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What Drives Changes in Carbon Emissions? An Index Decomposition Approach for 40 Countries

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Abstract

This study analyzes carbon emission trends and drivers in 40 major economies using the WIOD database, a harmonized and consistent dataset of input-output table time series accompanied by environmental satellite data. We use logarithmic mean Divisia index decomposition to (1) study trends in global carbon emissions between 1995 and 2009, (2) attribute changes in carbon emissions to either influences of economic activity, changes in technology, changes in the structure of the economy, alterations of the fuel mix, or changes in carbon intensities of specific fuel types, and (3) highlight sectoral and regional differences. We first find that heterogeneity in each country is higher than heterogeneity in sectors. This finding might lead to the conclusion that, in order to abate CO_2, structural conditions in sectors prevail over regional circumstances. Regarding our results of the decomposition analysis, the drivers of changes in carbon emissions are very heterogeneous. Among the world's top ten emitters, in only three countries – China, Germany and Canada – the main driver of an improved emissions performance was technological change. Conversely, in Japan and Australia structural change of the economy contributed to less severe increases of emissions. The deployment of cleaner energy sources had a positive in some, mainly developed, economies. Moreover, our results for the global level suggest a general move towards more efficient means of production.

Keywords: Carbon emissions, Logarithmic mean Divisia index decomposition, WIOD database
JEL classification: Q43, C43

1. Introduction

Current and projected trends for population, income and energy demand growth suggest that the pressure on energy and natural resources will increase in the coming decades, especially in emerging and developing economies. This will result in higher levels of anthropogenic emissions unless the world economy switches away from fossil-based energy carriers by facilitating access to more efficient technologies, favoring structural change in the composition of economic activities or increasing the willingness to pay for a clean environment.[3] An important first step to reduce greenhouse gas emissions without negatively affecting economic welfare too heavily is the reduction of their intensity, i.e. their units of emissions per output unit. In particular, the intensity of the most significant greenhouse gas CO_2 is of major importance (Canadell et al., 2007, Raupach et al., 2007).

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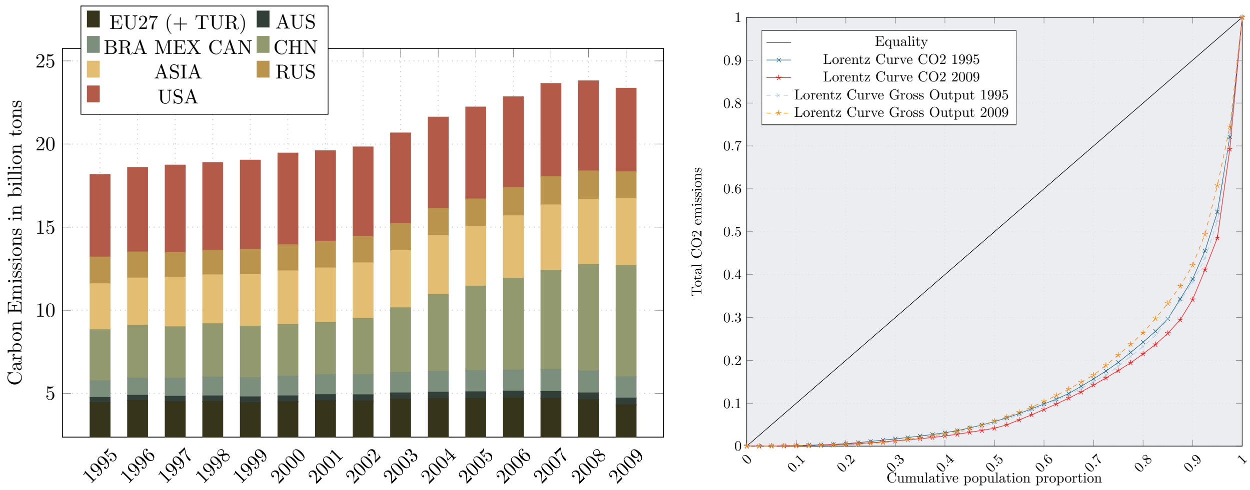
[3]By 2050, the United Nations projects global population to be almost 9.2 billion. Growth rates are projected to be positive in BRIICS (Brazil, Russia, India, Indonesia, China and South Africa) countries, but they are expected to be particularly high in Africa and South Asia, while population will fall in some European countries, Japan and Korea. Urbanization and average per capita income levels are also expected to increase (OECD, 2012). The increased demographic pressure in less developed countries will have important repercussions for energy demand and use, and hence CO_2 emissions will further increase. From 2010 to 2040 the US Energy Information Administration forecasts an energy-related CO_2 emission growth in OECD countries of 0.2% p.a., while emissions in non-OECD countries will grow by 1.9% p.a. (IEO, 2013, p. 159).



(a) Regional distribution in 2009

(b) Lorentz curves 1995 & 2009

Figure 1: Carbon emissions and Lorentz curves for 1995 and 2009

In 1995, industries worldwide emitted 18 gigatons of carbon dioxide. This number rose to 23 gigatons by 2009, cf. Figure 1a. Carbon emissions grew unequally in this time period. China's boosting role is particularly striking. Chinese carbon dioxide emissions more than doubled from 3 gigatons in 1995 to 6.7 gigatons in 2009. China also expanded its carbon dioxide emissions in relative terms. While China accounted for 16.9 % of worldwide carbon dioxide emissions in 1995, it was responsible for 28.7% of total carbon dioxide emissions in 2009 (calculations based on Dietzenbacher et al., 2013).[4] The economic rise of China and, to some extent, Brazil, Russia, India and Indonesia, may have two distributional effects. We use Lorentz curves to demonstrate two facts about global CO_2 emissions and gross output. Figure 1b presents the state of inequality in carbon emissions and gross output in 1995 and 2009. Once countries have been ranked by ascending order of carbon dioxide emissions, the cumulative percentage of population is measured on the horizontal axis of the figure. The cumulative percentage of carbon dioxide emissions and gross output is measured on the vertical axis. The Lorentz curve relates the cumulative emissions and the cumulative gross output to the cumulative population. If all countries had identical carbon dioxide emissions and gross output, the Lorentz curve would be identical to the 45-degree line shown in the figure. Apparently, this is not the case. Both gross output as well as carbon dioxide emissions are unequally distributed.[5] But while the distribution of gross output became more equal in 2009 (the curve is moving towards the equality line), the opposite holds true for carbon dioxide emissions (the curve moves towards inequality). We draw two conclusions based on Figure 1b. First, carbon emissions grew faster in one particular country compared to the rest of the country-sample. Otherwise the Lorentz curve for carbon dioxide emissions would have developed in a similar way as the gross output Lorentz curve. Second, and more importantly, this may have an important implication for the negotiations of international environmental agreements. If such an inequality trend continues, certain countries gain in market power with respect to carbon dioxide emissions, and the likelihood of an international environmental agreement decreases since countries with an increased market power may prevent such an international environmental agreement or assert a negotiation position due to self interest which does not correspond to the preferences of other countries (Lange et al., 2010).[6]

[4]All figures on carbon dioxide emissions exploit the whole environmental satellite accounts of the World Input-Output Database. The further analysis relies on data for the 40 countries with detailed information. Those 40 countries account for ≈ 80% of carbon dioxide emissions and 88% of economic output in 2009.

[5]The corresponding Gini indices for carbon emissions and gross output in 1995 and 2009 are: CO_2 (1995): 0.714, CO_2 (2009): 0.740, Gross Output (1995): 0.731, Gross Output (2009): 0.705.

[6]The Herfindahl-Hirschman index for global carbon emissions rose from 0.125 in 1995 to 0.146 in 2009 indicating an increase in market concentration.

The evolution of carbon emissions may be attributable to several separate factors, namely changes in the structural composition of the world economy, improvements in the technologies used for production worldwide, an alteration of the fuel mix and economic growth. Economies have shifted toward less carbon intensive sectors, resulting in declining carbon intensities throughout most countries. At the same time, carbon intensity within all sectors of the world's economies is likely to decrease further as a result of more efficient production technologies and newer vintages of capital equipment inducing advanced CO_2 abatement options.

Understanding the drivers behind the national and sectoral dynamics of carbon emissions and the interplay of structural changes, altering fuel mixes and improved sectoral abatement options has therefore important policy implications. It raises the following questions: Is the development of carbon emissions similar in the same sector across different countries? Is the development on a global scale driven by changes in some economies and sectors rather than others? Most importantly, is the development of carbon emissions caused by changes in the economic structure from "dirty" to "cleaner" sectors or do actual technology improvements induce these reductions?

Answering these questions helps clarify if the decoupling between output and carbon emissions is attributable to increased sectoral abatement options and better technologies. In this case, policies encouraging technology transfers, economies of scale and learning-by-doing effects can be put in place to replicate improvements in less developed regions which still display higher emissions levels. These improvements would then come at relatively low costs since required technologies are already available. This also has implications for the negotiations of international environmental agreements and the optimal policy design. If technological improvements can be replicated, the implementation of agreements based on technology transfer might be a better choice in terms of incentive compatibility than the design of new regulatory frameworks to promote the participation of developing countries (Aldy et al., 2010).

This study makes three contributions to the literature. First, we provide an overview of carbon emissions development with a temporal and geographical focus that is greater than in prior studies (Greening et al., 1998, Greening, 2004). Second, by focusing on sectors and showing their performance across countries, we provide a novel perspective that sheds light on the heterogeneity of sectoral carbon emissions development across countries. We also present a more traditional country-based analysis, in which the sectoral composition of each economy is taken into account. We exploit the international dimension of the WIOD database, which covers the period between 1995 and 2009 and contains data on 34 sectors in 40 major economies, including BRIC (Brazil, Russia, India and China) and other developing countries. The economies included in our analysis represented approximately 88% of the world's GDP and 80% of carbon dioxide emissions in 2009. Third, we analyze carbon emissions developments based on index decomposition. This is to some degree an extension of the index decomposition literature which has so far mainly focused on energy efficiency issues (Ang, 1994, Boyd and Roop, 2004, Choi and Ang, 2012, Mulder and De Groot, 2012, Voigt et al., 2014). We use logarithmic mean Divisia index decomposition analysis to disentangle five different effects and their relative contribution to the development of carbon dioxide emissions. We account for economic growth (*activity effect*), efficiency improvements within the sectors of an economy (*technology effects*), structural change (*structural effects*) which accounts for the sectoral composition of the world's economy, an altering fuel mix (*fuel mix effect*) and changes in the carbon content of the energy carriers (*emission factor effect*). Compared to most of the previous literature on decomposition, we thus further disaggregate the technology effect. The "classical" technology effect (e.g. in a two factor decomposition) encompasses three instances, namely an improvement in the efficiency of production, changes in the composition of energy carriers, and carbon intensity changes of specific fuel types, and may hence be afflicted with an aggregation bias. Our five factor analysis disentangles these three aspects of technological progress.

We perform this exercise both at the aggregate and at the country level and provide insights into the heterogeneity of the drivers of carbon emissions developments in our sample.

The remainder of the paper is organized as follows. In section 2 we present the data used in the analysis. Section 3 describes the development of carbon emissions in our sample both from the sectoral and the country perspective. Section 4 introduces the index decomposition framework and section 5 presents the result of this exercise. Section 6 concludes by highlighting the main implications of our findings.

NACE	WIOD industries
AtB	Agriculture, hunting, forestry and fishing
C	Mining and quarrying
15t16	Food , beverages and tobacco
17t18	Textiles and textile products
19	Leather, leather products and footwear
20	Wood and products of wood and cork
21t22	Pulp, paper, paper products, printing and publishing
23	Coke, refined petroleum and nuclear fuel
24	Chemicals and chemical products
25	Rubber and plastics
26	Other non-metallic mineral products
27t28	Basic metals and fabricated metal products
29	Machinery nec
30t33	Electrical and optical equipment
34t35	Transport equipment
36t37	Manufacturing nec, recycling
E	Electricity, gas and water supply
F	Construction
50	Sale, maintenance and repair of motor vehicles
51	Wholesale trade and commission trade
52	Retail trade, except of motor vehicles and motorcycles
H	Hotels and restaurants
60	Inland transport
61	Water transport
62	Air transport
63	Supporting and auxiliary transport activities
64	Post and telecommunications
J	Financial intermediation
70	Real estate activities
71t74	Renting of machinery and equipment and other business activities
L	Public administration and defence, social security
M	Education
N	Health and social work
O	Other community, social and personal services

Table 1: WIOD industries and definition by NACE

2. Data Description: The WIOD Database

The main data source for our analysis is the newly released World Input-Output Database (WIOD, 2012).[7] The WIOD database is built on national accounts data which was developed within the 7th Framework Programme of the European Commission.[8] The relevant information for the analysis of carbon emissions developments is included in the Social Economic Accounts (*SEA*) and the emissions information which are accompanying satellite accounts to the WIOD database. Carbon emissions (C) are measured in physical units (kt) and are aggregated across 26 energy carriers. The measure of sectoral economic activity relevant for our analysis is gross output (GO) which is expressed in monetary units in basic 1995 prices and converted to million US$ (1995) using market exchange rates. The WIOD database has two main advantages. First, throughout the data collection effort, harmonization procedures were applied to ensure international comparability of the basic data. This ensures data quality and minimizes the risk of measurement errors which are now rather unlikely to occur. Second, WIOD includes sectoral price deflators, the use of which allows to retain important information and the heterogeneity of the sectors with respect to price developments. This represents an improvement over the use of aggregate national price deflators. A complete list of

[7]The WIOD database and all satellite accounts are available at http://www.wiod.org. In this paper we use data released in April 2012.

[8]The WIOD project has been funded by the European Commission, Research Directorate General as part of the 7th Framework Programme, Theme 8: Socio-Economic Sciences and Humanities. Grant Agreement no: 225 281.

the 34 sectors that represent one of our units of observation over the period from 1995 to 2009 is presented in Table 1.[9]

The structure of the WIOD database hence allows us to address the research questions outlined above by focusing on many heterogeneous countries over a fairly long time span. This is an improvement over the previously available literature which was more limited geographically and with respect to the time dimension.

3. Carbon Emissions Developments between 1995 and 2009

Before diving into the decomposition analysis, we examine some descriptive characteristics of carbon emissions growth in our sample between the beginning and the end of the sample period. We first show the performance of each sector covered in the database and then move on to the country analysis. From 1995 to 2009, aggregate CO_2 emissions of the 40 economies included in our sample increased by 28.6% (Figure 1a). Over the time period considered, we can identify three time intervals characterized by a different pace of emissions growth: 1995 to 2002 when carbon emissions increased modestly by 9.2%, 2002 to 2007 when the rise occurred at a much higher pace, i.e. 19.2% in five years, and 2007 to 2009 when emissions even declined by 1.2%.

3.1. Sectoral Developments

This aggregate increase of carbon emissions is the result of very heterogeneous sectoral dynamics. Figure 2 provides an overview in this respect. We calculate box plots of average annual CO_2 emissions changes within our sample period for each sector in each country. Each box/whisker combination in Figure 2 shows the heterogeneity of these sectoral changes across countries. The bottom of the box represents the first quartile in annual carbon emissions changes, the top represents the third quartile. The lower and upper bounds of the whisker stand for the 10th and 90th percentile, respectively. The median is marked with a band inside the box while the dot represents the carbon emissions change of the sector aggregated over the 40 countries in the sample. The gray bar shows the sectoral share in total carbon emissions in 2009.[10]

The average sectoral annual rates of change aggregated over countries range from -3.2% for leather (19) to 4.1% for water transport (61) and supporting transport activities (63). Other notable sectors with large CO_2 emissions reductions (more than 1.5% p.a.) are manufacturing (36t37), wholesale trade (51) and textiles (17t18), while tremendous emission growth rates (greater than 3% p.a.) can be observed for electricity (E) and mining and quarrying (C) apart from the sectors outlined previously. Moreover, in many sectors the median value of carbon emissions change is negative, meaning that more than half of the countries experienced reductions in CO_2 emissions over the sample period. Most notably, the leather and the textiles sectors (19 and 17t18) exhibit median values less than 6%. Notwithstanding, a small majority of the sectors shows median values greater than zero, with the sector renting of machinery and equipment (71t74) having the highest median growth rate (3.6%). Nevertheless, many of these sectors show growth rates only slightly above zero. A somewhat pessimistic picture is given by the electricity sector (E). Being responsible for approximately half of the emissions in our sample, it has one of the highest aggregate growth rates. However, at least the median growth is relatively small (0.8%) showing some successful abatement efforts in a number of countries.

When comparing median growth and aggregate growth, we can gain general insights on the country distribution with respect to carbon emissions development. If the aggregate growth rate is above the median, this indicates that countries with a high share of gross output and CO_2 emissions within the specific sector performed worse than the majority of other countries. The largest divergence between aggregate and median change in carbon emissions occurs in the sectors textiles (17t18), non-metallic minerals (26), mining and quarrying (C), leather (19) and water transport (61). In all these sectors, fast growing economies such as India, Indonesia, but particularly China, with increased

[9]The countries in the database include all EU27 member states, other OECD member states including all the large developed countries, and the most important emerging economies including the BRIC countries (Brazil, Russia, India, China). All other countries are summarized in an aggregate region "Rest of the World" (RoW) which is used however only to complete the trade data, i.e. no separate accounts for this region are provided. In addition to providing economic time series data for the period from 1995 to 2009, WIOD contains several consistent satellite accounts with the same sectoral classification as the core dataset. The satellite accounts consist of bilateral trade data, socioeconomic data (i.e. skill types of labor, sectoral and total capital stocks) and, most important for our purpose, a rich set of environmental information, including CO_2 emissions separated by sector and numerous energy carriers (fossil, non-fossil, renewables, etc.).

[10]The bar for sector E (electricity) is truncated for clarity reasons. Its share value is 49.8%.

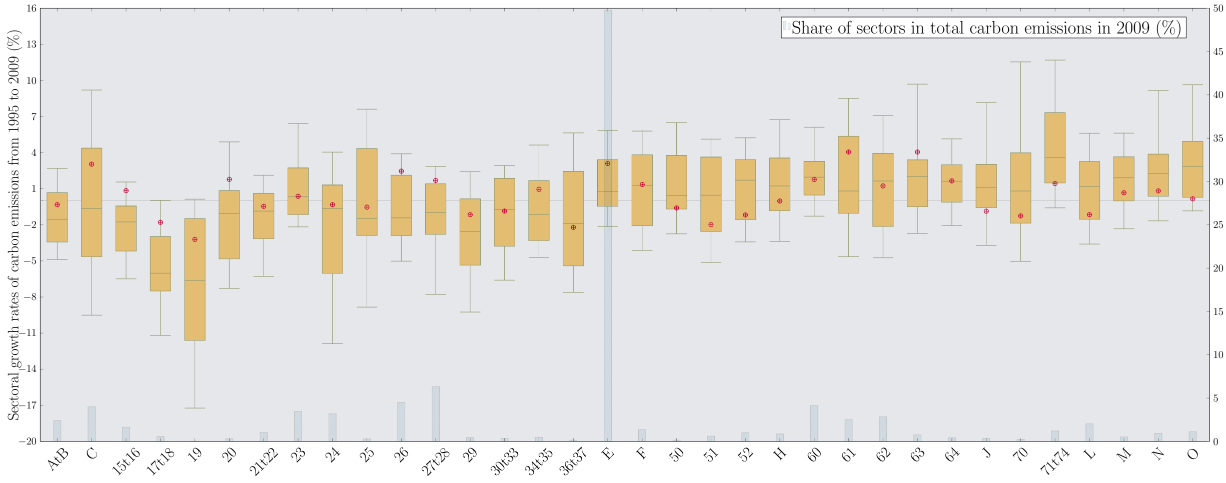


Figure 2: Annual sectoral changes in CO_2 emissions. For the sector definition, see Table 1. Bottom of box represents first quartile, top represents third quartile, band marks median. Lower and upper bounds of whisker represent 10th and 90th percentile, respectively. Dots mark carbon emissions change of the sector aggregated over the sample countries.

importance and high sectoral output and emission shares determine this finding. Especially in the non-metallic minerals, mining and quarrying and water transport sectors, where median growth is either negative or just slightly greater than zero, the consequences are thus quite severe. Emissions abatement should concentrate on such countries to improve the global performance in these sectors. Sectoral marginal abatement costs in these countries are expected to be relatively low. This gives rise to sectoral approaches in order to achieve aggregate emissions reductions.

Conversely, some sectors show lower aggregate than median growth rates. In these cases, countries with high gross output and emissions shares presumably performed better than the majority. The four sectors with the largest wedge in this regard are retail trade (52), other community services (O), wholesale trade (51) and public administration and defence (L). These results are dominated by large developed economies, above all the United States, and could hence be replicated in emerging economies through technology transfer. However, all these sectors are service sectors with a very low share in global emissions and are thus hardly able to influence aggregate emissions reductions on a large scale.

A number of sectors perform particularly well showing reductions in carbon emissions in the vast majority of our sample countries, as the third quartile lies below or slightly above zero. These include textiles (17t18), leather (19), food, beverages and tobacco (15t16), pulp and paper (21t22), and agriculture, hunting, forestry and fishing (AtB).

Two sectors show a markedly high heterogeneity of carbon emissions changes across countries, namely the leather (19) and the mining and quarrying (C) sectors. Among the sectors with the smallest heterogeneity across countries three industries are particularly worth mentioning due to their relatively high share in global CO_2 emissions: electricity (E), inland transport (60) and coke and refined petroleum products (23). As the former two sectors exhibit quite large increases during the sample period, this result may give grounds for some pessimism since there seems to be no country taking a strong leading role in reducing carbon emissions.

The aggregate sectoral analysis has shown that in some sectors heterogeneity of carbon emissions changes across countries is high. This suggests that in these sectors there might be benefit from supporting the diffusion of efficient technologies from more frontier countries to the laggards. Technology diffusion and transfer could improve the overall performance, in particular if directed toward the biggest economies in terms of gross output and CO_2 emissions shares. However, in some sectors with high emissions shares, there seems to be a quite homogeneous development across the world. Therefore, in these sectors a global effort to reduce carbon emissions might be a promising approach for a sustainable improvement.

The analysis presented so far shows a mixed picture of emission reduction achievements throughout our sample sectors. In particular, the electricity sector as the world's largest emitter shows high growth rates while the largest emissions reduction occurred primarily in service sectors as well as in the textile and leather sectors. Moreover, heterogeneity can be detected in many economic branches with respect to the performance of different countries.

In the following subsection we present a similar descriptive analysis focusing on the country level before moving to the decomposition analysis.

3.2. *Country Level Developments*

We now explore the heterogeneity of changes in carbon emissions across countries. Figure 3 shows their distribution for all sectors within a given country. The box plots are constructed in a manner analogous to those shown in Figure 2. Also in this case, if the growth rate aggregated over all sectors within one country (dot) is above the median (band within box), this indicates that sectors with a high share of gross output and CO_2 emissions within the specific country performed worse than the majority of other sectors and vice versa.

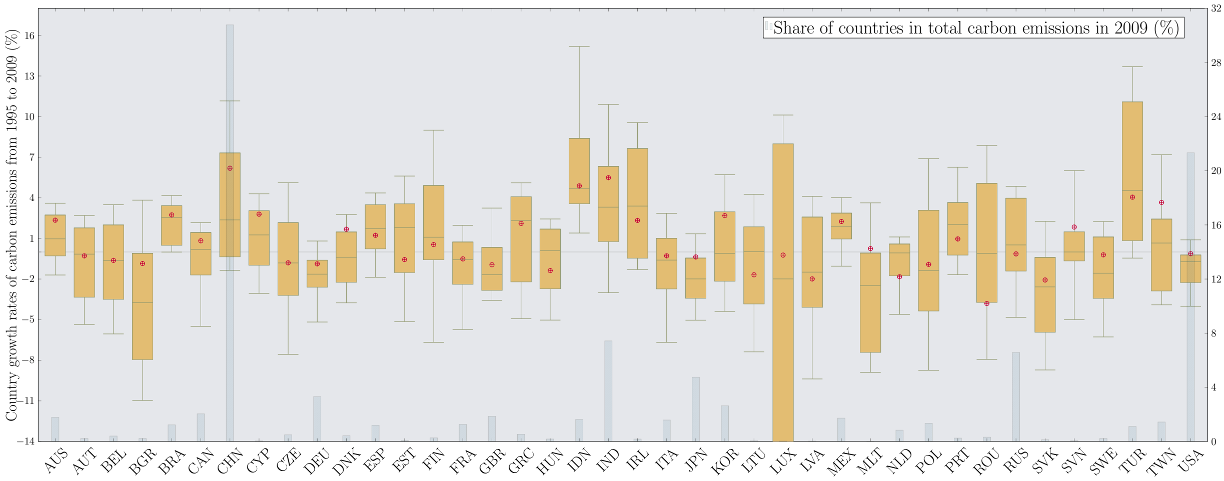


Figure 3: Annual regional changes in CO_2 emissions. Bottom of box represents first quartile, top represents third quartile, band marks median. Lower and upper bounds of whisker represent 10th and 90th percentile, respectively. Dots mark carbon emissions change of the country aggregated over the sample sectors.

Similar to the sectoral analysis, we observe a mixed picture between countries that were able to reduce carbon emissions and those that increased their emissions. While the former group consists to a high extent of countries in the former Eastern Bloc, i.e. in these cases the development may be attributed to the economic recession after the political transition in 1989/1990, a large share of the latter group are emerging economies. The extent of the changes covers a broad span. The highest reduction rates are achieved in Romania (3.8% p.a.), Slovakia (2.1% p.a.) and Latvia (2.0% p.a.), whereas we observe the largest emission growth rates in China (6.2% p.a.), India (5.5% p.a.) and Indonesia (4.9% p.a.) – three of the most prominent emerging economies. The picture is heterogeneous also for the four economies with high CO_2 emissions shares, i.e. China, the US, India and Russia, where the US and Russia kept their emissions more or less stable when considering only the years 1995 and 2009. The results are clearly driven by the evolution of economic growth, especially in the emerging economies. We will have a deeper look at this aspect as well as at the country-specific temporal development in the context of our decomposition analysis in section 5.

With respect to the spread of carbon emissions changes across the sectors in each country we observe large differences. Some countries – namely the US, Japan, Germany, Bulgaria, Slovakia and Malta– have third quartiles below zero, i.e. a vast majority of the sectors actually reduced their CO_2 emission levels. The opposite, i.e. the first quartile is above zero, is true for India, Brazil, Mexico, Indonesia, Spain and Turkey. Hence, these countries exhibit not only an aggregate emissions increase, but also the majority of sectors raised their carbon emissions.

Also in this case, we can compare median growth rates with aggregate growth rates. Contrary to the sectoral case however, in half of the countries the difference between both parameters is less than one, i.e. there are no significant outlier sectors distorting the overall outcomes. Some notable counterexamples are China, Taiwan and South Korea with aggregate above median growth rates, and Romania and Estonia with aggregate below median growth rates. In the former countries mainly mining and quarrying as well as the transport sectors performed worse than most other sectors, while in the latter group heavy industrial sectors, e.g. metals, machinery and chemicals, reduced emissions tremendously – once again indicating the industrial decay in Eastern European countries after the political transition.

In comparison to the sectoral analysis presented in Figure 2, heterogeneity in the change of carbon emissions is, in general, more pronounced within countries than within sectors. The average difference between the 90th and the 10th percentile is 12.6 for countries while it is 11.0 for the sectoral perspective. This indicates that conditions in a given sector have a stronger influence on the development of carbon emissions than conditions in a given country implying a possible similarity of sectors across the globe with respect to CO_2 abatement options.

The descriptive analysis presented in this subsection shows a very heterogeneous performance in terms of carbon emissions development among our sample countries. The largest emission reductions have been achieved by Eastern European countries as well as by some Western developed economies, whereas emerging economies exhibit the highest increases. Also the spread of change across domestic sectors is broad. We kept the descriptive analysis at the country level quite brief as a deeper analysis will follow in the remainder of this paper. Hence, in the next sections, we describe the applied decomposition approach and decompose the development of both aggregate and country carbon emission levels to show to what extent they have been due to economic growth, to shifts in the sectoral composition of global and country production, to the improvements of the technological component, to changes in the fuel mix, or to modifications in the carbon content of the different fuel types.

4. The Mean Divisia Index Decomposition of Carbon Emissions

While the descriptive analysis presented so far is illustrative of the emissions development across sectors and countries, it does not inform about the drivers behind the changes which have occurred. In this section, we use a decomposition analysis of carbon emissions to shed light on these issues, both at the aggregate and the country level.

The development of carbon emissions in the economy can be attributed to five different but equally relevant changes. First, carbon emissions can increase or decline as a result of changes in the activity level of the entire economy (*activity effect*). Second, the development of carbon emissions depends on changes in the industrial activity composition (*structural effect*). Third, changes in overall carbon emissions may also result from sectoral energy intensity improvements or deteriorations (*technology* or *intensity effect*). Fourth, the composition of the fuel mix influences the extent of carbon emissions (*fuel mix effect*). And fifth, the emission factors of the specific fuel types may change over time and hence affect the amount of total carbon emissions (*emission factor effect*), e.g. switching from a low to a higher quality type of gasoline.

The main purpose of this paper is to study the trends in carbon emissions in 40 economies and disentangle in detail the contributions from each of the above mentioned effects. Such a research question can be addressed using two broad categories of decomposition methodologies: approaches based on input-output analysis, called structural decomposition analysis (SDA), and disaggregation techniques which can be referred to as index decomposition analysis (IDA) and which are related to index number theory in economics.[11]

We use an index decomposition approach (IDA) as described by Ang and Zhang (2000), Ang and Liu (2001), Boyd and Roop (2004), Ang and Liu (2007) and more recently by Choi and Ang (2012) or Su and Ang (2012) for total, sectoral and national energy intensities and adjust this approach to analyze carbon emissions. We focus on the structural changes that affect the supply side of the economy (productive sectors) and thus exclude the private households.

Following Ang and Zhang (2000), we rely on multiplicative decomposition and use the logarithmic mean Divisia index (LMDI-I) approach (Ang and Choi, 1997). This methodology offers very important advantages: (1) it is zero-value robust (Ang et al., 1998, p. 491) and (2) it "yields perfect decomposition" (Ang et al., 1998, p. 495), i.e. no unexplained residual exists. The latter is a considerable advantage with respect to the arithmetic mean Divisia index

[11]The roots of index numbers can be traced back to the French Dutot in 1738 and the Italian Carli in 1764 (Chance, 1966, Diewert, 1993). See also Diewert (1993) for a technical summary of index number theory. Boyd and Roop (2004) offer a more comprehensive review of different indices in the context of energy intensity and the index number problem in economics. The SDA and IDA are not the only approaches for analyzing energy intensity trends. Kim and Kim (2012), for instance, employ Data Envelopment Analysis (DEA) to compare international energy intensity trends. The DEA approach allows to find the countries lying on a technological frontier and to calculate the distances of other countries to this frontier. Ma and Stern (2008) summarize the main advantages and disadvantages of each approach.

where the residual can be different from zero "when changes in the variables [...] are substantial", as in the case where the methodology is used in cross-country analyses (Ang and Zhang, 2000, p. 1165).[12]

Our variable of interest is total carbon emissions of each country $j = 1, \ldots, 40$ at time t which can be represented using five components,

$$C_t = \sum_{i,k} C_{i,k,t} = \sum_{i,k} GO_t \frac{GO_{i,t}}{GO_t} \frac{EU_{i,t}}{GO_{i,t}} \frac{EU_{i,k,t}}{EU_{i,t}} \frac{C_{i,k,t}}{EU_{i,k,t}} = \sum_{i,k} GO_t S_{i,t} I_{i,t} F_{i,k,t} EF_{i,k,t}, \tag{1}$$

with the following notation:

- period: $t \in (1995, 2009)$,
- sectors: $i = 1, \ldots, 34$,
- fuel types: $k = 1, \ldots, 26$,[13]
- CO_2 emissions of fuel type k in sector i and period t: $C_{i,k,t}$,
- CO_2 emissions of country j in period t: $C_t = \sum_{i,k} C_{i,k,t}$,
- energy use of fuel type k in sector i and period t: $EU_{i,k,t}$,
- energy use of sector i in period t: $EU_{i,t} = \sum_k EU_{i,k,t}$,
- gross output of sector i in period t: $GO_{i,t}$, and
- gross output as a measure of economic activity of a country in period t: $GO_t = \sum_i GO_{i,t}$.

Hence, in this notation total carbon emissions consist of (i) the sectoral emission factors of specific fuel types, $EF_{i,k,t} = \frac{C_{i,k,t}}{EU_{i,k,t}}$, (ii) the share of each fuel type in sectoral energy use, $F_{i,k,t} = \frac{EU_{i,k,t}}{EU_{i,t}}$, (iii) sectoral energy intensity, $I_{i,t} = \frac{EU_{i,t}}{GO_{i,t}}$, (iv) the gross output share of each sector within a country, $S_{i,t} = \frac{GO_{i,t}}{GO_t}$, and (v) gross output of the country, GO_t.

The multiplicative decomposition of changes in total carbon emissions between the periods t and $t+1$ is then described by

$$D_{Tot,t+1} = \frac{C_{t+1}}{C_t} = D_{Act,t+1} D_{Str,t+1} D_{Int,t+1} D_{Mix,t+1} D_{Emf,t+1}. \tag{2}$$

$D_{Act,t+1}$ is the estimated impact of economic growth or declines on carbon emissions (*activity effect*). $D_{Str,t+1}$ is the estimated impact of *structural change* on total carbon emissions. $D_{Int,t+1}$ describes the effect of changes in the sectoral energy intensity levels on carbon emissions which can be explained by a change in the efficiency of the corresponding sector (*technology* or *intensity effect*). $D_{Mix,t+1}$ is the impact of *changes in the fuel mix*, and $D_{Emf,t+1}$ is the effect of *changes in emission factors* of specific fuel types. The formulae for the log mean Divisia index decomposition are

$$D_{Act,t+1} = \exp\left(\sum_{i,k} \omega_{i,k} \ln\left(\frac{GO_{t+1}}{GO_t}\right)\right), \tag{3}$$

$$D_{Str,t+1} = \exp\left(\sum_{i,k} \omega_{i,k} \ln\left(\frac{S_{i,t+1}}{S_{i,t}}\right)\right), \tag{4}$$

[12] An alternative approach is additive decomposition. In addition, one could choose between alternative indicators, such as Paasche or Laspeyres indices. However, due to unexplained residuals during the decomposition procedure which also arise for those types of indices, we prefer the logarithmic mean Divisia index.

[13] The fuel types include three different types of coal, eight types of liquid energy carriers, two types of gas, nine renewable sources, nuclear, heat, electricity, and residual category.

$$D_{Int,t+1} = \exp\left(\sum_{i,k} \omega_{i,k} \ln\left(\frac{I_{i,t+1}}{I_{i,t}}\right)\right), \quad (5)$$

$$D_{Mix,t+1} = \exp\left(\sum_{i,k} \omega_{i,k} \ln\left(\frac{F_{i,k,t+1}}{F_{i,k,t}}\right)\right), \quad (6)$$

$$D_{Emf,t+1} = \exp\left(\sum_{i,k} \omega_{i,k} \ln\left(\frac{EF_{i,k,t+1}}{EF_{i,k,t}}\right)\right), \quad (7)$$

where

$$\omega_{i,k} = \frac{(C_{i,k,t+1} - C_{i,k,t})/(\ln C_{i,k,t+1} - \ln C_{i,k,t})}{(C_{t+1} - C_t)/(\ln C_{t+1} - \ln C_t)} \quad (8)$$

serves as a weighting scheme in the index decomposition framework (Ang and Zhang, 2000). As proposed by Ang and Liu (2007), we use chaining decomposition, i.e. the specific annual values are computed on a rolling basis (from 1995 to 1996, from 1996 to 1997 etc.) where the value for 1995 is set equal to 1. These results are "chained" to obtain a time series from 1995 to 2009 (Ang and Liu, 2007, p. 1428).[14]

We first provide a global analysis with an aggregate of all sample countries which represents the reference for the country-specific decomposition. Following that, the global trends are compared to country trends in order to highlight region-specific dynamics.

5. Decomposition of Carbon Emissions: Country Level and Global Results

5.1. Aggregate Decomposition

Before analyzing the different drivers of the CO_2 emissions development in our 40 sample countries, let us first have a look at the global level. Figure 4 highlights the contribution of the five different effects on aggregate carbon emission changes. We compute these effects according to equations 3 to 7. All graphs displaying the results of the index decomposition analyses, either at the aggregate level or for the individual countries in the next subsection, can be interpreted in an analogous manner. The total effect (red line) is the change of carbon emissions relative to 1995. For instance, aggregate carbon emissions are approximately 30 per cent larger in 2009 than in 1995. The other lines correspond to the five components into which we decompose the total effect. An activity effect (green line) of greater than one means that economic growth drove carbon emissions above 1995 levels. If the structural effect (orange line with a star as mark) is above one, sectoral composition shifted towards more polluting sectors. An intensity effect (blue line) of less than one implies that sectoral carbon emissions based on energy intensity declined (i.e. "energy efficiency" rose). The evolution of the fuel mix effect (purple line) describes the shift of global or a country's composition in terms of carbon emissions related to different sources of energy supply. A decrease of the fuel mix can be interpreted such that power generation is increasingly based on less carbon intensive energy sources (as e.g. gas, nuclear power or the renewable sector). Finally, the emission factor effect (dark orange line with dashes as mark) describes the carbon content of different energy carriers. The total effect equals the product of these five effects.

The decomposition highlights that rapid economic growth was the principal driver for rising carbon emissions levels in the period between 1995 and 2009. However, due to structural changes toward less polluting industries and to technology improvements, the growth of CO_2 emissions could be decoupled from economic growth to a certain degree. When looking in more detail at the temporal development, we can distinguish three different phases. The first phase between 1995 and 2002 is characterized by a relatively slow growth of the total effect. Although the activity effect exhibits a steep increase, the technology effect and, to a lesser extent, the structural effect decline and hence attenuate the influence of economic growth. In the second phase between 2002 and 2007 the total effect grew at a considerably higher pace. This is mainly due to fairly stable structural and technology components while the activity effect did not show a significantly different behavior than in the first period. The third phase (after 2007) is clearly

[14] For a theoretical consideration of chaining decomposition see also Ang (1994, pp. 169ff.).

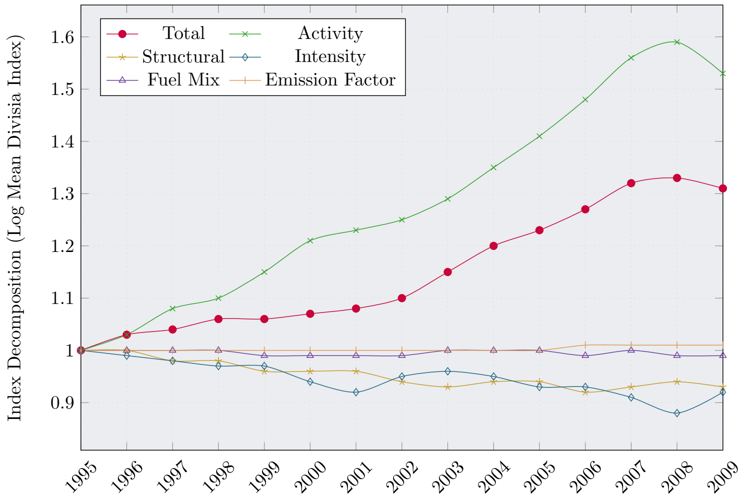


Figure 4: LMDI decomposition of global carbon emissions

marked by a stagnation of total CO_2 emissions which is, according to our calculations, a direct effect of the economic crisis of 2008 and 2009. However, also the technology effect and the fuel mix contributed to this trend in parts.

Summarizing, the development of aggregate carbon emissions is driven by the activity, the technology and the structural effects whereas the fuel mix and the emission factor effects played a negligible role. The most rapid declines in the technology effect occurred between 1995 and 2001 and again between 2003 and 2008. However, in the latter phase the technology and the structural effects have opposing trends so that the steady decline in energy intensity could not dampen the steep increase of carbon emissions. Nevertheless, these global trends differ, in parts substantially, from specific country results, as we will see during the following subsection.

5.2. Country Level Decomposition

5.2.1. Classification of countries

We base our country classification on Figure 5 which depicts growth rates of gross output and CO_2 emissions of our sample countries. The best performing group is located in the bottom right part of the chart where high output growth rates (higher than average) are coupled with relatively low growth rates of carbon emissions (lower than average). It consists mainly of Eastern European countries. Conversely, the worst performing group is located in the upper left of the chart. It consists of emerging economies, e.g. Brazil and Mexico, as well as of developed countries, such as Denmark and Australia, and shows low growth rates of gross output in combination with above-average increases in carbon emissions. Within the third cluster in the bottom left, performance is mixed, i.e. these countries exhibit low emissions growth rates (or even declines), but this is partly due to below-average output growth. This behavior is characteristic of highly developed economies and all countries in this group belong to the "triad" (Western Europe, North America and Japan). The fourth group can be found in the upper right part of the graph and includes important emerging economies, such as China, India, Taiwan, Turkey and South Korea, where both output and emissions growth rates were high. Our country-level decomposition analysis below will be based on the classification just outlined.

5.2.2. IDA for Countries with Low Gross Output Growth and High Emissions Growth

The first group consists of countries with a, compared to the world average, low gross output growth and high emissions growth. Australia, Brazil, Canada, Denmark, Greece, Indonesia, Mexico, Portugal, Slovenia and Spain are very heterogeneous in terms of their economic development (see Figure 6). The reasons behind the increasing trends in carbon emissions can therefore also be expected to be quite different.

Total Effect: The total effect is above one in 2009 for all countries in this group, i.e. all countries emitted more carbon dioxide than in 1995. While the increase was rather moderate for Canada, the observed growth in carbon emissions is substantial in countries like Brazil and particulary in Indonesia. In both countries, the total effect even

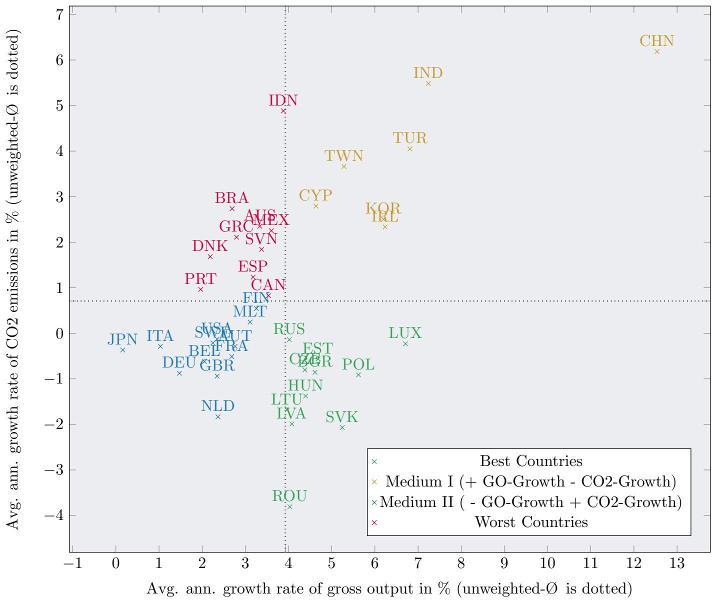
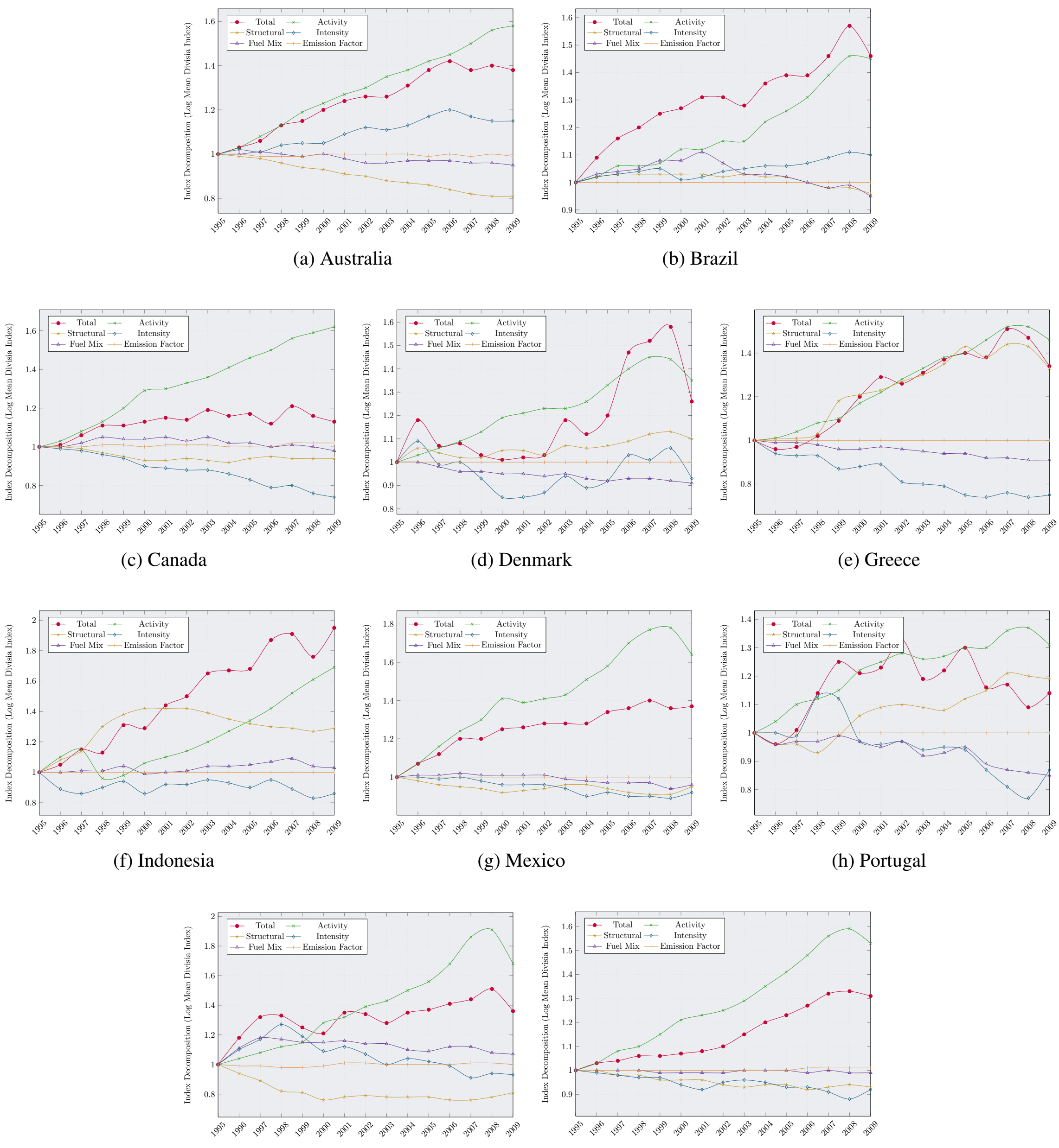


Figure 5: Correlation between growth rates of gross output and CO_2 emissions

outperforms economic growth (the activity effect). However, the drivers behind this development are different. While Indonesia could improve its technology and held its fuel mix almost constant, substantial structural change occurred towards more carbon intensive sectors. In Brazil, the fuel mix trended upwards until 2001 and decreased afterwards towards levels below 1995. Structural change played only a minor role in Brazil. A crucial cause of Brazil's development of total carbon emissions was the use of less energy efficient technologies. In combination with substantial economic growth this has resulted in increasing carbon dioxide emissions in Brazil. Canada's development of carbon emissions is a result of a slight decrease of the fuel mix effect, by significant structural change towards less carbon intensive sectors and especially by improvements of the technology effect. In combination, these three effects dampened the activity effect. The development of Australia's emissions is due to economic growth which could not have been offset by the use of less fossil fuels or technology improvements. Together with Brazil, it is the only country with a technology effect above 1995 levels. This confirms early findings on carbon emissions in Australia by Hamilton and Turton (2002). Denmark and two Southern European countries, Greece and Portugal, are characterized by a shift towards more carbon intensive sectors. Their overall improvement is due to a decreasing technology effect and a shift of the fuel mix towards less carbon emitting energy sources. While the improvement of the technology effect is almost steady for Greece, we observe much more volatility for Denmark and Portugal. The patterns of Mexico and Spain are very similar and the increase of the activity effect is partially compensated by a combination of decreasing technology and fuel mix effects as well as structural change. The only Eastern European country in this group is Slovenia. In contrast to other Eastern European countries, the Slovenian technology effect could not improve significantly. Furthermore, the fuel mix changed towards more carbon dioxide emitting energy carriers. The overall development is mainly due to a positive development of the structural effect.

5.2.3. IDA for Countries with Low Gross Output Growth and Low Emissions Growth

Countries with low gross output growth and low carbon emissions growth are shown in Figure 7. This group consists exclusively of mature Western economies in Europe and North America and Japan. Not surprisingly, total carbon emissions have either remained rather stable or even have decreased by 2009 compared to 1995. However, the temporal development within the sample period differs to quite a high extent. France, Germany, the Netherlands, Sweden and the UK exhibit a similar path, i.e. a constant slight decline, while e.g. Italy, Japan Finland and the US are characterized by rising emissions levels throughout most of the period but a decline towards the last years of our time horizon. Regarding the activity effect, the trend is very similar in all respective countries – a growing



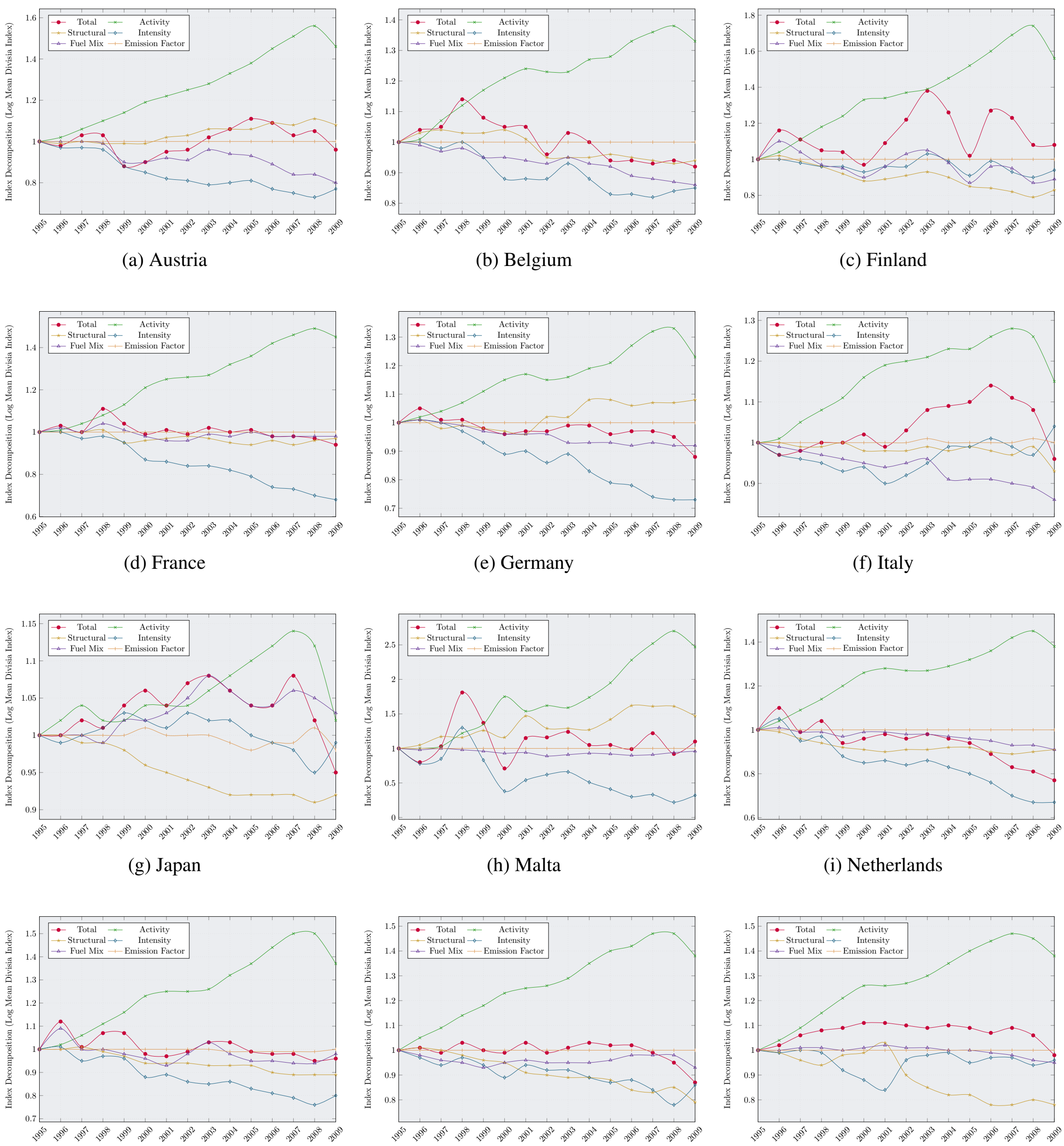
(a) Australia (b) Brazil

(c) Canada (d) Denmark (e) Greece

(f) Indonesia (g) Mexico (h) Portugal

(i) Slovenia (j) Spain

Figure 6: IDA for countries with low gross output growth and high emissions growth



(a) Austria (b) Belgium (c) Finland

(d) France (e) Germany (f) Italy

(g) Japan (h) Malta (i) Netherlands

(j) Sweden (k) United Kingdom (l) United States

Figure 7: IDA for countries with low gross output growth and low emissions growth

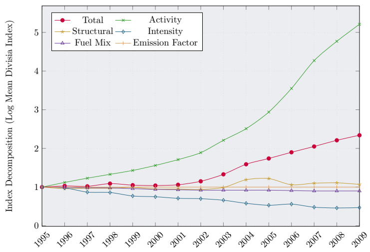
economy until 2007/2008 and a sharp decrease thereafter. Nevertheless, Italian and particularly Japanese growth rates are significantly smaller than those of the other countries. The structural effect is decreasing in most countries, i.e. "cleaner" sectors gained weight within the respective economies, with three exceptions – Austria, Germany and Malta – where a shift towards sectors with higher carbon emissions occurred. This is also reflected in the development of the technology effect in these three countries. It rapidly declines and hence compensates the increase of the structural effect. Especially Germany exhibits one of the greatest declines of the technology effect. In general, the pattern of technology improvements differs quite tremendously between the sample countries. Besides Germany, the most rapid decreases can be observed in Austria, France, Malta, the Netherlands, Sweden and the UK. On the other hand, Italy, Japan and the United States saw a rather stable development when comparing the years 1995 and 2009. While Italy and the US experienced relatively large technology improvements in the first half of the sample period which was more or less revoked in the second half, Japan effectively exhibited almost no change in this component. When comparing the technology effect with the total effect, one can clearly observe similarities between them in most countries of this group, inducing a strong influence of technology improvements on the development of carbon emissions. Finally, more than in any other group, the fuel mix had a considerable influence on the total effect. Except for France, Sweden and the US – with little change or only a slight decline – and Japan with a moderate increase, all countries saw a decline by almost 10% or more during the sample period, implying a shift towards cleaner fuel inputs. The path of the fuel mix effect is also similar to that of the total effect in many countries of this group.

5.2.4. IDA for Countries with High Gross Output Growth and High Emissions Growth

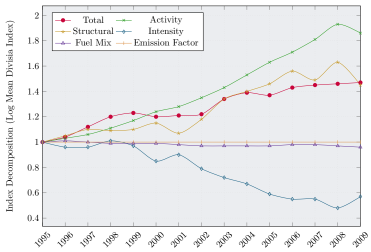
The third group consists of seven countries, mainly from Asia. All countries are characterized by a high output growth in combination with a high emissions growth rate. The results for the respective countries are presented in Figure 8. The total effect is substantially higher for all countries compared to 1995. The two major developing countries in this group, India and China, more than doubled their emissions of carbon dioxide. The difference between these two countries is that China had a far higher growth rate in terms of gross output than India. China could compensate its tremendous growth in gross output through a decrease of the technology effect, i.e. the deployment of more energy efficient technologies. This development is steady throughout the period we consider. The other effects played only a minor role for China. Also India's value for the intensity effect declined. Additionally, the structure of India's economy shifted slightly towards less carbon intensive sectors. Cyprus is the only country in this group in which structural change played a significant role. While the index for the intensity effect declined steadily since 1999, carbon intensive sectors gained far more importance in Cyprus compared to 1995. The second European country, Ireland, is characterized by an almost stable development of the intensity effect (despite a one year increase between 1998 and 1999) until 2004. Afterwards, the intensity effect declined until 2009. The structural effect follows a U-shaped pattern between 1995 and 2006 and remained stable after 2006. Taiwan and Turkey share similar patterns for the structural and the fuel mix effect. The main driver behind the development of carbon emissions in both countries was a substantial improvement of the intensity effect. All countries in this group have in common that the fuel mix remained almost unaltered in terms of contribution to national carbon emissions. We draw the tentative conclusion that policies geared towards altering the fuel mix could be a valid option to achieve carbon emission reductions in these countries.

5.2.5. IDA for Countries with High Gross Output Growth and Low Emissions Growth

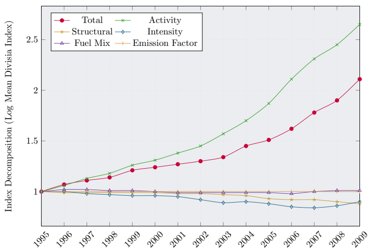
The decomposition results for countries with above average gross output growth and below average carbon emissions growth are shown in Figure 9. Apart from Luxembourg, all members of this group are Eastern European countries. These economies experienced the largest structural change as also shown by other recent studies (Mulder and De Groot, 2012). Nevertheless, the evolution of carbon dioxide emissions shows very different patterns with respect to the development of its components. Remarkably, all countries with the exception of Luxembourg have kept their carbon dioxide emissions at least constant, Latvia, Lithuania, Romania and Slovakia even reduced their emissions substantially. Bulgaria is the only country in this group in which the fuel mix changed towards more carbon emitting energy carriers and where carbon intensive sectors gained weight. The main reason behind Bulgaria's modest decline in carbon emissions was the utilization of more energy efficient technologies, i.e. a substantial improvement of the intensity effect. All other Eastern European countries exhibited a large structural change towards less carbon intensive sectors. We expect this to be the aftermath of the fall of the iron curtain and the subsequent deindustrialization in the former communist countries. A changing fuel mix towards less carbon emitting energy carriers can be observed in



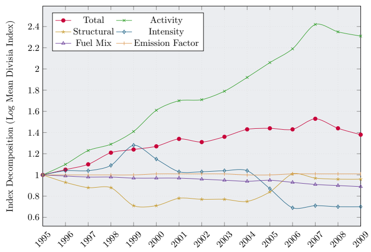
(a) China



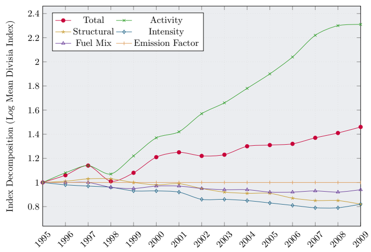
(b) Cyprus



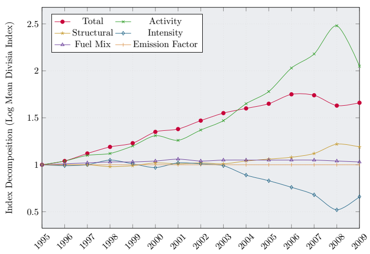
(c) India



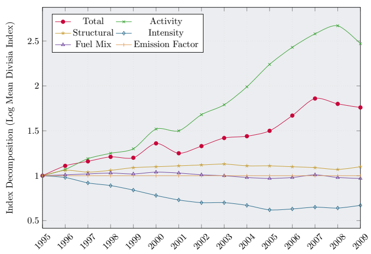
(d) Ireland



(e) South Korea

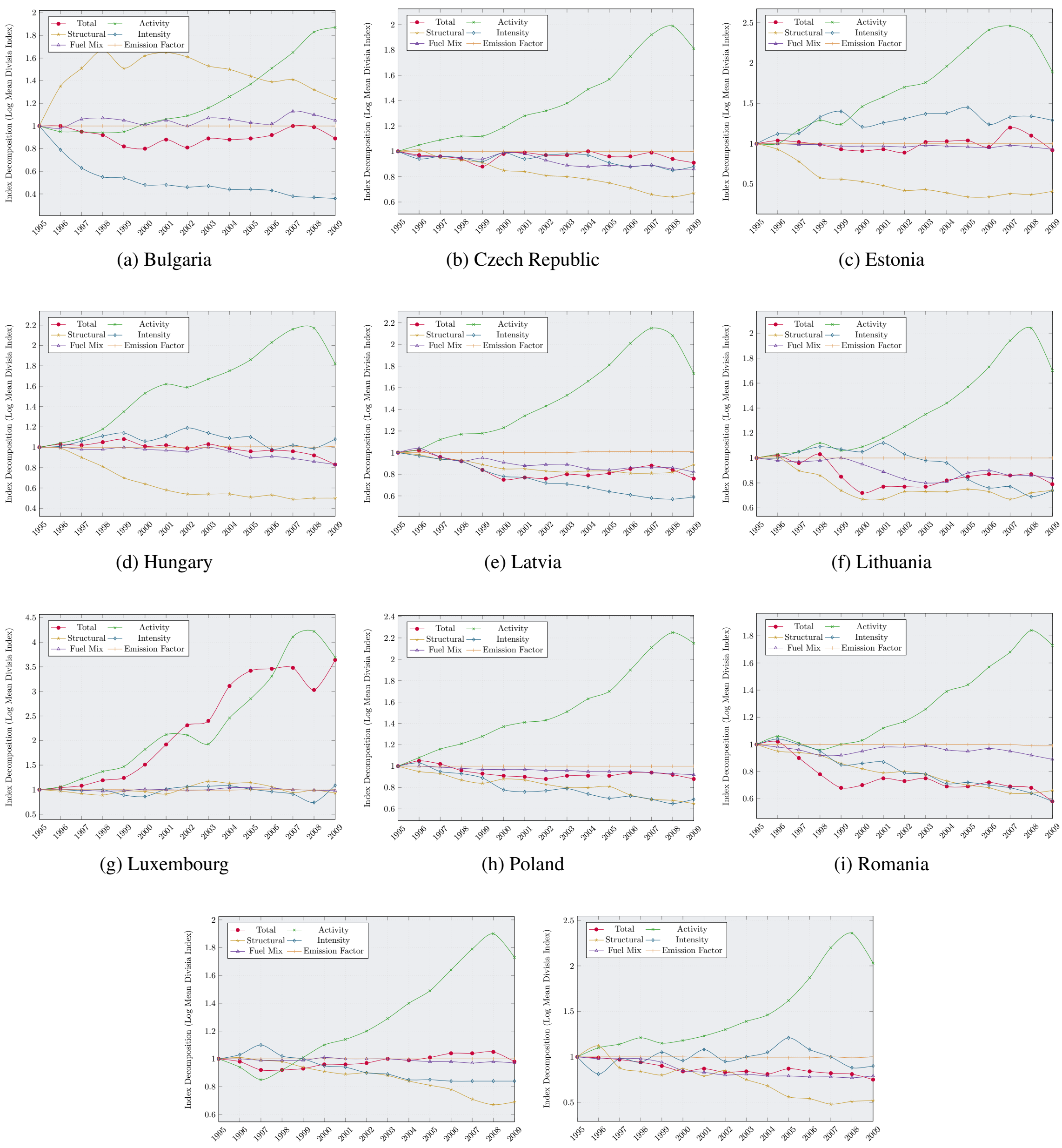


(f) Taiwan



(g) Turkey

Figure 8: IDA for countries with high gross output growth and high emissions growth



(a) Bulgaria (b) Czech Republic (c) Estonia

(d) Hungary (e) Latvia (f) Lithuania

(g) Luxembourg (h) Poland (i) Romania

(j) Russia (k) Slovakia

Figure 9: IDA for countries with high gross output growth and low emissions growth

the Czech Republic, Hungary, Latvia, Lithuania, Romania and Slovakia. In Bulgaria, Latvia and Poland the carbon emissions development is to a very high extent determined by technology improvements. On the contrary, in Estonia and Hungary carbon emissions development can almost entirely be assigned to structural changes of the economy. The former country even saw technological deterioration over the whole sample period while this trend was reversed in Hungary after 2002/2003.

6. Conclusion

This paper analyzes trends in carbon emissions for 40 major economies between 1995 and 2009. It contributes to the literature in index decomposition analysis in several ways. First, so far most of the index decomposition literature has mainly analyzed energy intensity. This perspective is extended in our study to examine carbon emissions for a wide variety of countries. Second, it employs a novel socio-economic database consistently accompanied by environmental satellite accounts to construct measures of carbon emissions for 34 sectors. Based on this harmonized dataset, a comprehensive compendium of carbon emissions time series has been computed. Third, we show that – with respect to the development of CO_2 emissions – heterogeneity in each country across sectors is higher than heterogeneity in sectors across countries. This finding might lead to the conclusion that structural conditions in sectors prevail over regional circumstances, such as regulatory measures. Fourth, the paper decomposes carbon emissions into five different factors, the activity effect, the structural effect, the fuel mix effect, the emission factor and the technology effect in order to examine what share of temporal variation is due to actual changes in the technology within the economy's sectors or in the fuel mix and is hence replicable, and what share is based merely on structural changes of the economy.

We classify our sample countries into four groups according to the level of their gross output and CO_2 emissions growth rates. The best performing group – with high output and low emissions growth or even declines – consists mainly of Eastern European countries. They reduced their carbon intensity levels by up to 60% over the sample period. On the other hand, the worst performing group – with low gross output and high emissions growth – achieved mean carbon intensity reductions of approximately 10 to 15% between 1995 and 2009. However, the drivers of this development, in particular the technological and the structural component, are very heterogeneous and we cannot generalize our results for the different groups. Among the world's top ten emitters as of 2009, in only three countries – Canada, China and Germany – the main driver of carbon emission development was technology improvement. Conversely, in Japan and the United States structural change of the economy was responsible for the development of carbon emissions. In the other countries, i.e. India, Russia, South Korea and the United Kingdom, both effects drove the evolution of carbon emissions. In the US and in Russia the structural component was slightly dominant, while in India, South Korea and the UK the technology component contributed to a higher degree. At the global level, carbon emissions development is driven by both the technology effect as well as structural change towards less carbon intensive sectors. Nevertheless, absolute global CO_2 emission levels increased by one third over the sample period. Therefore, an important challenge for policy makers is to translate carbon intensity reduction, which can still be accompanied by rising emissions levels, into actual declines in CO_2 emissions. Given our results of the descriptive analysis, an interesting approach could be to start at the sectoral level. This view is also supported by others as "sectoral approaches may be a better way to attack negative competitiveness effects and leakage. They are consistent with desires of developing countries to curtail emissions for domestic reasons and raise fewer issues of economic imperialism" (McLure, 2014, p. 556). Another field of potential which could be leveraged are changes in the fuel mix of individual countries. While the fuel mix effect contributes to a significant extent in some European countries such as Austria, Denmark, Germany, Greece and Italy, there seems to exist large space for improvement in other countries, e.g. Australia, China, India, Japan and the United States. Finally, the impact of emission factor changes of specific fuel types is negligible, i.e. within this relatively short time horizon carbon efficiency of fuels hardly improved.

Our analysis hence suggests some interesting directions for future research. A first step would be to explore the determinants of a country's heterogeneity in performance in order to isolate those factors that can promote technological change and thus bring about long lasting improvements in carbon emissions and CO_2 abatement. Finally, a case study analysis of those countries where the impact of the technology effect was significant is clearly worthwhile.

Acknowledgments

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