0.787)	(0.206)	(0.531)	(0.722)	(0.592)	(0.950)	(0.453)	(0.695)	(0.788)
ln(CDD)	-0.001	-0.003	0.003***	0.000	-0.004	0.002	-0.007	-0.007	-0.003**	-0.001
	(0.856)	(0.304)	(0.004)	(0.798)	(0.106)	(0.365)	(0.228)	(0.261)	(0.014)	(0.355)
ln(HDD)	0.088***	-0.062***	0.001	0.008	0.054***	-0.020	0.087*	-0.094*	0.001	-0.007**
	(0.000)	(0.005)	(0.950)	(0.373)	(0.002)	(0.260)	(0.061)	(0.053)	(0.688)	(0.044)
Time FE/Country FE	Yes/Yes		Yes/Yes		Yes/Yes		Yes/Yes		Yes/Yes	
Obs.	920		920		920		920		920	
AIC	-4278.15		-5858.61		-4176.63		-2954.85		-6097.26	
BIC	-3907.56		-5492.77		-3815.55		-2598.52		-5745.68	
R2	0.22		0.57		0.10		0.13		0.18	

Column titles indicate the sub-equations. L0: contemporaneous effect, L1: effect from one time lag. * $p<0.1$, ** $p<0.05$, *** $p<0.01$, p-values in parenthesis

Table E5: Country Specification, alternative ordering 5: gdp, energy price, technology

Variable and Statistics	CO2		GDP		Energy Price		Technology		GHG Pol. String.	
	L0	L1	L0	L1	L0	L1	L0	L1	L0	L1
ln(GHG Pol. String.)	-0.166***	0.039	-0.044**	0.015	0.045	-0.159***	-0.086	-0.188*	-	-0.019
	(0.004)	(0.511)	(0.012)	(0.370)	(0.352)	(0.001)	(0.444)	(0.093)	-	(0.576)
ln(GDP)	0.027**	0.013	0.012***	0.007*	-0.015	0.010	-	0.020	-	0.003
	(0.014)	(0.235)	(0.004)	(0.077)	(0.160)	(0.353)	-	(0.561)	-	(0.272)
ln(Energy Price)	-0.019	0.033	-0.014	0.007	-	0.034	-	-0.091	-	0.004
	(0.386)	(0.133)	(0.103)	(0.390)	-	(0.312)	-	(0.102)	-	(0.373)
ln(Technology)	0.617***	-0.036	-	0.386***	-	0.050	-	0.069	-	-0.008
	(0.000)	(0.517)	-	(0.000)	-	(0.291)	-	(0.531)	-	(0.466)
ln(CO2)	-	-0.129***	-	0.008	-	-0.060***	-	0.173***	-	0.003
	-	(0.000)	-	(0.381)	-	(0.009)	-	(0.000)	-	(0.642)
ln(Corruption)	-0.003	0.003	0.006	0.003	-0.004	0.006	0.001	-0.013	0.001	-0.001
	(0.795)	(0.787)	(0.206)	(0.531)	(0.722)	(0.592)	(0.950)	(0.453)	(0.695)	(0.788)
ln(CDD)	-0.001	-0.003	0.003***	0.000	-0.004	0.002	-0.007	-0.007	-0.003**	-0.001
	(0.856)	(0.304)	(0.004)	(0.798)	(0.106)	(0.365)	(0.228)	(0.261)	(0.014)	(0.355)
ln(HDD)	0.088***	-0.062***	0.001	0.008	0.054***	-0.020	0.087*	-0.094*	0.001	-0.007**
	(0.000)	(0.005)	(0.950)	(0.373)	(0.002)	(0.260)	(0.061)	(0.053)	(0.688)	(0.044)
Time FE/Country FE	Yes/Yes		Yes/Yes		Yes/Yes		Yes/Yes		Yes/Yes	
Obs.	920		920		920		920		920	
AIC	-4278.15		-5858.61		-4176.63		-2954.85		-6097.26	
BIC	-3907.56		-5492.77		-3815.55		-2598.52		-5745.68	
R2	0.22		0.57		0.10		0.13		0.18	

Column titles indicate the sub-equations. L0: contemporaneous effect, L1: effect from one time lag. * p<0.1, ** p<0.05, *** p<0.01, p-values in parenthesis

Table E6: Country Specification, forward lag

Dep. Var	Indep. Var	Time Lag	Coeff.	P-Value
CO2	GHG Pol. String.	-1	-0.092*	(0.080)
		0	-0.170***	(0.004)
		1	0.068	(0.259)
	Technology	0	0.018	(0.105)
		1	0.006	(0.563)
		2	0.007	(0.555)
	Energy Price	0	-0.034	(0.124)
		1	0.048**	(0.026)
		2	-0.007	(0.757)
	GDP	0	0.646***	(0.000)
		1	0.066	(0.353)
		2	0.001	(0.990)
	CO2	1	-0.167***	(0.000)
		2	0.018	(0.579)
	Corruption	0	-0.001	(0.242)
		1	-0.002	(0.114)
		2	0.006***	(0.007)
	CDD	0	-0.004	(0.327)
		1	-0.005	(0.146)
		2	-0.002*	(0.061)
	HDD	0	0.000	(0.966)
		1	-0.101	(0.269)
		2	0.002	(0.641)
	Time FE/Country FE		Yes/Yes	
	R2		0.266	
	Obs.		920	

Dep. Var	Indep. Var	Time Lag	Coeff.	P-Value
GDP	GHG Pol. String.	-1	0.015	(0.377)
		0	-0.044**	(0.018)
		1	0.020	(0.278)
	Technology	0	0.011***	(0.007)
		1	0.012***	(0.004)
		2	0.008*	(0.059)
	Energy Price	0	-0.006	(0.472)
		1	0.008	(0.315)
		2	0.009	(0.278)
	GDP	1	0.371***	(0.000)
		2	-0.026	(0.362)
	CO2	1	0.001	(0.922)
		2	-0.011	(0.266)
	Corruption	0	-0.006	(0.353)
		1	-0.005	(0.459)
		2	-0.005	(0.788)
	CDD	0	0.100**	(0.035)
		1	-0.058	(0.258)
		2	0.011*	(0.070)
	HDD	0	-0.012	(0.500)
		1	0.379	(0.577)
		2	-0.007	(0.891)
	Time FE/Country FE		Yes/Yes	
	R2		0.579	
	Obs.		920	

Dep. Var	Indep. Var	Time Lag	Coeff.	P-Value
Energy Price	GHG Pol. String.	-1	0.053	(0.245)
		0	0.047	(0.354)
		1	-0.155***	(0.002)
	Technology	0	-0.018	(0.102)
		1	0.011	(0.332)
		2	0.008	(0.451)
	Energy Price	1	0.033	(0.355)
		2	-0.070*	(0.051)
	GDP	1	0.054	(0.432)
		2	0.077	(0.170)
	CO2	1	-0.058**	(0.022)
		2	0.007	(0.784)
	Corruption	0	-0.004	(0.181)
		1	0.005*	(0.061)
		2	0.012	(0.296)
	CDD	0	0.053**	(0.004)
		1	-0.017	(0.392)
		2	0.007**	(0.015)
	HDD	0	0.004	(0.730)
		1	0.201	(0.474)
		2	0.019	(0.329)
	Time FE/Country FE		Yes/Yes	
	R2		0.113	
	Obs.		920	

Dep. Var	Indep. Var	Time Lag	Coeff.	P-Value
Technology	GHG Pol. String.	-1	0.265***	(0.008)
		0	-0.103	(0.363)
		1	-0.206*	(0.086)
	Technology	1	0.006	(0.873)
		2	0.031	(0.364)
	Energy Price	1	-0.092	(0.106)
		2	-0.102*	(0.072)
	GDP	1	-0.216	(0.169)
		2	0.259**	(0.042)
	CO2	1	0.215***	(0.000)
		2	-0.009	(0.841)
	Corruption	0	0.004***	(0.002)
		1	0.000	(0.922)
		2	-0.002	(0.724)
	CDD	0	-0.001	(0.947)
		1	0.011	(0.239)
		2	0.000	(0.826)
	HDD	0	0.001	(0.847)
		1	-0.456***	(0.000)
		2	-0.002	(0.842)
	Time FE/Country FE		Yes/Yes	
	R2		0.144	
	Obs.		920	

Dep. Var	Indep. Var	Time Lag	Coeff.	P-Value
GHG. Pol. String.	GHG Pol. String.	-1	0.007	(0.839)
		0	-0.042	(0.191)
	Technology	-1	-0.002	(0.578)
		0	-0.001	(0.806)
	Energy Price	-1	0.006	(0.111)
		0	-0.006	(0.110)
	GDP	-1	0.012	(0.389)
		0	-0.015	(0.203)
	CO2	-1	-0.007	(0.270)
		0	0.013**	(0.032)
	Corruption	-1	-0.002	(0.438)
		0	-0.008***	(0.008)
		1	0.030***	(0.003)
	CDD	-1	0.073***	(0.001)
		0	-0.062***	(0.008)
		1	-0.003	(0.338)
	HDD	-1	-0.002	(0.825)
		0	0.136	(0.595)
		1	-0.044*	(0.058)
	Time FE/Country FE		Yes/Yes	
	R2		0.155	
	Obs.		920	

* p<0.1, ** p<0.05, *** p<0.01, p-values in parenthesis

Table E7: Sector Specification, 2 groups

Variable and Statistics	CO2				GDP			
	Clean		Dirty		Clean		Dirty	
	L0	L1	L0	L1	L0	L1	L0	L1
GHG Pol. String.	-0.226***	0.077**	-0.138***	-0.063*	-0.029*	0.049***	-0.044**	0.017
	(0.000)	(0.043)	(0.000)	(0.069)	(0.092)	(0.006)	(0.039)	(0.463)
ln(Technology)	-0.007	0.010*	0.001	0.003	0.005*	-0.000	0.001	-0.009**
	(0.174)	(0.063)	(0.764)	(0.535)	(0.086)	(0.934)	(0.781)	(0.015)
ln(Energy prices)	-0.058***	-0.057***	-0.083***	-0.054***	-0.041***	-0.000	-0.015*	-0.002
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.987)	(0.066)	(0.801)
ln(GDP)	0.102***	0.046***	0.067***	0.030***	-	0.109***	-	0.065***
	(0.000)	(0.000)	(0.000)	(0.000)	-	(0.000)	-	(0.000)
ln(CO2)	-	-0.083***	-	-0.068***	-	0.007**	-	0.013***
	-	(0.000)	-	(0.000)	-	(0.012)	-	(0.002)
ln(Corruption)	-0.019***	-0.018***	-0.019***	-0.018***	0.003	0.003	0.003	0.003
	(0.000)	(0.000)	(0.000)	(0.000)	(0.257)	(0.205)	(0.257)	(0.205)
ln(CDD)	0.006***	-0.004***	0.006***	-0.004***	0.001	0.001	0.001	0.001
	(0.000)	(0.004)	(0.000)	(0.004)	(0.190)	(0.134)	(0.190)	(0.134)
ln(HDD)	0.010	-0.008	0.010	-0.008	-0.004	0.004	-0.004	0.004
	(0.257)	(0.349)	(0.257)	(0.349)	(0.454)	(0.444)	(0.454)	(0.444)
Time FE/Country FE	Yes/Yes				Yes/Yes			
Obs.	16660				16660			
Pseudo R2	0.10				0.03			

Variable and Statistics	Energy Price				Technology			
	Clean		Dirty		Clean		Dirty	
	L0	L1	L0	L1	L0	L1	L0	L1
GHG Pol. String.	0.058***	-0.057***	0.036***	-0.059***	0.234***	-0.274***	0.234***	-0.271***
	(0.000)	(0.000)	(0.003)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
ln(Technology)	0.015***	0.014***	0.002	0.005*	-	0.035***	-	0.035***
	(0.000)	(0.000)	(0.485)	(0.055)	-	(0.000)	-	(0.000)
ln(Energy prices)	-	0.056***	-	0.058***	-	-0.031***	-	-0.031***
	-	(0.000)	-	(0.000)	-	(0.000)	-	(0.000)
ln(GDP)	-	0.002	-	0.004*	-	-0.000	-	-0.000
	-	(0.578)	-	(0.059)	-	(0.705)	-	(0.904)
ln(CO2)	-	-0.002	-	-0.004*	-	0.000	-	0.000
	-	(0.384)	-	(0.094)	-	(0.646)	-	(0.934)
ln(Corruption)	-0.001	0.026***	-0.001	0.026***	-0.040***	0.013***	-0.040***	0.013***
	(0.654)	(0.000)	(0.654)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
ln(CDD)	-0.002***	0.006***	-0.002***	0.006***	0.015***	0.025***	0.015***	0.025***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
ln(HDD)	0.071***	0.009*	0.071***	0.009*	-0.043***	-0.046***	-0.043***	-0.046***
	(0.000)	(0.066)	(0.000)	(0.066)	(0.000)	(0.000)	(0.000)	(0.000)
Time FE/Country FE	Yes/Yes				Yes/Yes			
Obs.	16660				16660			
Pseudo R2	0.17				0.04			

Variable and Statistics	GHG Pol. String.			
	Clean		Dirty	
	L0	L1	L0	L1
GHG Pol. String.	-	-0.079***	-	-0.049***
	-	(0.000)	-	(0.000)
ln(Technology)	-	-0.002***	-	-0.002***
	-	(0.000)	-	(0.000)
ln(Energy prices)	-	0.009***	-	0.009***
	-	(0.000)	-	(0.000)
ln(GDP)	-	-0.000	-	-0.000
	-	(0.990)	-	(0.819)
ln(CO2)	-	-0.000	-	0.000
	-	(0.702)	-	(0.856)
ln(Corruption)	0.002***	-0.001***	0.002***	-0.001***
	(0.000)	(0.009)	(0.000)	(0.009)
ln(CDD)	-0.002***	-0.001***	-0.002***	-0.001***
	(0.000)	(0.009)	(0.000)	(0.009)
ln(HDD)	0.004***	-0.001***	0.004***	-0.001***
	(0.000)	(0.000)	(0.000)	(0.000)
Time FE/Country FE	Yes/Yes			
Obs.	16660			
Pseudo R2	0.25			

Column titles indicate the sector groups. L0: contemporaneous effect, L1: effect from one time lag. * $p<0.1$, ** $p<0.05$, *** $p<0.01$, p-values in parenthesis

Table E8: Sector Specification, 3 groups

Variable and Statistics	CO2						GDP					
	Clean		Middle		Dirty		Clean		Middle		Dirty	
	L0	L1	L0	L1	L0	L1	L0	L1	L0	L1	L0	L1
GHG Pol. String.	-0.250***	0.017	-0.155***	-0.002	-0.131***	-0.028	-0.045**	0.053***	0.005	0.010	-0.095***	0.013
	(0.000)	(0.688)	(0.001)	(0.964)	(0.001)	(0.487)	(0.018)	(0.007)	(0.823)	(0.679)	(0.002)	(0.669)
ln(Technology)	-0.008	0.010	0.004	0.011*	-0.004	0.000	0.004	0.002	0.002	-0.002	0.008	-0.012**
	(0.273)	(0.148)	(0.509)	(0.087)	(0.411)	(0.931)	(0.242)	(0.433)	(0.633)	(0.539)	(0.125)	(0.011)
ln(Energy prices)	-0.127***	-0.147***	-0.129***	-0.134***	-0.050***	-0.087***	-0.051***	-0.006	-0.047***	-0.005	0.044***	-0.026*
	(0.000)	(0.000)	(0.000)	(0.000)	(0.003)	(0.000)	(0.000)	(0.470)	(0.000)	(0.652)	(0.001)	(0.069)
ln(GDP)	0.100***	0.047***	0.106***	0.034***	0.052***	0.031***	-	0.137***	-	0.083***	-	0.033**
	(0.000)	(0.001)	(0.000)	(0.003)	(0.000)	(0.000)	-	(0.000)	-	(0.000)	-	(0.025)
ln(CO2)	-	-0.088***	-	-0.091***	-	-0.057***	-	0.006**	-	0.009**	-	0.032***
	-	(0.000)	-	(0.000)	-	(0.000)	-	(0.045)	-	(0.023)	-	(0.000)
ln(Corruption)	-0.015***	-0.026***	-0.015***	-0.026***	-0.015***	-0.026***	0.005*	0.000	0.005*	0.000	0.005*	0.000
	(0.001)	(0.000)	(0.001)	(0.000)	(0.001)	(0.000)	(0.097)	(0.968)	(0.097)	(0.968)	(0.097)	(0.968)
ln(CDD)	0.004***	-0.005***	0.004***	-0.005***	0.004***	-0.005***	0.001	0.002*	0.001	0.002*	0.001	0.002*
	(0.007)	(0.000)	(0.007)	(0.000)	(0.007)	(0.000)	(0.169)	(0.063)	(0.169)	(0.063)	(0.169)	(0.063)
ln(HDD)	-0.023**	-0.042***	-0.023**	-0.042***	-0.023**	-0.042***	-0.010*	0.001	-0.010*	0.001	-0.010*	0.001
	(0.029)	(0.000)	(0.029)	(0.000)	(0.029)	(0.000)	(0.078)	(0.871)	(0.078)	(0.871)	(0.078)	(0.871)
Time FE/Country FE	Yes/Yes						Yes/Yes					
Obs.	16660						16660					
Pseudo R2	0.10						0.05					

Variable and Statistics	Energy Price						Technology					
	Clean		Middle		Dirty		Clean		Middle		Dirty	
	L0	L1	L0	L1	L0	L1	L0	L1	L0	L1	L0	L1
GHG Pol. String.	0.035**	-0.060***	0.034**	-0.058***	0.038**	-0.051***	0.138***	0.160***	0.138***	0.160***	0.138***	0.160***
	(0.023)	(0.000)	(0.028)	(0.000)	(0.012)	(0.001)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
ln(Technology)	0.008***	0.009***	0.008***	0.009***	0.007**	0.011***	-	-0.111***	-	-0.111***	-	-0.111***
	(0.006)	(0.002)	(0.006)	(0.002)	(0.012)	(0.000)	-	(0.000)	-	(0.000)	-	(0.000)
ln(Energy prices)	-	0.056***	-	0.056***	-	0.053***	-	0.144***	-	0.144***	-	0.144***
	-	(0.000)	-	(0.000)	-	(0.000)	-	(0.000)	-	(0.000)	-	(0.000)
ln(GDP)	-	0.000	-	0.007	-	0.004*	-	-0.000	-	-0.000	-	-0.000
	-	(0.938)	-	(0.166)	-	(0.084)	-	(0.912)	-	(0.874)	-	(0.917)
ln(CO2)	-	-0.003	-	0.001	-	-0.005	-	-0.000	-	-0.000	-	0.000
	-	(0.118)	-	(0.775)	-	(0.209)	-	(0.973)	-	(0.956)	-	(0.954)
ln(Corruption)	-0.003	0.027***	-0.003	0.027***	-0.003	0.027***	-0.059***	0.025***	-0.059***	0.025***	-0.059***	0.025***
	(0.139)	(0.000)	(0.139)	(0.000)	(0.139)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
ln(CDD)	-0.002***	0.006***	-0.002***	0.006***	-0.002***	0.006***	0.014***	0.009***	0.014***	0.009***	0.014***	0.009***
	(0.001)	(0.000)	(0.001)	(0.000)	(0.001)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
ln(HDD)	0.065***	0.012**	0.065***	0.012**	0.065***	0.012**	-0.125***	0.128***	-0.125***	0.128***	-0.125***	0.128***
	(0.000)	(0.011)	(0.000)	(0.011)	(0.000)	(0.011)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Time FE/Country FE	Yes/Yes						Yes/Yes					
Obs.	16660						16660					
Pseudo R2	0.17						0.08					

Variable and Statistics	GHG Pol. String.					
	Clean		Middle		Dirty	
	L0	L1	L0	L1	L0	L1
GHG Pol. String.	-	-0.060***	-	-0.060***	-	-0.060***
	-	(0.000)	-	(0.000)	-	(0.000)
ln(Technology)	-	-0.004***	-	-0.004***	-	-0.004***
	-	(0.000)	-	(0.000)	-	(0.000)
ln(Energy prices)	-	0.011***	-	0.011***	-	0.011***
	-	(0.000)	-	(0.000)	-	(0.000)
ln(GDP)	-	-0.000	-	-0.000	-	-0.000
	-	(0.827)	-	(0.948)	-	(0.857)
ln(CO2)	-	-0.000	-	-0.000	-	-0.000
	-	(0.724)	-	(0.895)	-	(0.976)
ln(Corruption)	-0.010***	-0.014***	-0.010***	-0.014***	-0.010***	-0.014***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
ln(CDD)	-0.002***	-0.002***	-0.002***	-0.002***	-0.002***	-0.002***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
ln(HDD)	-0.016***	-0.010***	-0.016***	-0.010***	-0.016***	-0.010***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Time FE/Country FE	Yes/Yes					
Obs.	16660					
Pseudo R2	0.22					

Column titles indicate the sector groups. L0: contemporaneous effect, L1: effect from one time lag. * $p<0.1$, ** $p<0.05$, *** $p<0.01$, p-values in parenthesis

Table E9: Sector Specification alternative ordering 1: technology, gdp, energy price (continued on next page)

Variable and Statistics	CO2							
	Very Clean		Clean		Dirty		Very Dirty	
	L0	L1	L0	L1	L0	L1	L0	L1
GHG Pol. String.	-0.271***	0.023	-0.197***	0.030	-0.082*	0.017	-0.176***	-0.017
	(0.000)	(0.653)	(0.000)	(0.543)	(0.088)	(0.736)	(0.000)	(0.722)
ln(Technology)	0.001	0.008	0.011*	0.014**	0.010*	-0.002	0.004	-0.005
	(0.842)	(0.271)	(0.079)	(0.023)	(0.090)	(0.703)	(0.419)	(0.366)
ln(GDP)	0.102***	0.036**	0.110***	0.068***	0.079***	0.002	0.064***	0.042***
	(0.000)	(0.025)	(0.000)	(0.000)	(0.000)	(0.810)	(0.000)	(0.000)
ln(Energy price)	-0.111***	-0.059***	-0.073***	-0.057***	-0.087***	-0.063***	-0.009	-0.012
	(0.000)	(0.003)	(0.000)	(0.002)	(0.000)	(0.001)	(0.600)	(0.503)
ln(CO2)	-	-0.079***	-	-0.097***	-	-0.080***	-	-0.051***
	-	(0.000)	-	(0.000)	-	(0.000)	-	(0.003)
ln(Corruption)	-0.019***	-0.017***	-0.019***	-0.017***	-0.019***	-0.017***	-0.019***	-0.017***
	(0.004)	(0.004)	(0.004)	(0.004)	(0.004)	(0.004)	(0.004)	(0.004)
ln(CDD)	0.006***	-0.005***	0.006***	-0.005***	0.006***	-0.005***	0.006***	-0.005***
	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
ln(HDD)	0.011	-0.008	0.011	-0.008	0.011	-0.008	0.011	-0.008
	(0.009)	(0.009)	(0.009)	(0.009)	(0.009)	(0.009)	(0.009)	(0.009)
Time FE/Country FE	Yes/Yes							
Obs.	16,660							
Pseudo R2	0.09							

Variable and Statistics	GDP							
	Very Clean		Clean		Dirty		Very Dirty	
	L0	L1	L0	L1	L0	L1	L0	L1
GHG Pol. String.	-0.045**	0.033	-0.013	0.042*	0.034*	-0.061***	-0.102***	-0.020
	(0.035)	(0.131)	(0.598)	(0.093)	(0.064)	(0.001)	(0.005)	(0.596)
ln(Technology)	0.003	0.003	0.003	-0.003	0.007**	0.025***	0.009	-0.003
	(0.402)	(0.389)	(0.380)	(0.436)	(0.027)	(0.000)	(0.131)	(0.590)
ln(GDP)	-	0.148***	-	0.069***	-0.002	0.010**	-	0.029*
	-	(0.000)	-	(0.000)	(0.710)	(0.036)	-	(0.081)
ln(Energy price)	-	0.002	-	-0.008	-	0.056***	-	-0.013
	-	(0.829)	-	(0.413)	-	(0.000)	-	(0.399)
ln(CO2)	-	0.003	-	0.008**	-	-0.001	-	0.037***
	-	(0.347)	-	(0.040)	-	(0.787)	-	(0.000)
ln(Corruption)	0.002	0.003	0.002	0.003	0.002	0.003	0.002	0.003
	(0.451)	(0.290)	(0.451)	(0.290)	(0.451)	(0.290)	(0.451)	(0.290)
ln(CDD)	0.001*	0.001	0.001*	0.001	0.001*	0.001	0.001*	0.001
	(0.091)	(0.268)	(0.091)	(0.268)	(0.091)	(0.268)	(0.091)	(0.268)
ln(HDD)	-0.007	0.003	-0.007	0.003	-0.007	0.003	-0.007	0.003
	(0.147)	(0.501)	(0.147)	(0.501)	(0.147)	(0.501)	(0.147)	(0.501)
Time FE/Country FE	Yes/Yes							
Obs.	16,660							
Pseudo R2	0.04							

Variable and Statistics	Energy Price							
	Very Clean		Clean		Dirty		Very Dirty	
	L0	L1	L0	L1	L0	L1	L0	L1
GHG Pol. String.	0.034*	-0.063***	0.035**	-0.061***	-0.038	0.038	0.040**	-0.052***
	(0.059)	(0.001)	(0.042)	(0.001)	(0.221)	(0.241)	(0.024)	(0.005)
ln(Technology)	0.007**	0.024***	0.007**	0.024***	0.001	-0.004	0.007**	0.025***
	(0.024)	(0.000)	(0.015)	(0.000)	(0.800)	(0.397)	(0.027)	(0.000)
ln(GDP)	-0.006	0.002	0.001	0.003	-	0.093***	0.002	0.003
	(0.315)	(0.750)	(0.859)	(0.682)	-	(0.000)	(0.404)	(0.131)
ln(Energy price)	-	0.057***	-	0.057***	-	-0.011	-	0.055***
	-	(0.000)	-	(0.000)	-	(0.346)	-	(0.000)
ln(CO2)	-	-0.004*	-	0.001	-	0.012**	-	-0.004
	-	(0.096)	-	(0.832)	-	(0.021)	-	(0.331)
ln(Corruption)	-0.002	0.027***	-0.002	0.027***	-0.002	0.027***	-0.002	0.027***
	(0.281)	(0.000)	(0.281)	(0.000)	(0.281)	(0.000)	(0.281)	(0.000)
ln(CDD)	-0.002***	0.006***	-0.002***	0.006***	-0.002***	0.006***	-0.002***	0.006***
	(0.002)	(0.000)	(0.002)	(0.000)	(0.002)	(0.000)	(0.002)	(0.000)
ln(HDD)	0.071***	0.008	0.071***	0.008	0.071***	0.008	0.071***	0.008
	(0.000)	(0.108)	(0.000)	(0.108)	(0.000)	(0.108)	(0.000)	(0.108)
Time FE/Country FE	Yes/Yes							
Obs.	16,660							
Pseudo R2	0.17							

Column titles indicate the sector groups. L0: contemporaneous effect, L1: effect from one time lag. * p<0.1, ** p<0.05, *** p<0.01, p-values in parenthesis

Table E9: Sector Specification alternative ordering 1: technology, gdp, energy price (continued)

Variable and Statistics	Technology							
	Very Clean		Clean		Dirty		Very Dirty	
	L0	L1	L0	L1	L0	L1	L0	L1
GHG Pol. String.	0.126*** (0.009)	0.047 (0.372)	0.163*** (0.000)	0.012 (0.815)	0.159*** (0.001)	0.033 (0.522)	0.126*** (0.005)	0.043 (0.384)
ln(Technology)	- -	-0.082*** (0.000)	- -	-0.086*** (0.000)	- -	-0.086*** (0.000)	- -	-0.090*** (0.000)
ln(GDP)	- -	-0.026** (0.030)	- -	-0.060*** (0.000)	- -	-0.032** (0.012)	- -	-0.003 (0.657)
ln(Energy price)	- -	-0.016 (0.220)	- -	-0.013 (0.283)	- -	-0.018 (0.174)	- -	-0.012 (0.329)
ln(CO2)	- -	0.010* (0.093)	- -	-0.004 (0.517)	- -	-0.022*** (0.006)	- -	0.006 (0.329)
ln(Corruption)	-0.017*** (0.000)	0.012*** (0.000)	-0.017*** (0.000)	0.012*** (0.000)	-0.017*** (0.000)	0.012*** (0.000)	-0.017*** (0.000)	0.012*** (0.000)
ln(CDD)	0.022*** (0.000)	0.015*** (0.000)	0.022*** (0.000)	0.015*** (0.000)	0.022*** (0.000)	0.015*** (0.000)	0.022*** (0.000)	0.015*** (0.000)
ln(HDD)	-0.035*** (0.000)	0.030*** (0.000)	-0.035*** (0.000)	0.030*** (0.000)	-0.035*** (0.000)	0.030*** (0.000)	-0.035*** (0.000)	0.030*** (0.000)
Time FE/Country FE	Yes/Yes							
Obs.	16,660							
Pseudo R2	0.08							
Variable and Statistics	GHG Policy Stringency							
	Very Clean		Clean		Dirty		Very Dirty	
	L0	L1	L0	L1	L0	L1	L0	L1
GHG Pol. String.	- -	-0.060*** (0.000)	- -	-0.060*** (0.000)	- -	-0.058*** (0.000)	- -	-0.042*** (0.007)
ln(Technology)	- -	-0.004*** (0.000)	- -	-0.004*** (0.000)	- -	-0.004*** (0.000)	- -	-0.004*** (0.000)
ln(GDP)	- -	0.000 (0.956)	- -	-0.000 (0.968)	- -	-0.000 (0.746)	- -	-0.000 (0.938)
ln(Energy price)	- -	0.010*** (0.000)	- -	0.010*** (0.000)	- -	0.010*** (0.000)	- -	0.010*** (0.000)
ln(CO2)	- -	-0.000 (0.787)	- -	-0.000 (0.793)	- -	0.000 (0.730)	- -	0.000 (0.995)
ln(Corruption)	0.002*** (0.000)	0.000 (0.272)	0.002*** (0.000)	0.000 (0.272)	0.002*** (0.000)	0.000 (0.272)	0.002*** (0.000)	0.000 (0.272)
ln(CDD)	-0.002*** (0.000)	0.000 (0.412)	-0.002*** (0.000)	0.000 (0.412)	-0.002*** (0.000)	0.000 (0.412)	-0.002*** (0.000)	0.000 (0.412)
ln(HDD)	0.003*** (0.000)	-0.001* (0.052)	0.003*** (0.000)	-0.001* (0.052)	0.003*** (0.000)	-0.001* (0.052)	0.003*** (0.000)	-0.001* (0.052)
Time FE/Country FE	Yes/Yes							
Obs.	16,660							
Pseudo R2	0.25							

Column titles indicate the sector groups. L0: contemporaneous effect, L1: effect from one time lag. * $p<0.1$, ** $p<0.05$, *** $p<0.01$, p-values in parenthesis

Table E10: Sector Specification alternative ordering 2: energy price, technology, gdp (continued on next page)

Variable and Statistics	CO2							
	Very Clean		Clean		Dirty		Very Dirty	
	L0	L1	L0	L1	L0	L1	L0	L1
GHG Pol. String.	-0.271***	0.023	-0.197***	0.030	-0.082*	0.017	-0.176***	-0.017
	(0.000)	(0.653)	(0.000)	(0.543)	(0.088)	(0.736)	(0.000)	(0.722)
ln(Energy price)	-0.111***	-0.059***	-0.073***	-0.057***	-0.087***	-0.063***	-0.009	-0.012
	(0.000)	(0.003)	(0.000)	(0.002)	(0.000)	(0.001)	(0.600)	(0.503)
ln(Technology)	0.001	0.008	0.011*	0.014**	0.010*	-0.002	0.004	-0.005
	(0.842)	(0.271)	(0.079)	(0.023)	(0.090)	(0.703)	(0.419)	(0.366)
ln(GDP)	0.102***	0.036**	0.110***	0.068***	0.079***	0.002	0.064***	0.042***
	(0.000)	(0.025)	(0.000)	(0.000)	(0.000)	(0.810)	(0.000)	(0.000)
ln(CO2)	-	-0.079***	-	-0.097***	-	-0.080***	-	-0.051***
	-	(0.000)	-	(0.000)	-	(0.000)	-	(0.003)
ln(Corruption)	0.002	0.003	0.002	0.003	0.002	0.003	0.002	0.003
	(0.003)	(0.002)	(0.003)	(0.002)	(0.003)	(0.002)	(0.003)	(0.002)
ln(CDD)	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001
	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
ln(HDD)	-0.003	0.004	-0.003	0.004	-0.003	0.004	-0.003	0.004
	(0.005)	(0.005)	(0.005)	(0.005)	(0.005)	(0.005)	(0.005)	(0.005)
Time FE/Country FE	Yes/Yes							
Obs.	16,660							
Pseudo R2	0.09							

Variable and Statistics	GDP							
	Very Clean		Clean		Dirty		Very Dirty	
	L0	L1	L0	L1	L0	L1	L0	L1
GHG Pol. String.	-0.043**	0.036*	-0.010	0.044*	-0.035	0.038	-0.099***	-0.025
	(0.041)	(0.094)	(0.682)	(0.082)	(0.262)	(0.249)	(0.007)	(0.504)
ln(Energy price)	-0.041***	-0.000	-0.037***	-0.009	-0.022**	-0.011	0.030**	-0.013
	(0.000)	(0.955)	(0.000)	(0.371)	(0.038)	(0.330)	(0.028)	(0.393)
ln(Technology)	0.004	0.004	0.005	-0.001	0.002	-0.003	0.007	-0.005
	(0.186)	(0.175)	(0.172)	(0.764)	(0.626)	(0.512)	(0.226)	(0.443)
ln(GDP)	-	0.149***	-	0.071***	-	0.094***	-	0.028
	-	(0.000)	-	(0.000)	-	(0.000)	-	(0.103)
ln(CO2)	-	0.003	-	0.008**	-	0.013**	-	0.036***
	-	(0.333)	-	(0.023)	-	(0.020)	-	(0.000)
ln(Corruption)	0.002	0.003	0.002	0.003	0.002	0.003	0.002	0.003
	(0.451)	(0.290)	(0.451)	(0.290)	(0.451)	(0.290)	(0.451)	(0.290)
ln(CDD)	0.001*	0.001	0.001*	0.001	0.001*	0.001	0.001*	0.001
	(0.091)	(0.268)	(0.091)	(0.268)	(0.091)	(0.268)	(0.091)	(0.268)
ln(HDD)	-0.007	0.003	-0.007	0.003	-0.007	0.003	-0.007	0.003
	(0.147)	(0.501)	(0.147)	(0.501)	(0.147)	(0.501)	(0.147)	(0.501)
Time FE/Country FE	Yes/Yes							
Obs.	16,660							
Pseudo R2	0.04							

Variable and Statistics	Energy Price							
	Very Clean		Clean		Dirty		Very Dirty	
	L0	L1	L0	L1	L0	L1	L0	L1
GHG Pol. String.	0.038**	-0.067***	0.037**	-0.065***	-0.038	0.038	0.043**	-0.054***
	(0.040)	(0.000)	(0.045)	(0.001)	(0.221)	(0.241)	(0.017)	(0.003)
ln(Energy price)	-	0.059***	-	0.058***	0.001	-0.004	-	0.057***
	-	(0.000)	-	(0.000)	(0.800)	(0.397)	-	(0.000)
ln(Technology)	-	0.021***	-	0.021***	-	0.093***	-	0.022***
	-	(0.000)	-	(0.000)	-	(0.000)	-	(0.000)
ln(GDP)	-	0.002	-	0.011**	-	-0.011	-	0.003
	-	(0.726)	-	(0.025)	-	(0.346)	-	(0.168)
ln(CO2)	-	-0.004*	-	-0.001	-	0.012**	-	-0.005
	-	(0.085)	-	(0.775)	-	(0.021)	-	(0.298)
ln(Corruption)	-0.002	0.027***	-0.002	0.027***	-0.002	0.027***	-0.002	0.027***
	(0.359)	(0.000)	(0.359)	(0.000)	(0.359)	(0.000)	(0.359)	(0.000)
ln(CDD)	-0.002***	0.006***	-0.002***	0.006***	-0.002***	0.006***	-0.002***	0.006***
	(0.001)	(0.000)	(0.001)	(0.000)	(0.001)	(0.000)	(0.001)	(0.000)
ln(HDD)	0.073***	0.007	0.073***	0.007	0.073***	0.007	0.073***	0.007
	(0.000)	(0.129)	(0.000)	(0.129)	(0.000)	(0.129)	(0.000)	(0.129)
Time FE/Country FE	Yes/Yes							
Obs.	16,660							
Pseudo R2	0.17							

Column titles indicate the sector groups. L0: contemporaneous effect, L1: effect from one time lag. * p<0.1, ** p<0.05, *** p<0.01, p-values in parenthesis

Table E10: Sector Specification alternative ordering 2: energy price, technology, gdp (continued)

Variable and Statistics	Technology							
	Very Clean		Clean		Dirty		Very Dirty	
	L0	L1	L0	L1	L0	L1	L0	L1
GHG Pol. String.	0.133***	0.223***	0.133***	0.223***	0.133***	0.223***	0.133***	0.223***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
ln(Energy price)	0.085***	0.002	0.085***	0.002	0.085***	0.002	0.085***	0.002
	(0.000)	(0.842)	(0.000)	(0.842)	(0.000)	(0.842)	(0.000)	(0.842)
ln(Technology)	-	-0.125***	-	-0.125***	-	-0.125***	-	-0.125***
	-	(0.000)	-	(0.000)	-	(0.000)	-	(0.000)
ln(GDP)	-	-0.000	-	-0.000	-	-0.000	-	-0.000
	-	(0.914)	-	(0.832)	-	(0.854)	-	(0.925)
ln(CO2)	-	-0.000	-	-0.000	-	-0.000	-	0.000
	-	(0.983)	-	(0.916)	-	(0.864)	-	(0.956)
ln(Corruption)	-0.030***	0.029***	-0.030***	0.029***	-0.030***	0.029***	-0.030***	0.029***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
ln(CDD)	0.025***	0.011***	0.025***	0.011***	0.025***	0.011***	0.025***	0.011***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
ln(HDD)	-0.085***	0.069***	-0.085***	0.069***	-0.085***	0.069***	-0.085***	0.069***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Time FE/Country FE	Yes/Yes							
Obs.	16,660							
Pseudo R2	0.10							

Variable and Statistics	GHG Policy Stringency							
	Very Clean		Clean		Dirty		Very Dirty	
	L0	L1	L0	L1	L0	L1	L0	L1
GHG Pol. String.	-	-0.060***	-	-0.060***	-	-0.058***	-	-0.042***
	-	(0.000)	-	(0.000)	-	(0.000)	-	(0.007)
ln(Energy price)	-	0.010***	-	0.010***	-	0.010***	-	0.010***
	-	(0.000)	-	(0.000)	-	(0.000)	-	(0.000)
ln(Technology)	-	-0.004***	-	-0.004***	-	-0.004***	-	-0.004***
	-	(0.000)	-	(0.000)	-	(0.000)	-	(0.000)
ln(GDP)	-	0.000	-	-0.000	-	-0.000	-	-0.000
	-	(0.956)	-	(0.968)	-	(0.746)	-	(0.938)
ln(CO2)	-	-0.000	-	-0.000	-	0.000	-	0.000
	-	(0.787)	-	(0.793)	-	(0.730)	-	(0.995)
ln(Corruption)	0.002***	0.000	0.002***	0.000	0.002***	0.000	0.002***	0.000
	(0.000)	(0.272)	(0.000)	(0.272)	(0.000)	(0.272)	(0.000)	(0.272)
ln(CDD)	-0.002***	0.000	-0.002***	0.000	-0.002***	0.000	-0.002***	0.000
	(0.000)	(0.413)	(0.000)	(0.413)	(0.000)	(0.413)	(0.000)	(0.413)
ln(HDD)	0.003***	-0.001*	0.003***	-0.001*	0.003***	-0.001*	0.003***	-0.001*
	(0.000)	(0.052)	(0.000)	(0.052)	(0.000)	(0.052)	(0.000)	(0.052)
Time FE/Country FE	Yes/Yes							
Obs.	16,660							
Pseudo R2	0.25							

Column titles indicate the sector groups. L0: contemporaneous effect, L1: effect from one time lag. * p<0.1, ** p<0.05, *** p<0.01, p-values in parenthesis

Table E11: Sector Specification alternative ordering 3: gdp, technology, energy price (continued on next page)

Variable and Statistics	CO2							
	Very Clean		Clean		Dirty		Very Dirty	
	L0	L1	L0	L1	L0	L1	L0	L1
GHG Pol. String.	-0.271***	0.023	-0.197***	0.030	-0.082*	0.017	-0.176***	-0.017
	(0.000)	(0.653)	(0.000)	(0.543)	(0.088)	(0.736)	(0.000)	(0.722)
ln(GDP)	0.102***	0.036**	0.110***	0.068***	0.079***	0.002	0.064***	0.042***
	(0.000)	(0.025)	(0.000)	(0.000)	(0.000)	(0.810)	(0.000)	(0.000)
ln(Technology)	0.001	0.008	0.011*	0.014**	0.010*	-0.002	0.004	-0.005
	(0.842)	(0.271)	(0.079)	(0.023)	(0.090)	(0.703)	(0.419)	(0.366)
ln(Energy price)	-0.111***	-0.059***	-0.073***	-0.057***	-0.087***	-0.063***	-0.009	-0.012
	(0.000)	(0.003)	(0.000)	(0.002)	(0.000)	(0.001)	(0.600)	(0.503)
ln(CO2)	-	-0.079***	-	-0.097***	-	-0.080***	-	-0.051***
	-	(0.000)	-	(0.000)	-	(0.000)	-	(0.003)
ln(Corruption)	-0.019***	-0.017***	-0.019***	-0.017***	-0.019***	-0.017***	-0.019***	-0.017***
	(0.004)	(0.004)	(0.004)	(0.004)	(0.004)	(0.004)	(0.004)	(0.004)
ln(CDD)	0.006***	-0.005***	0.006***	-0.005***	0.006***	-0.005***	0.006***	-0.005***
	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
ln(HDD)	0.011	-0.008	0.011	-0.008	0.011	-0.008	0.011	-0.008
	(0.009)	(0.009)	(0.009)	(0.009)	(0.009)	(0.009)	(0.009)	(0.009)
Time FE/Country FE	Yes/Yes							
Obs.	16,660							
Pseudo R2	0.09							

Variable and Statistics	GDP							
	Very Clean		Clean		Dirty		Very Dirty	
	L0	L1	L0	L1	L0	L1	L0	L1
GHG Pol. String.	-0.044**	0.033	-0.012	0.041	-0.038	0.038	-0.100***	-0.015
	(0.038)	(0.132)	(0.619)	(0.106)	(0.222)	(0.248)	(0.005)	(0.677)
ln(GDP)	-	0.148***	-	0.069***	-	0.093***	-	0.030*
	-	(0.000)	-	(0.000)	-	(0.000)	-	(0.076)
ln(Technology)	-	0.002	-	-0.004	-	-0.004	-	-0.006
	-	(0.564)	-	(0.293)	-	(0.321)	-	(0.289)
ln(Energy price)	-	0.001	-	-0.008	-	-0.011	-	-0.015
	-	(0.895)	-	(0.385)	-	(0.336)	-	(0.326)
ln(CO2)	-	0.003	-	0.008**	-	0.012**	-	0.036***
	-	(0.337)	-	(0.038)	-	(0.020)	-	(0.000)
ln(Corruption)	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002
	(0.483)	(0.294)	(0.483)	(0.294)	(0.483)	(0.294)	(0.483)	(0.294)
ln(CDD)	0.001*	0.001	0.001*	0.001	0.001*	0.001	0.001*	0.001
	(0.098)	(0.245)	(0.098)	(0.245)	(0.098)	(0.245)	(0.098)	(0.245)
ln(HDD)	-0.007	0.003	-0.007	0.003	-0.007	0.003	-0.007	0.003
	(0.132)	(0.497)	(0.132)	(0.497)	(0.132)	(0.497)	(0.132)	(0.497)
Time FE/Country FE	Yes/Yes							
Obs.	16,660							
Pseudo R2	0.04							

Variable and Statistics	Energy Price							
	Very Clean		Clean		Dirty		Very Dirty	
	L0	L1	L0	L1	L0	L1	L0	L1
GHG Pol. String.	0.034*	-0.063***	0.035**	-0.061***	0.034*	-0.061***	0.040**	-0.052***
	(0.059)	(0.001)	(0.042)	(0.001)	(0.064)	(0.001)	(0.024)	(0.005)
ln(GDP)	-0.006	0.002	0.001	0.003	-0.002	0.010**	0.002	0.003
	(0.315)	(0.750)	(0.859)	(0.682)	(0.710)	(0.036)	(0.404)	(0.131)
ln(Technology)	0.007**	0.024***	0.007**	0.024***	0.007**	0.025***	0.007**	0.025***
	(0.024)	(0.000)	(0.015)	(0.000)	(0.027)	(0.000)	(0.027)	(0.000)
ln(Energy price)	-	0.057***	-	0.057***	-	0.056***	-	0.055***
	-	(0.000)	-	(0.000)	-	(0.000)	-	(0.000)
ln(CO2)	-	-0.004*	-	0.001	-	-0.001	-	-0.004
	-	(0.096)	-	(0.832)	-	(0.787)	-	(0.331)
ln(Corruption)	-0.002	0.027***	-0.002	0.027***	-0.002	0.027***	-0.002	0.027***
	(0.281)	(0.000)	(0.281)	(0.000)	(0.281)	(0.000)	(0.281)	(0.000)
ln(CDD)	-0.002***	0.006***	-0.002***	0.006***	-0.002***	0.006***	-0.002***	0.006***
	(0.002)	(0.000)	(0.002)	(0.000)	(0.002)	(0.000)	(0.002)	(0.000)
ln(HDD)	0.071***	0.008	0.071***	0.008	0.071***	0.008	0.071***	0.008
	(0.000)	(0.108)	(0.000)	(0.108)	(0.000)	(0.108)	(0.000)	(0.108)
Time FE/Country FE	Yes/Yes							
Obs.	16,660							
Pseudo R2	0.17							

Column titles indicate the sector groups. L0: contemporaneous effect, L1: effect from one time lag. * p<0.1, ** p<0.05, *** p<0.01, p-values in parenthesis

Table E11: Sector Specification alternative ordering 3: gdp, technology, energy price (continued)

Variable and Statistics	Technology							
	Very Clean		Clean		Dirty		Very Dirty	
	L0	L1	L0	L1	L0	L1	L0	L1
GHG Pol. String.	0.122**	0.056	0.158***	0.022	0.160***	0.037	0.128***	0.038
	(0.011)	(0.291)	(0.000)	(0.656)	(0.001)	(0.476)	(0.005)	(0.441)
ln(GDP)	-0.024**	-0.026**	-0.024**	-0.063***	-0.013	-0.033***	-0.002	-0.003
	(0.032)	(0.030)	(0.036)	(0.000)	(0.276)	(0.009)	(0.806)	(0.659)
ln(Technology)	-	-0.080***	-	-0.086***	-	-0.084***	-	-0.088***
	-	(0.000)	-	(0.000)	-	(0.000)	-	(0.000)
ln(Energy price)	-	-0.016	-	-0.012	-	-0.019	-	-0.013
	-	(0.205)	-	(0.327)	-	(0.157)	-	(0.293)
ln(CO2)	-	0.010*	-	-0.005	-	-0.022***	-	0.006
	-	(0.096)	-	(0.432)	-	(0.006)	-	(0.326)
ln(Corruption)	-0.017***	0.012***	-0.017***	0.012***	-0.017***	0.012***	-0.017***	0.012***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
ln(CDD)	0.022***	0.015***	0.022***	0.015***	0.022***	0.015***	0.022***	0.015***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
ln(HDD)	-0.034***	0.029***	-0.034***	0.029***	-0.034***	0.029***	-0.034***	0.029***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Time FE/Country FE	Yes/Yes							
Obs.	16,660							
Pseudo R2	0.08							
Variable and Statistics	GHG Policy Stringency							
	Very Clean		Clean		Dirty		Very Dirty	
	L0	L1	L0	L1	L0	L1	L0	L1
GHG Pol. String.	-	-0.060***	-	-0.060***	-	-0.058***	-	-0.042***
	-	(0.000)	-	(0.000)	-	(0.000)	-	(0.007)
ln(GDP)	-	0.000	-	-0.000	-	-0.000	-	-0.000
	-	(0.956)	-	(0.968)	-	(0.746)	-	(0.938)
ln(Technology)	-	-0.004***	-	-0.004***	-	-0.004***	-	-0.004***
	-	(0.000)	-	(0.000)	-	(0.000)	-	(0.000)
ln(Energy price)	-	0.010***	-	0.010***	-	0.010***	-	0.010***
	-	(0.000)	-	(0.000)	-	(0.000)	-	(0.000)
ln(CO2)	-	-0.000	-	-0.000	-	0.000	-	0.000
	-	(0.787)	-	(0.793)	-	(0.730)	-	(0.995)
ln(Corruption)	0.002***	0.000	0.002***	0.000	0.002***	0.000	0.002***	0.000
	(0.000)	(0.272)	(0.000)	(0.272)	(0.000)	(0.272)	(0.000)	(0.272)
ln(CDD)	-0.002***	0.000	-0.002***	0.000	-0.002***	0.000	-0.002***	0.000
	(0.000)	(0.410)	(0.000)	(0.410)	(0.000)	(0.410)	(0.000)	(0.410)
ln(HDD)	0.003***	-0.001*	0.003***	-0.001*	0.003***	-0.001*	0.003***	-0.001*
	(0.000)	(0.052)	(0.000)	(0.052)	(0.000)	(0.052)	(0.000)	(0.052)
Time FE/Country FE	Yes/Yes							
Obs.	16,660							
Pseudo R2	0.25							

Column titles indicate the sector groups. L0: contemporaneous effect, L1: effect from one time lag. * p<0.1, ** p<0.05, *** p<0.01, p-values in parenthesis

Table E12: Sector Specification alternative ordering 4: energy price, gdp, technology (continued on next page)

Variable and Statistics	CO2							
	Very Clean		Clean		Dirty		Very Dirty	
	L0	L1	L0	L1	L0	L1	L0	L1
GHG Pol. String.	-0.271***	0.023	-0.197***	0.030	-0.082*	0.017	-0.176***	-0.017
	(0.000)	(0.653)	(0.000)	(0.543)	(0.088)	(0.736)	(0.000)	(0.722)
ln(Energy prices)	-0.111***	-0.059***	-0.073***	-0.057***	-0.087***	-0.063***	-0.009	-0.012
	(0.000)	(0.003)	(0.000)	(0.002)	(0.000)	(0.001)	(0.600)	(0.503)
ln(GDP)	0.102***	0.036**	0.110***	0.068***	0.079***	0.002	0.064***	0.042***
	(0.000)	(0.025)	(0.000)	(0.000)	(0.000)	(0.810)	(0.000)	(0.000)
ln(Technology)	0.001	0.008	0.011*	0.014**	0.010*	-0.002	0.004	-0.005
	(0.842)	(0.271)	(0.079)	(0.023)	(0.090)	(0.703)	(0.419)	(0.366)
ln(CO2)	-	-0.079***	-	-0.097***	-	-0.080***	-	-0.051***
	-	(0.000)	-	(0.000)	-	(0.000)	-	(0.003)
ln(Corruption)	-0.019***	-0.017***	-0.019***	-0.017***	-0.019***	-0.017***	-0.019***	-0.017***
	(0.004)	(0.004)	(0.004)	(0.004)	(0.004)	(0.004)	(0.004)	(0.004)
ln(CDD)	0.006***	-0.005***	0.006***	-0.005***	0.006***	-0.005***	0.006***	-0.005***
	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
ln(HDD)	0.011	-0.008	0.011	-0.008	0.011	-0.008	0.011	-0.008
	(0.009)	(0.009)	(0.009)	(0.009)	(0.009)	(0.009)	(0.009)	(0.009)
Time FE/Country FE	Yes/Yes							
Obs.	16,660							
Pseudo R2	0.09							

Variable and Statistics	GDP							
	Very Clean		Clean		Dirty		Very Dirty	
	L0	L1	L0	L1	L0	L1	L0	L1
GHG Pol. String.	-0.042**	0.036*	-0.009	0.041*	-0.034	0.036	-0.097***	-0.022
	(0.047)	(0.097)	(0.719)	(0.099)	(0.267)	(0.265)	(0.008)	(0.559)
ln(Energy prices)	-0.040***	-0.002	-0.036***	-0.009	-0.021**	-0.012	0.032**	-0.015
	(0.000)	(0.841)	(0.000)	(0.332)	(0.048)	(0.310)	(0.016)	(0.330)
ln(GDP)	-	0.149***	-	0.072***	-	0.094***	-	0.028*
	-	(0.000)	-	(0.000)	-	(0.000)	-	(0.099)
ln(Technology)	-	0.003	-	-0.003	-	-0.004	-	-0.007
	-	(0.370)	-	(0.475)	-	(0.378)	-	(0.230)
ln(CO2)	-	0.004	-	0.009**	-	0.013**	-	0.035***
	-	(0.312)	-	(0.022)	-	(0.018)	-	(0.000)
ln(Corruption)	0.002	0.003	0.002	0.003	0.002	0.003	0.002	0.003
	(0.397)	(0.184)	(0.397)	(0.184)	(0.397)	(0.184)	(0.397)	(0.184)
ln(CDD)	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001
	(0.165)	(0.133)	(0.165)	(0.133)	(0.165)	(0.133)	(0.165)	(0.133)
ln(HDD)	-0.004	0.004	-0.004	0.004	-0.004	0.004	-0.004	0.004
	(0.452)	(0.390)	(0.452)	(0.390)	(0.452)	(0.390)	(0.452)	(0.390)
Time FE/Country FE	Yes/Yes							
Obs.	16,660							
Pseudo R2	0.04							

Variable and Statistics	Energy Price							
	Very Clean		Clean		Dirty		Very Dirty	
	L0	L1	L0	L1	L0	L1	L0	L1
GHG Pol. String.	0.038**	-0.067***	0.038**	-0.065***	0.037**	-0.065***	0.043**	-0.054***
	(0.040)	(0.000)	(0.028)	(0.000)	(0.045)	(0.001)	(0.017)	(0.003)
ln(Energy prices)	-	0.059***	-	0.058***	-	0.058***	-	0.057***
	-	(0.000)	-	(0.000)	-	(0.000)	-	(0.000)
ln(GDP)	-	0.002	-	0.002	-	0.011**	-	0.003
	-	(0.726)	-	(0.727)	-	(0.025)	-	(0.168)
ln(Technology)	-	0.021***	-	0.021***	-	0.021***	-	0.022***
	-	(0.000)	-	(0.000)	-	(0.000)	-	(0.000)
ln(CO2)	-	-0.004*	-	0.001	-	-0.001	-	-0.005
	-	(0.085)	-	(0.795)	-	(0.775)	-	(0.298)
ln(Corruption)	-0.002	0.027***	-0.002	0.027***	-0.002	0.027***	-0.002	0.027***
	(0.359)	(0.000)	(0.359)	(0.000)	(0.359)	(0.000)	(0.359)	(0.000)
ln(CDD)	-0.002***	0.006***	-0.002***	0.006***	-0.002***	0.006***	-0.002***	0.006***
	(0.001)	(0.000)	(0.001)	(0.000)	(0.001)	(0.000)	(0.001)	(0.000)
ln(HDD)	0.073***	0.007	0.073***	0.007	0.073***	0.007	0.073***	0.007
	(0.000)	(0.129)	(0.000)	(0.129)	(0.000)	(0.129)	(0.000)	(0.129)
Time FE/Country FE	Yes/Yes							
Obs.	16,660							
Pseudo R2	0.17							

Column titles indicate the sector groups. L0: contemporaneous effect, L1: effect from one time lag. * p<0.1, ** p<0.05, *** p<0.01, p-values in parenthesis

Table E12: Sector Specification alternative ordering 4: energy price, gdp, technology (continued)

Variable and Statistics	Technology							
	Very Clean		Clean		Dirty		Very Dirty	
	L0	L1	L0	L1	L0	L1	L0	L1
GHG Pol. String.	0.117**	0.075	0.155***	0.042	0.157***	0.059	0.121***	0.060
	(0.014)	(0.151)	(0.001)	(0.397)	(0.001)	(0.243)	(0.007)	(0.216)
ln(Energy prices)	0.024*	-0.022	0.029**	-0.020	0.027**	-0.025*	0.021*	-0.017
	(0.060)	(0.110)	(0.019)	(0.140)	(0.036)	(0.073)	(0.089)	(0.207)
ln(GDP)	-0.020*	-0.027**	-0.022*	-0.064***	-0.011	-0.035***	-0.002	-0.004
	(0.067)	(0.023)	(0.057)	(0.000)	(0.342)	(0.005)	(0.802)	(0.545)
ln(Technology)	-	-0.086***	-	-0.092***	-	-0.090***	-	-0.094***
	-	(0.000)	-	(0.000)	-	(0.000)	-	(0.000)
ln(CO2)	-	0.009	-	-0.006	-	-0.023***	-	0.005
	-	(0.121)	-	(0.344)	-	(0.004)	-	(0.354)
ln(Corruption)	-0.022***	0.015***	-0.022***	0.015***	-0.022***	0.015***	-0.022***	0.015***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
ln(CDD)	0.022***	0.015***	0.022***	0.015***	0.022***	0.015***	0.022***	0.015***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
ln(HDD)	-0.044***	0.035***	-0.044***	0.035***	-0.044***	0.035***	-0.044***	0.035***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Time FE/Country FE	Yes/Yes							
Obs.	16,660							
Pseudo R2	0.09							
Variable and Statistics	GHG Policy Stringency							
	Very Clean		Clean		Dirty		Very Dirty	
	L0	L1	L0	L1	L0	L1	L0	L1
GHG Pol. String.	-	-0.060***	-	-0.060***	-	-0.058***	-	-0.042***
	-	(0.000)	-	(0.000)	-	(0.000)	-	(0.007)
ln(Energy prices)	-	0.010***	-	0.010***	-	0.010***	-	0.010***
	-	(0.000)	-	(0.000)	-	(0.000)	-	(0.000)
ln(GDP)	-	0.000	-	-0.000	-	-0.000	-	-0.000
	-	(0.956)	-	(0.968)	-	(0.746)	-	(0.938)
ln(Technology)	-	-0.004***	-	-0.004***	-	-0.004***	-	-0.004***
	-	(0.000)	-	(0.000)	-	(0.000)	-	(0.000)
ln(CO2)	-	-0.000	-	-0.000	-	0.000	-	0.000
	-	(0.787)	-	(0.793)	-	(0.730)	-	(0.995)
ln(Corruption)	0.002***	0.000	0.002***	0.000	0.002***	0.000	0.002***	0.000
	(0.000)	(0.273)	(0.000)	(0.273)	(0.000)	(0.273)	(0.000)	(0.273)
ln(CDD)	-0.002***	0.000	-0.002***	0.000	-0.002***	0.000	-0.002***	0.000
	(0.000)	(0.414)	(0.000)	(0.414)	(0.000)	(0.414)	(0.000)	(0.414)
ln(HDD)	0.003***	-0.001*	0.003***	-0.001*	0.003***	-0.001*	0.003***	-0.001*
	(0.000)	(0.058)	(0.000)	(0.058)	(0.000)	(0.058)	(0.000)	(0.058)
Time FE/Country FE	Yes/Yes							
Obs.	16,660							
Pseudo R2	0.25							

Column titles indicate the sector groups. L0: contemporaneous effect, L1: effect from one time lag. * p<0.1, ** p<0.05, *** p<0.01, p-values in parenthesis

Table E13: Sector Specification alternative ordering 5: gdp, energy price, technology (continued on next page)

Variable and Statistics	CO2							
	Very Clean		Clean		Dirty		Very Dirty	
	L0	L1	L0	L1	L0	L1	L0	L1
GHG Pol. String.	-0.271***	0.023	-0.197***	0.030	-0.082*	0.017	-0.176***	-0.017
	(0.000)	(0.653)	(0.000)	(0.543)	(0.088)	(0.736)	(0.000)	(0.722)
ln(GDP)	0.102***	0.036**	0.110***	0.068***	0.079***	0.002	0.064***	0.042***
	(0.000)	(0.025)	(0.000)	(0.000)	(0.000)	(0.810)	(0.000)	(0.000)
ln(Energy prices)	-0.111***	-0.059***	-0.073***	-0.057***	-0.087***	-0.063***	-0.009	-0.012
	(0.000)	(0.003)	(0.000)	(0.002)	(0.000)	(0.001)	(0.600)	(0.503)
ln(Technology)	0.001	0.008	0.011*	0.014**	0.010*	-0.002	0.004	-0.005
	(0.842)	(0.271)	(0.079)	(0.023)	(0.090)	(0.703)	(0.419)	(0.366)
ln(CO2)	-	-0.079***	-	-0.097***	-	-0.080***	-	-0.051***
	-	(0.000)	-	(0.000)	-	(0.000)	-	(0.003)
ln(Corruption)	-0.019***	-0.017***	-0.019***	-0.017***	-0.019***	-0.017***	-0.019***	-0.017***
	(0.004)	(0.004)	(0.004)	(0.004)	(0.004)	(0.004)	(0.004)	(0.004)
ln(CDD)	0.006***	-0.005***	0.006***	-0.005***	0.006***	-0.005***	0.006***	-0.005***
	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
ln(HDD)	0.011	-0.008	0.011	-0.008	0.011	-0.008	0.011	-0.008
	(0.009)	(0.009)	(0.009)	(0.009)	(0.009)	(0.009)	(0.009)	(0.009)
Time FE/Country FE	Yes/Yes							
Obs.	16,660							
Pseudo R2	0.09							

Variable and Statistics	GDP							
	Very Clean		Clean		Dirty		Very Dirty	
	L0	L1	L0	L1	L0	L1	L0	L1
GHG Pol. String.	-0.044**	0.033	-0.012	0.041	-0.038	0.038	-0.1***	-0.015
	(0.038)	(0.132)	(0.619)	(0.106)	(0.222)	(0.248)	(0.005)	(0.677)
ln(GDP)	-	0.148***	-	0.069***	-	0.093***	-	0.03*
	-	(0.000)	-	(0.000)	-	(0.000)	-	(0.076)
ln(Energy prices)	-	0.001	-	-0.008	-	-0.011	-	-0.015
	-	(0.895)	-	(0.385)	-	(0.336)	-	(0.326)
ln(Technology)	-	0.002	-	-0.004	-	-0.004	-	-0.006
	-	(0.564)	-	(0.293)	-	(0.321)	-	(0.289)
ln(CO2)	-	0.003	-	0.008**	-	0.012**	-	0.036***
	-	(0.337)	-	(0.038)	-	(0.020)	-	(0.000)
ln(Corruption)	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002
	(0.483)	(0.294)	(0.483)	(0.294)	(0.483)	(0.294)	(0.483)	(0.294)
ln(CDD)	0.001*	0.001	0.001*	0.001	0.001*	0.001	0.001*	0.001
	(0.098)	(0.245)	(0.098)	(0.245)	(0.098)	(0.245)	(0.098)	(0.245)
ln(HDD)	-0.007	0.003	-0.007	0.003	-0.007	0.003	-0.007	0.003
	(0.132)	(0.497)	(0.132)	(0.497)	(0.132)	(0.497)	(0.132)	(0.497)
Time FE/Country FE	Yes/Yes							
Obs.	16,660							
Pseudo R2	0.04							

Variable and Statistics	Energy Price							
	Very Clean		Clean		Dirty		Very Dirty	
	L0	L1	L0	L1	L0	L1	L0	L1
GHG Pol. String.	0.037**	-0.067***	0.038**	-0.065***	0.037**	-0.065***	0.043**	-0.055***
	(0.042)	(0.000)	(0.028)	(0.000)	(0.045)	(0.001)	(0.016)	(0.003)
ln(GDP)	-0.006	0.002	0.000	0.002	-0.002	0.010**	0.002	0.004
	(0.304)	(0.770)	(0.868)	(0.736)	(0.701)	(0.034)	(0.413)	(0.120)
ln(Energy prices)	-	0.059***	-	0.059***	-	0.058***	-	0.057***
	-	(0.000)	-	(0.000)	-	(0.000)	-	(0.000)
ln(Technology)	-	0.021***	-	0.021***	-	0.021***	-	0.022***
	-	(0.000)	-	(0.000)	-	(0.000)	-	(0.000)
ln(CO2)	-	-0.004*	-	0.001	-	-0.001	-	-0.005
	-	(0.090)	-	(0.794)	-	(0.793)	-	(0.299)
ln(Corruption)	-0.002	0.027***	-0.002	0.027***	-0.002	0.027***	-0.002	0.027***
	(0.366)	(0.000)	(0.366)	(0.000)	(0.366)	(0.000)	(0.366)	(0.000)
ln(CDD)	-0.002***	0.006***	-0.002***	0.006***	-0.002***	0.006***	-0.002***	0.006***
	(0.001)	(0.000)	(0.001)	(0.000)	(0.001)	(0.000)	(0.001)	(0.000)
ln(HDD)	0.073***	0.007	0.073***	0.007	0.073***	0.007	0.073***	0.007
	(0.000)	(0.127)	(0.000)	(0.127)	(0.000)	(0.127)	(0.000)	(0.127)
Time FE/Country FE	Yes/Yes							
Obs.	16,660							
Pseudo R2	0.17							

Column titles indicate the sector groups. L0: contemporaneous effect, L1: effect from one time lag. * p<0.1, ** p<0.05, *** p<0.01, p-values in parenthesis

Table E13: Sector Specification alternative ordering 5: gdp, energy price, technology (continued)

Variable and Statistics	Technology							
	Very Clean		Clean		Dirty		Very Dirty	
	L0	L1	L0	L1	L0	L1	L0	L1
GHG Pol. String.	0.117**	0.075	0.155***	0.042	0.157***	0.059	0.121***	0.06
	(0.014)	(0.151)	(0.001)	(0.397)	(0.001)	(0.243)	(0.007)	(0.216)
ln(GDP)	-0.020*	-0.027**	-0.022*	-0.064***	-0.011	-0.035***	-0.002	-0.004
	(0.067)	(0.023)	(0.057)	(0.000)	(0.342)	(0.005)	(0.802)	(0.545)
ln(Energy prices)	0.024*	-0.022	0.029**	-0.020	0.027**	-0.025*	0.021*	-0.017
	(0.060)	(0.110)	(0.019)	(0.140)	(0.036)	(0.073)	(0.089)	(0.207)
ln(Technology)	-	-0.086***	-	-0.092***	-	-0.090***	-	-0.094***
	-	(0.000)	-	(0.000)	-	(0.000)	-	(0.000)
ln(CO2)	-	0.009	-	-0.006	-	-0.023***	-	0.005
	-	(0.121)	-	(0.344)	-	(0.004)	-	(0.354)
ln(Corruption)	-0.022***	0.015***	-0.022***	0.015***	-0.022***	0.015***	-0.022***	0.015***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
ln(CDD)	0.022***	0.015***	0.022***	0.015***	0.022***	0.015***	0.022***	0.015***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
ln(HDD)	-0.044***	0.035***	-0.044***	0.035***	-0.044***	0.035***	-0.044***	0.035***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Time FE/Country FE	Yes/Yes							
Obs.	16,660							
Pseudo R2	0.09							
Variable and Statistics	GHG Policy Stringency							
	Very Clean		Clean		Dirty		Very Dirty	
	L0	L1	L0	L1	L0	L1	L0	L1
GHG Pol. String.	-	-0.060***	-	-0.060***	-	-0.058***	-	-0.042***
	-	(0.000)	-	(0.000)	-	(0.000)	-	(0.007)
ln(GDP)	-	0.000	-	-0.000	-	-0.000	-	0
	-	(0.956)	-	(0.968)	-	(0.746)	-	(0.938)
ln(Energy prices)	-	0.010***	-	0.010***	-	0.010***	-	0.01***
	-	(0.000)	-	(0.000)	-	(0.000)	-	(0.000)
ln(Technology)	-	-0.004***	-	-0.004***	-	-0.004***	-	-0.004***
	-	(0.000)	-	(0.000)	-	(0.000)	-	(0.000)
ln(CO2)	-	-0.000	-	-0.000	-	0.000	-	0
	-	(0.787)	-	(0.793)	-	(0.730)	-	(0.995)
ln(Corruption)	0.002***	0.000	0.002***	0.000	0.002***	0.000	0.002***	0.000
	(0.000)	(0.273)	(0.000)	(0.273)	(0.000)	(0.273)	(0.000)	(0.273)
ln(CDD)	-0.002***	0.000	-0.002***	0.000	-0.002***	0.000	-0.002***	0.000
	(0.000)	(0.411)	(0.000)	(0.411)	(0.000)	(0.411)	(0.000)	(0.411)
ln(HDD)	0.003***	-0.001*	0.003***	-0.001*	0.003***	-0.001*	0.003***	-0.001*
	(0.000)	(0.058)	(0.000)	(0.058)	(0.000)	(0.058)	(0.000)	(0.058)
Time FE/Country FE	Yes/Yes							
Obs.	16,660							
Pseudo R2	0.25							

Column titles indicate the sector groups. L0: contemporaneous effect, L1: effect from one time lag. * p<0.1, ** p<0.05, *** p<0.01, p-values in parenthesis

General Conclusion

1 Main Findings

This thesis investigates empirically three important aspects in the context of combating climate change: regulatory responsibility, the measurement of observed environmental policy stringency as well as the impact of the latter on anthropogenic CO_2 emissions. Although distinct, all three aspects are inherently interrelated, and a proper understanding is crucial in order to effectively combat climate change. Three main findings can be identified.

First, while the descriptive analyses in Chapter 1 and Chapter 2 clearly indicates the existence of a historical responsibility of the West, a convergence in terms of per capita CO_2 emissions of different countries can be observed over the last decades. This finding is confirmed by the observed decrease of the contribution of between country spatial emission inequality to overall inequality. The latter holds for both major greenhouse gases, CO_2 and CH_4. At the same time the contribution of specific zones within countries as well as specific sectors to overall inequality increases fast. Those results suggest that while the regulatory responsibility of countries is converging (i.e. the responsibility in terms of applied regulations), the one of specific sectors and zones is rapidly increasing. Those results could profoundly reshape the structure of future negotiations on global climate change mitigation strategies (cf. Section (2) of this general conclusion).

Second, Chapter 3 emphasizes the importance of an appropriate methodological framework allowing to quantify concepts like environmental policy stringency. Being able to clearly distinguish which aspect of environmental policy one attempts to measure, i.e. the input, process or output dimension, allows to measure the concept in question more precisely. It is unclear, why this general structure, advocated by many in the index construction literature (e.g. Nardo et al. (2008)), has been ignored so far. This is especially surprising, as many variables frequently used in empirical Economics - including the ones we use to quantify “production” - are based upon the same trinity.

Third, the empirical country-level analysis in Chapter 4 shows that, while an increase in GHG policy stringency does reduce anthropogenic CO_2 emissions, it does so at a relatively high cost in terms of GDP. This policy induced CO_2 emission reduction found at the country level, is composed of two distinct effects on the sectoral level with potentially opposing consequences for the global climate system. On the one hand, the CO_2 efficiency of all sector groups, independently of their relative dirtiness, improves. On the other hand, the sectoral composition of economies, in terms of relatively dirty and relatively clean sectors, is altered. The size of the dirtiest 25% of sectors is being reduced, while we observe no significant impact on size of the cleaner sectors. The latter results could well be bad news for the global climate system, especially if this reduction is achieved by “‘pollution outsourcing”, i.e. outsourcing of relatively dirty production to relatively unregulated countries.

2 Policy Implications

Two general policy implications can be identified in light of the results of this thesis. The first one concerns the general architecture of the global climate change policy system. Negotiations which led to the Kyoto protocol framework and the current negotiations for a post-Kyoto policy architecture have been - and still are - shaped, by the implications of the historical responsibility of the West (e.g. Barrett and Stavins (2003) or Mattoo and Subramanian (2012)) and by the fact that countries or group of countries are the main negotiating units. The outcome of those negotiations was an agreement which is based on country-wide GHG emission reductions, while excluding several sectors, some developed countries, and all developing countries from the agreement. Numerous voices advocate the inclusion of those omitted parts in a future agreement. Others, like Barrett (2008), propose however a different approach, and suggest to split the problem up, and rely on global sector and gas specific agreements. Barrett motivates his proposal by a theoretical argument, stating that bundling all gases, sectors and countries together may risk to compromise enforcement, as the latter will depend on the weakest links within the broad global system. This thesis contains several results on regulatory responsibility and on actual effects of current policies, which provide an additional - empirical - motivation to support this alternative proposal. First, as per capita CO_2 emissions are converging, and between country CO_2 and CH_4 emission inequalities are declining, regulatory responsibilities of countries are converging as well. Simultaneously, the sharp increase in between sector emission inequalities suggests that the regulatory responsibility of some sectors is increasing fast. Moreover, while one can observe this general increase for both major GHGs, the responsible sectors differ depending on the specific gas. Thus, a global gas and sector specific treaty would be well suited to take those evolutions into account. Additionally, such agreements could mitigate the fears of pollution outsourcing, as for a given sector, identical requirements would apply, no matter the country.

The second general policy implication concerns instruments of environmental policy. Most ex-ante estimations of greenhouse gas emission reductions assume a cost-effective implementation of GHG policies, and suggest that is is possible to achieve the emission reduction goals with relatively moderate costs (e.g., Stern et al. (2006), Barker et al. (2007), Clarke et al. (2009) or Tavoni and Tol (2010)). But as Leahy and Tol (2012) state, there is no reason to assume that actual policies are least cost solutions and thus that costs will be moderate. And indeed, we find rather high opportunity costs of policy induced CO_2 emission reductions. One has however to keep in mind, that our results are based on data covering the recent past, and thus do not include potential future learning effects nor future economies of scope and scale in green technologies, which might considerably lower these opportunity costs over the next decades. Nevertheless, given our results, a stronger focus on least-cost policy solutions, like a CO_2 tax, could be an effective way to lower costs and thereby foster the willingness of different countries to increase the stringency of their GHG policy regimes.

3 General limitations and further research

The four analyses clearly have multiple drawbacks. Besides the various specific limitations mentioned in each Chapter, three general limitations of this thesis can be identified. The first and probably most important limitation concerns the analysis conducted in Chapter 1 and 2. While it is true that the production based accounting approach determines the responsibility in terms of the applied regulation, as most policies regulate emissions at their production source, the responsibility analysis is far from complete. This because an increasing part of total anthropogenic emissions is released during the production of products which are consumed elsewhere (e.g. IPCC (2014b)). Therefore actual responsibility is being gradually decoupled from the regulatory responsibility which has been analyzed in this thesis. In line with the extensive literature on CO_2 and SO_2 emissions embodied in trade (e.g. Grether et al. (2012a) or Sato (2014)), further research on consumption-based accounting has thus to be conducted. The latter would also be useful in order to determine who would have to pay for the advocated global gas and sector specific policy regime. Financial transfers from countries with an elevated per capita emission consumption to those with a rather low per capita emission consumption could be a fair solution to implement the regime based on actual responsibility.

The second general limitation concerns the implementation of the proposed methodological framework for measuring environmental policy stringency. Clearly, the proposed indexes are only a very rough representation of actual stringency. Besides refining the input index by, for instance, weighing policy instruments differently, further research should focus on the construction of a decent process indicator, which is urgently needed. This need is for instance illustrated in Chapter 4, where we had to use a crude proxy for implementation stringency, which is clearly not an ideal solution.

Finally, while the rather broad macro perspective of the empirical analysis in Chapter 4 allows to gain a general overview of the effects of GHG policy stringency on CO_2 emissions, it is at the same time also an important weakness. The estimates of policy induced emission reductions and associated opportunity costs in terms of GDP have to be taken carefully. This, because they represent only an average reaction of anthropogenic CO_2 emissions and GDP to a change in average GHG policy stringency, and do thus not allow to take a more differentiated perspective. Moreover, while we can show that a policy induced composition effect exists, we are unable to determine whether outsourcing or absolute reductions of the production in relatively dirty sectors is causing this effect. Further structural research should tackle this problem systematically. To do so, additional detailed sectoral data, covering all countries of the planet, will be needed, in order to assess this important question.

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