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Surveys

Index decomposition analysis applied to CO_2 emission studies

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ABSTRACT

Index decomposition analysis (IDA) was first extended from energy consumption to energy-related CO_2 emission studies in 1991. Since then many studies have been reported covering various countries and emission sectors. However, unlike the case of energy consumption studies, a comprehensive literature survey that focuses specifically on emission studies has so far not been reported. In this paper, we attempt to fill this gap by reviewing 80 papers appearing in peer-reviewed journals from 1991 to 2012 in this application area. The first part of this paper deals with the developments with regard to the IDA approaches used by researchers, and the scope and focus of their studies. In the second part, the empirical results reported in the surveyed studies are analyzed, consolidated, and presented by emission sector. The objective is to reveal the relative contributions of key effects on changes in the aggregate carbon intensity, and this is done by emission sector and by country. The findings of both parts are useful in understanding the development of IDA in the application area of emission study, as well as the key drivers of aggregate carbon intensities in the past and their possible future developments.

1. Introduction

Index decomposition analysis (IDA) has been widely used in studies dealing with energy consumption since around 1980. In many of these studies, the focus is to quantify drivers behind changes in an aggregate of interest, such as energy consumption or the aggregate energy intensity of a particular sector. The drivers of interest include the well-known activity structure change and energy intensity change. Over the years several hundred peer-reviewed journal papers have been published in this topic. Different IDA methods or ways of accounting were adopted by researchers in the 1980s and 1990s. Convergence took place in the 2000s and the approach now used by researchers is fairly standard. Relevant literature review can be found in Ang and Zhang (2000), Ang (2004), Liu and Ang (2007), and Ang et al. (2009).

The original impetus behind IDA studies was linked mainly to energy efficiency, and indirectly to energy security, in the aftermath of world oil crises in the 1970s. In this aspect, there was little change until around 1990. After 1990, with climate change and greenhouse gas (GHG) emissions becoming a global issue, IDA has been extended to study GHG emissions and in particular energy-related CO_2 emissions. In some recent years, there were actually more IDA studies, such as in peer-reviewed journal papers, that deal with carbon emissions than with energy consumption. However no comprehensive literature survey on emission studies similar to that for energy has so far been reported since the study by Ang and Zhang (2000).[1] One of the objectives of this paper is to fill this gap. In this study, a literature survey is conducted and the findings are presented from Sections 2 to 4. A specific area of interest is the differences between emission studies and energy studies in both the methodological and application fronts.

Another objective is to analyze the empirical results reported in previous emission studies, in particular the relative contributions of the effects of the defined factors in the IDA identity. Essentially, this means identifying the key drivers behind changes in the aggregate CO_2 emissions or intensity, and studying their relative importance. The study will cover different emission sectors and countries, with and without temporal changes taken into account. The results are compared and the findings are presented from Sections 5 to 7. Of particular interest are whether there were similar features or developments among sectors and among countries, and whether there were variations over time for a specific sector in a country or among countries. The findings will have implications on how emissions will evolve in future in general, such as for economies at different stages of development. The study covers economy-wide CO_2 emissions, emissions for four final energy consumption sectors (industry, transportation, residential, and service), and emissions from the electricity generation sector. We

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[1] The study by Ang and Zhang (2000) surveys IDA applied to energy and emissions. About a quarter of the 124 studies surveyed are about emissions. The survey also includes a number of studies using the technique of structural decomposition analysis. Ang and Zhang (2000) can therefore be taken as the first survey of decomposition analysis applied to emissions. The present study, more precisely, is the first comprehensive survey devoted specifically to IDA applied to CO_2 emissions.

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make extensive use of the information and findings reported in the literature. These are mostly unrelated studies and an attempt is made to reconcile the decomposition results and present them in a meaningful manner. This, to some extent, dictates how the surveyed results are compiled, analysed and presented. Finally, Section 8 concludes.

2. Main Features and Developments

In energy consumption studies, application of the conventional 3-factor IDA identity leads to three effects, namely the activity, structure, and intensity effects. In energy-related CO_2 emission studies, more effects are included as the aggregate emissions are dependent on the fuel mix in energy consumption. In a study of changes in industrial CO_2 emissions in nine OECD countries, Torvanger (1991) extended the conventional 3-factor IDA identity to a 5-factor identity by considering five effects, namely the activity, structure, energy intensity, fuel mix, and emission coefficient effects. Since then, a large number of emissions IDA studies have been reported. A list of 80 studies (or publications) covering the period 1991–2012 appearing in peer-reviewed journals is shown in Table A.1.[2]

The 80 publications in Table A.1 are mainly application studies; studies dealing mainly with methodology are rare. This feature is consistent with that in energy IDA studies. From Table A.1, the key features of emission IDA studies including the developments since 1990 can be summarized as follows. Studies on a wide range of countries or economies have been reported. In terms of the number of publications, the split between industrial countries and developing countries is fairly even. Over two-third of the studies decompose the absolute emissions change, and about 60% apply the additive decomposition scheme. Fig. 1 shows the numbers of publications and countries/economies studied by application area.[3] The industry sector and economy-wide decomposition are the two most popular application areas, followed by the electricity generation sector. The figure also shows that studies have been conducted for all the major emission sectors. An interesting feature observed is the relatively high number of studies for the electricity generation sector, as compared to the case of energy IDA studies. This issue will be looked into in later sections. By splitting 1991–2012 into three sub-periods, 1990–1999, 2000–2005, and 2006–2012, Fig. 2 shows a rise in the number of studies from the second to the most recent period for almost all application areas. This reflects the growing importance of and concern over climate change.

As in the energy IDA literature, the IDA methods used may be grouped into four types, i.e. Laspeyres (LASP), Shapley/Sun (S/S), logarithmic mean Divisia index (LMDI), and other Divisia method.[4] Fig. 3 shows a shift from the conventional Laspeyres method and other Divisia methods which leave a residual term in the decomposition results, to ideal decomposition methods such as LMDI and the S/S method and in particular LMDI. In the most recent period, 2006–2012, five out of every six publications adopt an ideal decomposition method and the overwhelming majority uses LMDI. This trend and the dominance of LMDI are also observed in the case of energy IDA literature. As pointed out earlier, emission studies generally have more factors in the IDA identity compared to energy studies. In the literature, the number of factors varies from three to more than ten. Further investigation shows that the proportion of studies using more than five factors increased from only 5% in 1991–1999 to 25% in 2000–2005, and then to 33% in the most recent period. The research trend is therefore towards using IDA identifies that have more factors and require more data, which provides more refined decomposition results. The increase in the number of factors in the IDA identify has an impact on the choice of decomposition method. LMDI which is easy to apply irrespective of the number of factors were preferred to the other methods. This feature is captured in Fig. 4 which shows the distribution of studies by decomposition method for different numbers of factors in the IDA identify. As can be seen, there is a strong preference for LMDI when the number of factors exceeds five.[5]

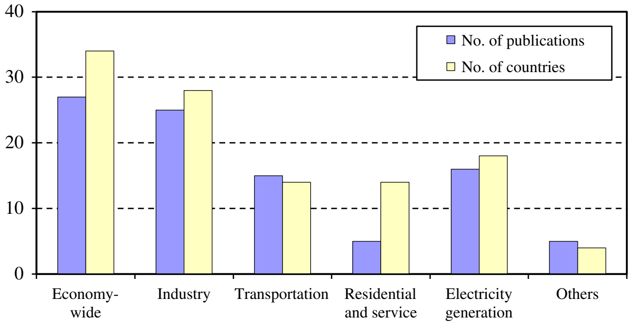

Fig. 1. Numbers of publications and countries studied by application area.

In summary, the number of emission IDA studies has been growing. Studies covering all the major sectors and for a large number of countries have been reported. The usefulness of IDA has been recognized by researchers and this study area is by now well established. Other than the economy-wide studies, the industry sector has been the most popular sector studied. An increasing proportion of studies adopt IDA methods that give ideal decomposition and in particular LMDI. In general, all these developments are very similar to those observed in the energy IDA literature, except for a higher proportion of studies focusing on electricity generation in emission IDA studies. Another difference between the two application areas is that in emissions studies more factors are considered and, as a result, LMDI is more likely to be applied.

3. Methodological Issues

We look into the emission IDA identities, both the conventional ones and their extensions for specific applications, as reported in the literature. Assume that an aggregate such as the CO_2 emissions of a sector is divided into a number of sub-categories such as sub-sectors.[6] Let C be the aggregate emissions and C_i be the emissions from sub-category i, A be the aggregate activity level, S_i $(=A_i / A)$ be the activity share, EI_i $(=E_i / A_i)$ be the sub-category energy intensity, and CF_i $(=C_i / E_i)$ be the carbon factor of sub-category i. We then have:

$$C = \sum_i C_i = \sum_i A \frac{A_i}{A} \frac{E_i}{A_i} \frac{C_i}{E_i} = \sum_i A \times S_i \times EI_i \times \mathrm{CF}_i \tag{1}$$

If the carbon factor is given as the product of fuel mix F_{ij} $(=E_{ij} / E_i)$ and the emission coefficient U_{ij} $(=C_{ij} / E_{ij})$ of fuel j, we have:

$$C = \sum_i \sum_j C_{ij} = \sum_i \sum_j A \frac{A_i}{A} \frac{E_i}{A_i} \frac{E_{ij}}{E_i} \frac{C_{ij}}{E_{ij}} = \sum_i \sum_j A \times S_i \times EI_i \times F_{ij} \times U_{ij} \tag{2}$$

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[2] We confine our survey to publications in peer-reviewed journals. If technical reports and conference papers are included, the total number would be a few hundred. Decomposition studies without considering sub-sectors, i.e. without a formal treatment of the effect of some structure change, such as those using the IPAT formula and Kaya identity, are excluded. Studies that are descriptive in nature are also excluded.

[3] Some studies involve more than one application area and/or one country or economy.

[4] The other Divisia category includes the arithmetic mean Divisia method (AMDI) and other parametric Divisia methods (Ang, 1995). For more details about the various IDA methods, refer to Ang (2004).

[5] When the number of factors increases, the S/S method becomes cumbersome and difficult to apply and this limits its applicability. For further details, see Ang (2004) and Ang et al. (2009).

[6] Unless otherwise specified, emissions in this study refer to energy-related emissions.

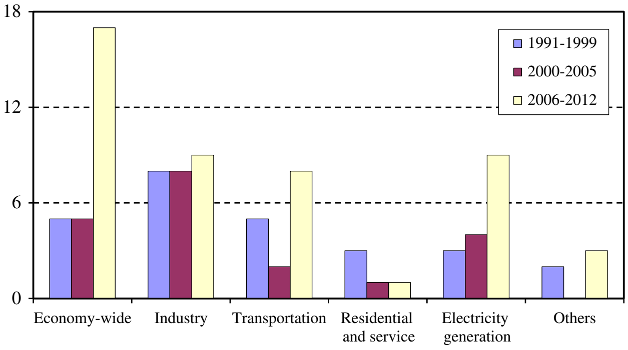

Fig. 2. Numbers of publications for different time periods by application area.

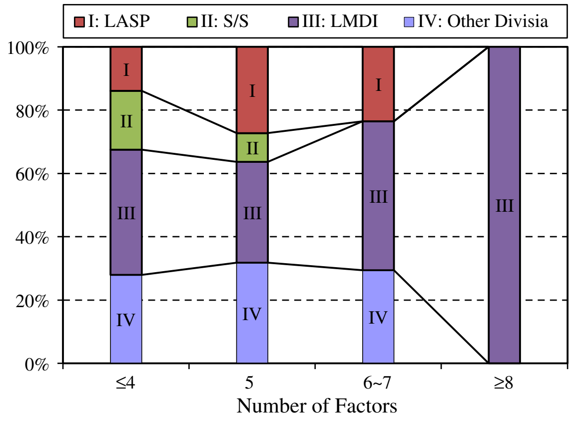

Fig. 4. Distribution of studies by the decomposition method used for different numbers of factors studied.

In some cases the emission coefficient effect is taken as null as it is assumed that the emission coefficient of a fuel is unchanged in a relative short time period. This assumption leads to a simplified form of Eq. (2) as:

$$C = \sum_i \sum_j A \times S_i \times EI_i \times F_{ij} \tag{3}$$

Eqs. (1) to (3) are three standard IDA identities in emission studies as revealed in the publications in Table A.1. The number of factors is normally either four or five.

Besides, other variations have been reported in some specific applications. A common one is the introduction of a new effect to bridge the gap between the activity effect and the structure effect when the activity indicator and the denominator of the structure indicator are different. Examples are the introduction of the load effect defined as the ratio of passenger-kilometers or tonne-kilometers to population in transportation sector studies (Greening, 2004; Lakshmanan and Han, 1997; Mazzarino, 2000; Schipper et al., 2011; Timilsina et al., 2009a,b; Wang et al., 2011), the electricity intensity effect given by the ratio of electricity generation to GDP in electricity generation sector studies (Shrestha et al., 2009), and the income effect defined as the ratio of GDP to population in economy-wide studies (Albrecht et al., 2002; de Freitas and Kaneko, 2011a,b; Lise, 2006; Tol et al., 2009). As a result, the number of effects in the IDA identity may increase to five or six as in some studies.

In economy-wide studies, a disadvantage of the conventional approach of using a single IDA identity is that the same activity indicator is required for all economic sectors in order to give a meaningful structure effect. This restriction reduces the flexibility of activity indicator selection and limits sector coverage. Non-production sectors such as residential and passenger transportation which are major emitters of CO_2 are often excluded from studies using such an approach (Albrecht et al., 2002; Nag and Parikh, 2000; Zhang et al., 2009). Arising from this drawback, Wu et al. (2005) propose a hybrid model and decompose the aggregate emission change into relevant effects at the sectoral level for the residential sector, transportation sector, and the rest of production sectors, respectively. In each case, an appropriate activity indicator is employed. The sectoral decomposition results are then aggregated to give the effects at the economy-wide level. Using this approach, Wu et al. (2005) analyze the drivers behind the aggregate emission change in China using 12 factors. A similar hybrid model for Brazil is reported in de Freitas and Kaneko (2011a).

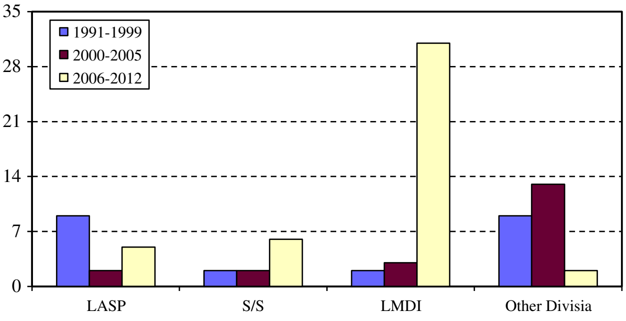

Fig. 3. Numbers of studies for different time periods by the decomposition method used.

How to treat emissions arising from electricity use is an issue that often arises in emission IDA studies. Whether to treat electricity as a product of energy service or an energy type will lead to different decomposition models. In the former, the fuels used to generate electricity are allocated to the corresponding energy consumption in the final consumption sectors. The standard decomposition models given by Eqs. (1) and (3) are then applicable. In the latter, the impact of carbon factor cannot be nullified and Eq. (2) should be applied. The impact of carbon factor change is mainly determined by the fuel mix in electricity generation. Comparisons of the decomposition results of these two approaches are given in Nag and Parikh (2000).

Furthermore, the electricity generation sector is an important application area in emission IDA studies. In the literature, at least 16 studies can be found. In terms of emissions, there are two different categories of energy sources in electricity generation: one with CO_2 emissions, i.e. primarily fossil fuels such as coal, oil and gas, while the other without such as nuclear, solar and hydro. Ang and Choi (2002) discuss issues related to the boundary problem for treating these energy sources in the IDA identity. More generally, depending on the system boundary used, IDA studies of CO_2 emissions in electricity generation can be divided into three types. In Type A, only electricity generation from fossil fuels is considered and a change in CO_2 emissions is decomposed to give the total generation effect, the generation mix effect (arising from changes in electricity generation share by different energy sources), the generation intensity effect (arising from changes in thermal efficiency), and the emission coefficient effect. Examples of such studies are Shrestha and Timilsina (1996) and Nag and Parikh (2000). In Type B, electricity generation from both fossil fuels and non-fossil fuels are taken into account. The same IDA identity as in Type A is used and the emission coefficients of non-fossil fuel sources are taken as zero. Examples of such studies are Ang et al. (1998), Malla (2009) and Shrestha et al. (2009). The problem of zero values in the calculation of Divisia methods may be an issue of the Type B model. To resolve this problem, the IDA identity may be modified by decomposing the generation mix factor into a fossil fuel share factor (defined as the proportion of fossil fuel generation in total electricity generation) and a fossil fuel generation mix factor (defined as fossil fuel generation mix) and this lead to a Type C model. Examples of such studies include Shrestha and Timilsina (1998), Nag and Kulshreshtha (2000), Steenhof (2007, 2009) and Steenhof and Weber (2011).

It can be seen from the foregoing that there are variations in the decomposition models used in different application areas of emission IDA studies, especially for the electricity generation sector. Although the standard IDA models given by Eqs. (1) to (3) are still widely adopted, these variations allow refinement to be made and provide additional information that are useful in specific applications.

4. Compilation of Decomposition Cases

The studies in Table A.1 include a large number of decomposition cases. The decomposition results in these cases are derived and presented differently among the studies. We now describe how we select and compile these decomposition cases to create a database. The database then provides the basis for the analyses in Sections 5 to 7, namely comparing the relative impacts of drivers to emission changes by sector, across country and over time. We first develop a framework for reporting the decomposition results. Further adjustments made are then described.

Despite the differences observed among studies, all the IDA models reported in the emission literature can be appropriately transformed into the following identity:

$$CI = \frac{C}{A} = \sum_i \frac{A_i}{A}\frac{E_i}{A_i}\frac{C_i}{E_i} = \sum_i S_i \times EI_i \times CF_i \tag{4}$$

where the aggregate CO_2 intensity of an emission sector, $CI = C / A$, is expressed as a function of activity structure S_i, energy intensity EI_i, and carbon factor CF_i. Hence a change in the aggregate carbon intensity can be decomposed and expressed in terms of three standard effects: the activity structure effect, energy intensity effect, and carbon factor effect. This standard form provides a basis whereby the empirical results reported in different studies in Table A.1 can be made consistent and compared.[7]

We focus on six application areas which cover most of the cases reported in the publications in Table A.1. They are (a) economy-wide including emissions from all the production sectors, (b) industry sector emissions covering either the entire manufacturing sector or manufacturing plus non-manufacturing industries such as mining and construction, (c) residential sector covering emissions from household energy consumption, (d) service sector emissions covering emissions from either the commercial sector or commercial plus non-commercial service sectors, (e) transport covering emissions from passenger transport and freight transport respectively, and (f) electricity generation sector covering emissions from either fossil fuel plants or fossil fuel and non-fossil fuel plants.

We also adopt the following guidelines. A decomposition study must include disaggregated data given at subsector level and emissions from all major fossil fuels. Thus, studies in any of the following categories are excluded: a single-sector study, a specific subsector study (e.g. iron and steel industry, road transport, or space heating), and a study that deals with GHG other than CO_2. In addition only country-level studies are included, and studies for cities or world regions are excluded. Spatial decomposition studies such as cross-country comparisons are also excluded.

Of the 80 publications in Table A.1, 51 meet the above guidelines. A publication may include several countries and/or several emission sectors. Decomposition results for several different time periods may also be reported. All the decomposition cases are extracted and, depending on the decomposition time period, they are adjusted if needed by splitting (i.e. for decomposition periods exceeding 15 years) and merging (i.e. for decomposing periods less than 5 years).[8] With all these adjustments, a total of 496 decomposition cases covering 43 countries are derived from the 51 publications.

Fig. 5 shows the numbers of cases for the three different time periods by application area. A sharp increase in the number of cases dealing with the electricity generation sector is observed in the most recent period. Decreases in the number of cases are generally observed for the other application areas. These decreases are by no means a shift in research interest. Rather, it is the result of a new research direction that focuses more on tracking a country's emission changes in greater depth. Such in-depth country-level policy evaluation and performance assessments, rather than comparisons of decomposition results among countries in earlier years, became the main focus of IDA emission studies in the most recent period.

5. Drivers of Carbon Intensity Change: Non-Temporal Features

From the foregoing, the decomposition results compiled are analyzed, classified and presented from Tables 1 to 4 by sector.[9] In each table, the cases are given by country. The countries are divided into two groups, where Group A comprises mainly the industrial countries and Group B the developing countries. They are arranged in descending order according to their 1990 per capita GDP.[10] The Roman numerals I to VIII at the top of each table denote eight possible impacts from the three effects on the aggregate emission intensity change. Correspondingly, the symbols "+" and "−" respectively denote that an effect contributed to an increase and a decrease in the aggregate carbon intensity. Under the columns marked I to VIII, the numbers within and without the brackets indicate the numbers of cases where the aggregate carbon intensity shows an increase and a decrease, respectively. Due to some "built-in" features in each study which affect decomposition results, e.g. the decomposition method used and the sector disaggregation chosen, the findings presented in the sections that follow should be interpreted with some limitations in mind.

5.1. Industry Sector

Table 1 summarizes the empirical results of the 145 decomposition cases for industry. Value added is used as the activity indicator for almost all these cases and the aggregate carbon intensity is given by CO_2 emissions per value added. In a small number of cases, mixed indicators with both value added and physical production are used. The carbon intensity for the sector decreased in most countries. This includes 91% of the cases for Group A and 94% for Group B. Energy intensity change was the main contributor to the decrease, and this includes

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[7] As mentioned in Section 2, about a third of the studies surveyed deal with the decomposition of aggregate carbon intensity change and the rest with actual CO_2 emissions change. For consistency and ease of comparisons, we have to consolidate these two types of studies into one so that the same aggregate is used in our analysis. The aggregate carbon intensity is chosen due to three reasons. First, we found that, in most cases, it is possible to convert the results of actual CO_2 emissions to aggregate carbon intensity but not the converse. Second, by excluding the overall activity effect, the survey results could be presented in a more manageable manner and effectively. Third, using the aggregate carbon intensity, the key effects that are of interest and policy relevance are captured. The same approach is used in Liu and Ang (2007).

[8] We follow the approach used in Liu and Ang (2007) for splitting and merging. The reasons are that useful information may be lost if decomposition results are computed and reported for a long time period and only short-term fluctuations may be captured if they are computed and reported for a short time period.

[9] We follow closely the format used in Liu and Ang (2007).

[10] The GDP per capita data are taken from World Bank (2011) and given in current US dollars. The GDP per capita for Taiwan is collected from National Statistics, Republic of China (2011). The year 1990 was chosen as it is close to the mid-point of the time period covered by the IDA cases in the publications in Table 1. The majority of the cases cover time periods between 1970 and 2010.

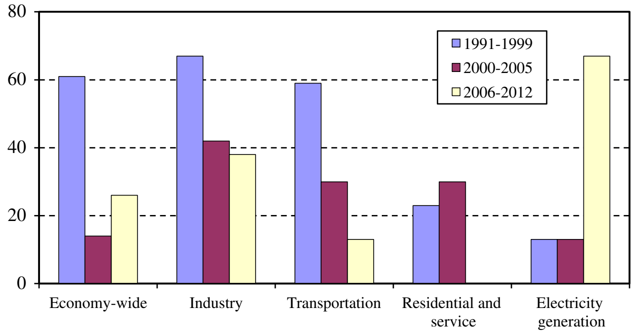

Fig. 5. Number of decomposition cases for different time periods by application area.

88% of the cases for both Group A and Group B. Most of the cases in Group A (78%) also show carbon factor change that contributed to a decrease in the aggregate carbon intensity. This, however, was not the case for Group B and fuel switching towards clean energy sources was less prevalent in the developing countries. The impact of activity structure change was marginal comparing to the other two effects. For cases with a study period less than 10 years, the impact of structure change was generally small. This, however, does not apply to the other two effects, which shows that changes in industrial structure generally takes a longer time.

Table 1
Impacts of energy intensity, carbon factor, and activity structure changes on aggregate carbon intensity change: industry sector.

Country/ economy	Type	I	II	III	IV	V	VI	VII	VIII	No. of cases
	Energy intensity	+	+	+	+	−	−	−	−	
	Carbon factor	+	+	−	−	+	+	−	−	
	Activity structure	+	−	+	−	+	−	+	−	
A: Industrial economies	1990 GDP/capita (US $)									
Luxembourg	33,182							1	1	2
Sweden	28,572			1			1	5	4	11
Finland	27,847		1					4	4	9
Norway	27,732			1				5	1	7
Denmark	26,428				1	2	2		5	10
Japan	24,754								7	7
USA	23,038						4	1	5	10
Germany	21,584							2	8	10
France	21,384							4	7	11
Austria	21,378		(1)					2	1	4
Canada	20,968								1	1
Belgium	20,323		(1)	(1)					2	4
Italy	19,983	(1)				7		2	1	11
Netherlands	19,721				(1)	1		1	2	5
Australia	19,431					1				1
UK	17,688		(1)				4	1	7	13
Ireland	13,649						1		1	2
Spain	13,415			(2)						2
Greece	9271				(2)			2		4
Portugal	7839				(1)			1, (1)	1	4
Sub-total		1	4	5	5	11	12	32	58	128
B: Developing economies										
Taiwan	8124					1	1			2
Korea	6153								2	2
Mexico	3116							1		1
Turkey	2784				1				1	2
Thailand	1495		(1)					1	1	3
China	314					1	6			7
Sub-total		0	1	0	1	2	7	2	4	17
No. of cases		1	5	5	6	13	19	34	62	145
Country counts		1	5	4	5	6	7	15	20	63*

Note: Two cases are not included in this table since at least one of the decomposition effects was found to be insignificant. For the eight combinations, the numbers enclosed by brackets indicate the numbers of cases with an increase in the aggregate emission intensity, while those without brackets indicate the numbers of cases with a decrease in the aggregate emission intensity. The number with an asterisk "*" represents the total country counts.

Table 2
(a): Impacts of energy intensity, carbon factor, and activity structure changes on aggregate carbon intensity change: passenger transportation sector.

Country/economy	Type	I	II	III	IV	V	VI	VII	VIII	No. of cases
	Energy intensity	+	+	+	+	−	−	−	−	
	Carbon factor	+	+	−	−	+	+	−	−	
	Activity structure	+	−	+	−	+	−	+	−	
A: Industrial economies	1990 GDP/capita (US $)									
Sweden	28,572			(2)	(1)					3
Finland	27,847			(2)				1		3
Norway	27,732		(1)			1		1		3
Denmark	26,428		(1)				1		1	3
Japan	24,754	(1)		(3)				1		5
USA	23,038			(1)		2, (2)	1	3		9
Germany	21,584	(2)		(1)		(1)				4
France	21,384				(1)			2		3
Italy	19,983	(1)	(1)			2, (1)				5
UK	17,688					1, (3)		1		5
No. of cases		4	3	9	2	13	2	9	1	43
Country counts		3	3	5	2	5	2	6	1	27*

Note: Eleven cases are not included in this table since at least one of the decomposition effects was found to be insignificant. See "Note" in Table 1 for the meanings of the numbers shown.

5.2. Transportation Sector

Tables 2(a) and (b) summarize the results for passenger and freight transportation respectively. The numbers of decomposition cases are about the same for both sectors and all of the cases are from

Table 2
(b): Impacts of energy intensity, carbon factor, and activity structure changes on aggregate carbon intensity change: Freight transportation sector.

Country/ economy	Type	I	II	III	IV	V	VI	VII	VIII	No. of cases
	Energy intensity	+	+	+	+	−	−	−	−	
	Carbon factor	+	+	−	−	+	+	−	−	
	Activity structure	+	−	+	−	+	−	+	−	
A: Industrial economies	1990 GDP/capita (US $)									
Sweden	28,572			(1)	(2)			(1)		4
Finland	27,847				(1)			1, (1)		3
Norway	27,732	(1)				1	1	1		4
Denmark	26,428	(2)	(1)					1		4
Japan	24,754	(1)				1, (2)				4
USA	23,038	(2)		(1)		2, (2)		(1)		8
Germany	21,584			(1)		(1)		2		4
France	21,384			(3)				(1)		4
Canada	20,968					1				1
Italy	19,983	(3)				(1)				4
UK	17,688	(1)				2	1			4
No. of cases		10	1	6	3	13	2	9	0	44
Country counts		6	1	4	2	7	2	7	0	29*

Note: Three cases are not included in this table since at least one of the decomposition effects was found to be insignificant. See "Note" in Table 1 for the meanings of the numbers shown.

Table 3
Impacts of energy intensity, carbon factor, and activity structure changes on aggregate carbon intensity change: residential sector.

Country/economy	Type	I	II	III	IV	V	VI	VII	VIII	No. of cases
	Energy intensity	+	+	+	+	−	−	−	−	
	Carbon factor	+	+	−	−	+	+	−	−	
	Activity structure	+	−	+	−	+	−	+	−	
A: Industrial economies	1990 GDP/capita (US $)									
Sweden	28,572			1				3		4
Finland	27,847					(1)		2, (1)		4
Norway	27,732							3	1	4
Denmark	26,428					(1)		3		4
Japan	24,754			1, (3)						4
USA	23,038							4		4
Germany	21,584			1				2, (1)		4
France	21,384					1		2, (1)		4
Italy	19,983			(1)		(2)		1		4
UK	17,688			1				3		4
No. of cases		0	0	8	0	5	0	26	1	40
Country counts		0	0	5	0	4	0	9	1	19*

Note: See "Note" in Table 1 for the meanings of the numbers shown.

Group A. Passenger-kilometers and tonne-kilometers are the activity indicators that were most often used. In terms of aggregate carbon intensity change, the passenger transportation sector experienced mixed performance with 53% of the cases showing an increase, while the corresponding figure for freight transportation is 68%, which indicates an increase in the aggregate carbon intensity. These developments are very different from that for industry. The relative impacts of the three effects are consistent for both sectors. Impacts of both the energy intensity effect and the carbon factor effect were mixed. However, the majority of the cases, or 81% for passenger transportation and 86% for freight transportation, show activity structure change leading to increases in the aggregate carbon intensities. It indicates that, for both sectors, there were shifts towards more carbon-intensive transportation modes in industrial countries.

Table 4
Impacts of energy intensity, carbon factor, and activity structure changes on aggregate carbon intensity change: service sector.

Country/economy	Type	I	II	III	IV	V	VI	VII	VIII	No. of cases
	Energy intensity	+	+	+	+	−	−	−	−	
	Carbon factor	+	+	−	−	+	+	−	−	
	Activity structure	+	−	+	−	+	−	+	−	
A: Industrial economies	1990 GDP/capita (US $)									
Sweden	28,572								1	1
Finland	27,847							1		1
Japan	24,754								1	1
USA	23,038						1			1
France	21,384								1	1
Canada	20,968							1		1
Australia	19,431	(1)								1
UK	17,688				1					1
No. of cases		1	0	0	1	0	1	2	3	8
Country counts		1	0	0	1	0	1	2	3	8*

Note: Five cases are not included in this table since at least one of the decomposition effects was found to be insignificant. See "Note" in Table 1 for the meanings of the numbers shown.

5.3. Residential Sector

Various activity indicators were used in the studies and they include the number of households, floor area, and population. The corresponding structure indicator captures the impact of housing type shifts or life style change. The data requirement is high in studies for this sector and all of the cases shown in Table 3 are from Group A. The majority of the cases (73%) show a decrease in the aggregate carbon intensity. Energy intensity change and carbon factor change respectively contributed to a decrease in the aggregate carbon intensity in 80% and 88% of the cases. Conversely, activity structure change contributed to an increase in almost all the cases (97.5%). The activity structure effect generally incorporates changes in lifestyle and consumption behavior, e.g. shifts to bigger apartments and increased levels of appliance penetration, and this differs from that for the other sectors. Sixty-five percent of the cases are of Type VII, which means the relative impacts of the three effects are fairly consistent among countries. Increased household incomes generally led to shifts in activity structure leading towards a higher level of energy consumption and CO_2 emissions, while improved technologies over time and fuel switching helped to reduce energy intensity and carbon factor respectively.

5.4. Service Sector

With only 13 decomposition cases, the number is small compared to the other sectors. Both value added and floor area have been used as the activity indicator, with the former more widely used. Among the 13 cases, 12 show a decrease in the aggregate carbon intensity. The energy intensity effect and carbon factor effect contributed to the decrease in 75% of these cases. The activity structure effect was generally small or insignificant. Overall the observed developments were very similar to those of the industry sector. Only the results of nine of the 13 cases are shown in Table 4. In the remaining five cases, either activity structure change or energy intensity change was insignificant. It is therefore not possible to place them in any of the cases under Type I to Type VIII.

5.5. Economy-Wide Analysis

Economy-wide analysis include two kinds: one uses economy-wide data with the activity indicators for all the production sectors given by value added, and the other is based on aggregating decomposition results computed independently for individual sectors. From Table 5, most of Group A countries experienced a decrease in the aggregate carbon intensity which applies to 83% of the cases. For Group B countries, the developments were mixed. As to the relative contributions of the three effects, energy intensity change contributed to a decrease in the aggregate carbon intensity in 78% of the cases, while carbon factor change contributed to a decrease in 75% of the cases, for Group A countries. Sixty percent of the cases are of Type VII and Type VIII, i.e. with decreases in both energy intensity and carbon factor. The impact of the activity structure change was mixed. For Group B countries, the situation was more complicated. The impacts of all the effects were mixed and the cases were fairly evenly distributed among Type I to Type VIII. A GDP per capita of 13,000 US dollars seems to be a demarcation for Group A countries. Cases for countries with a GDP per capita higher than this level were generally placed in Types V, VI, VII, and VIII, i.e. a decrease in the aggregate carbon intensity. While for countries with a per capita GDP lower than the level, two-third of the cases show an increase in the aggregate carbon intensity but no obvious pattern for the three effects were observed. The observed features for these Group A countries and those for Group B countries are very similar.

Table 5
Impacts of energy intensity, carbon factor, and activity structure changes on aggregate carbon intensity change: economy-wide.

Country/ economy	Type	I	II	III	IV	V	VI	VII	VIII	No. of cases
	Energy intensity	+	+	+	+	−	−	−	−	
	Carbon factor	+	+	−	−	+	+	−	−	
	Activity structure	+	−	+	−	+	−	+	−	
A: Industrial economies	1990 GDP/capita (US $)									
Switzerland	35,491				1				1	2
Luxembourg	33,182							2		2
Sweden	28,572				1			1	2	4
Finland	27,847				1			2		3
Norway	27,732							1	1	2
Denmark	26,428					1	1		1	3
Iceland	25,011		(1)	1						2
Japan	24,754			(1)				2		3
USA	23,038					2,(1)	1	2		6
Germany	21,584							3	1	4
France	21,384							2	2	4
Austria	21,378							1	1	2
Canada	20,968							1	1	2
Belgium	20,323						1		2	3
Italy	19,983					1			2	3
Netherlands	19,721					1			1	2
Australia	19,431	(1)						1		2
UK	17,688					1		1	2	4
Ireland	13,649						1	1		2
Spain	13,415			(1)					1	2
New Zealand	12,907			(1)	(1)					2
Greece	9271		(2)							2
Portugal	7839	(1)			(1)					2
Sub-total		2	3	4	5	7	4	20	18	63
B: Developing economies										
Argentina	4330							(1)		1
Korea	6153	(1)						1		2
Mexico	3116					1				1
Brazil	3087		(1)	1	3	(2)				7
Turkey	2784	(1)		(2)		(2)		3		8
Venezuela	2381			(1)						1
Colombia	1213					1				1
India	374	(1)	(1)	(3)		(1)		(1)		7
China	314	(1)	(1)			3	1	2	1	9
Sub-total		4	3	7	3	10	1	8	1	37
No. of cases		6	6	11	8	17	5	28	19	100
Country counts		6	5	8	6	11	5	18	14	73*

Note: A case is not included in this table since at least one of the decomposition effects was found to be not significant. See "Note" in Table 1 for the meanings of the numbers shown.

Table 6
Summary of impacts of activity structure effect, energy intensity effect, and carbon factor effect by application area for different country group.

Application area	Country group	Aggregate carbon intensity	Activity structure	Energy intensity	Carbon factor
Industry	A	Decrease (↓)	Marginal	Decrease (↓)	Decrease (↓)
	B	Decrease (↓)	Marginal	Decrease (↓)	Mixed
Transportation	–	Mixed	Increase(↑)	Mixed	Marginal
Residential	–	Decrease (↓)	Increase(↑)	Decrease (↓)	Decrease (↓)
Service	–	Decrease (↓)	Marginal	Decrease (↓)	Decrease (↓)
Economy-wide	A	Decrease (↓)	Mixed	Decrease (↓)	Decrease (↓)
	B	Mixed	Mixed	Mixed	Mixed

Note: Country groups are not applicable for the transportation sector and the residential and service sector as all the decomposition cases are collected from Group A. "Decrease", "Increase", "Mixed", and "Marginal", respectively, indicate that a decomposition effect mainly led to a decrease, an increase, a change that was evenly distributed between a decrease and an increase, and a marginal change in the aggregate emission intensity.

5.6. Summary of Findings

Table 6 summarizes the main findings. First, for each of the three effects, the impact was sector specific. For example, the impact of energy intensity change was mixed in the transportation sector but it generally led to a decrease in the aggregate carbon intensity in other sectors. Also, activity structure change generally led to an increase in the aggregate carbon intensity in the residential and transportation sectors, while its impact was marginal for the industry and service sectors. Second, some developments for the industrial countries and the developing countries were quite different. For example, in most cases for the industrial countries, energy intensity change and carbon factor change contributed to a decrease in the economy-wide aggregate carbon intensity, but their impacts were mixed in the developing countries. Although the impacts of energy intensity change for industry were consistent for the two country groups, this was not the case for carbon factor change.

The foregoing focuses primarily on the impacts of the three effects on the aggregate carbon intensity. We can go a step further to study their relative contributions in absolute terms. The findings can be summarized as follows. First, energy intensity change was the largest contributor to the reduction in the aggregate carbon intensity and this is the case for all the sectors. If energy intensity is taken as a proxy for energy efficiency, this means energy efficiency was the main contributor to reductions in aggregate carbon intensity in most countries. Second, the activity structure effect had the least influence on the aggregate carbon intensity except for the transportation sector. A strong shift to carbon-intensive transportation modes actually led to higher aggregate carbon intensities for transportation than otherwise. Third, the impacts of carbon factor change for the residential and service sectors were generally greater than those for the industry and transportation sectors. A possible reason is the high share of electricity in total energy consumption in the residential and service sectors, and the carbon intensity for electricity generation has been improving over time in most countries.

6. Drivers of Carbon Intensity Change: Temporal Features

Section 5 does not look into possible temporal changes. To study this specific aspect by sector, we construct and apply a two-dimensional plot as shown in Fig. 6. The *X*-axis captures the energy intensity effect while the *Y*-axis the carbon factor effect. The two boxes capture the activity structure effect, where the inner box indicates an activity structure change that results in a decrease, and the outer box an increase, in the aggregate carbon intensity. The plot is therefore divided into eight zones, denoted from I to VIII, which are consistent with those shown in Tables 1–5. Each decomposition case can be placed in one of the zones. For a specific country or region with cases for different time periods, the chronological shifts among zones from the points plotted reveal the temporal changes that took place.

Considering the large number of countries and a relative small number of cases for most countries, it is impractical to analyze the temporal features country by country. Instead, we focus on different country samples for different sectors. The following samples are used in the discussions and results are presented from Sections 6.1 to 6.4. The economy-wide level results in Section 6.1 include six countries: United States, Germany, Sweden, China, India and Brazil.[11] For the industry sector more decomposition cases are available, and we include 12 countries (United States, Germany, Sweden, United Kingdom, France, Italy, Denmark, Norway, Finland, India, China, and Japan), and the observed temporal features are discussed in Section 6.2. For the

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[11] They are chosen for the following reasons: good annual CO_2 emission level and economic development level coverage, good geographical spread, and a relative large number of empirical cases.

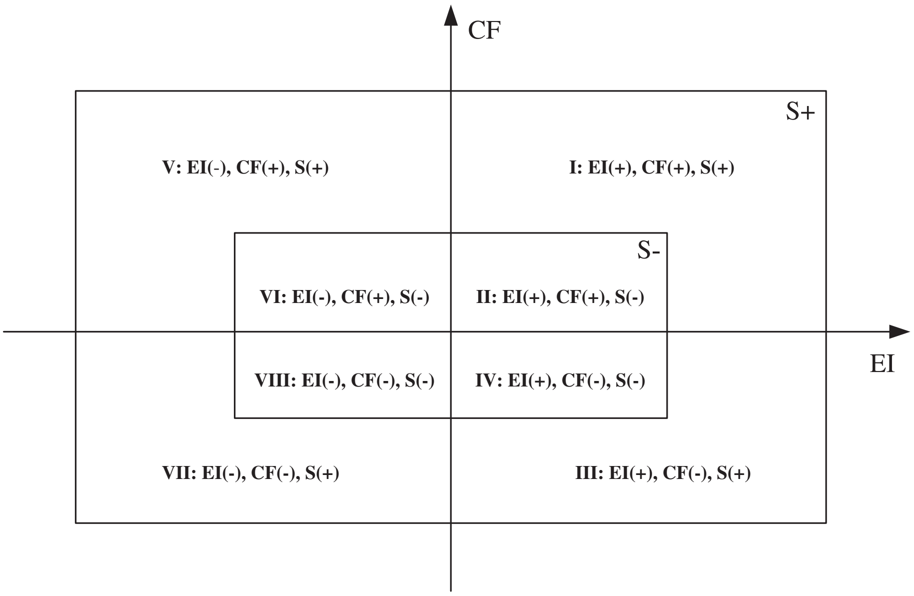

Fig. 6. A pictorial framework for depicting the contribution of changes in activity structure, energy intensity and carbon factor to economy-wide emission intensity change.

other sectors, the number of cases available is not enough for meaningful temporal analysis for most countries. We assume that the features are similar for countries with about the same level of economic development in the same geographical zone. The temporal features reported are therefore mostly for different country groups. With this, we generate the United States plot, the Northern European plot (Denmark, Finland, Norway and Sweden), and the rest of Europe plot (France, Germany, Italy, and United Kingdom) for the transport sector and residential sector in Sections 6.3 and 6.4 respectively. Due to data limitations, no analysis is conducted for the service sector.[12]

6.1. Economy-Wide Analysis

What was revealing about the United States is the consistency observed for the energy intensity effect and activity structure effect. Although the impact of carbon factor changed from one time period to another, a clear shift from Zone V to Zone VII indicates carbon factor improvements over time. The cases for Germany and Sweden were generally placed in Zone VII and Zone VIII. This means the energy intensity and carbon factor effects consistently contributed to aggregate carbon intensity reduction, while there was no obvious temporal trend for the activity structure effect. Most of the cases for China revealed the importance of the energy intensity effect in reducing its aggregate carbon intensity, while there were variations in the carbon factor effect over time. The temporal feature for the activity structure effect was less conclusive.[13] For India and Brazil, most decomposition cases were placed on the right-hand side of the *Y*-axis, i.e. an energy intensity effect leading to an increase in the aggregate carbon intensity. All the cases for India show an increase in the aggregate carbon intensity as a result of both energy intensity change and activity structure change. No obvious temporal trend was observed for the carbon factor effect. As to Brazil, the sign changed over time for the aggregate carbon intensity and all the three effects. Reduction in the aggregate carbon intensity has been achieved over time as a result of a shift towards less energy-intensive activity structure and improvements in the carbon factor. In summary, temporal changes varied among countries and larger shifts were observed for the developing countries studied.

6.2. Industry Sector

The observed patterns in the plot placed the industrial countries into three categories. The first is a relatively stable performance over time (Japan and Norway). For Japan, all the cases covering the period from 1973 to 1991 were placed in Zone VIII, which is the most ideal situation. For Norway, the cases were consistently placed in Zone VII where energy intensity change and carbon factor change contributed to a decrease, while activity structure change contributed to an increase, in the aggregate carbon intensity. Further investigation shows that the impacts of the three effects for the two countries reduced over time. The second category is countries whose performance worsened over time and they include Italy and Finland. For Italy, improvement in fuel quality was achieved in the 1980s and early 1990s as most of the cases in this period shift from Zone V to Zone VII. For both countries, more cases for more recent periods show a shift towards the upper-right corner of Fig. 6, which is the worst case where all three effects contributed to an increase in the aggregate carbon intensity. The third category is countries whose performance improved over time. A shift from Zone V/VI to Zone VII/VIII indicates a desirable development in fuel mix change, and the United Kingdom and the United States went through this development. A shift from Zone VII to Zone VIII indicates an activity mix change towards a less energy-intensive economy. This shift was observed for France and Germany.

The observed developments for the developing countries were more varied. In the early 1980s, their cases can be found in different zones depending largely on their level of economic development. Cases for more recent years show convergence towards Zone VII which indicates improvements in both energy efficiency and fuel mix.

From the foregoing, four general conclusions can be drawn. First, the energy intensity effect contributed the most and consistently over time to reductions in the aggregate industrial carbon intensity. Second, the long-term patterns of the three effects observed placed

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[12] Specific country plots of the economy-wide study and various final sectors are not given in this report as they are too many.

[13] Wu et al. (2005) used a hybrid model to track the emissions in China from 1985 to 1999 and show a structure effect that contributed to a decrease in the aggregate emission intensity, while estimates of the structure effect covering various periods and reported in other studies that adopt the conventional decomposition models show the converse.

most industrial countries in Zone VII and Zone VIII. This shows that they were successful in reducing their aggregate industrial carbon intensities over time. For the developing countries, the patterns observed were mixed. Third, changes in the three effects led to improvements or deteriorations in performance in the short-term patterns in different time periods in a country. For example, cases for some industrial countries shift from the upper half to the lower half of Fig. 6 as a result of improvements in the carbon factor, while those of other shift from the outer box to the inner box as a result of improvements in industrial structure. An interesting finding for the developing countries is the convergence of cases to Zone VII over time. Fourth, the short-term trends observed show declining level of positive impacts of the three effects in industrial countries.

6.3. Transportation Sector

For the United States, the plot for freight transportation shows shifts from Zone VII in 1960s to Zone I in 1970s, and to Zone V in more recent years. These shifts indicate initial worsening followed by improvement in performance. At the individual effect level, the energy intensity effect was the main contributor to reductions in the aggregate carbon intensity. The other two effects and in particular the activity structure effect consistently led to increases in the aggregate carbon intensity over time. In the case of passenger transportation, shifts from Zone III in 1960s to Zone V in 1970s and 1980s, and to Zone II in the past two decades were observed. They show improvements in performance from energy intensity change and carbon factor change initially, which were not found in later years. The impact of activity structure change which had led to increases in the aggregate carbon intensity was reversed in later years. The energy intensity effect was the main contributor to decreases in the aggregate change for both short and long terms. The long-term trend places US passenger transportation in Zone V, which is identical to that for freight transportation.

For “Northern Europe”, there was improvement arising from energy intensity change for freight transportation (from short-term shifts from Zone IV to Zone VII for Sweden and Finland, and from Zone I to Zone V for Norway). Denmark experienced deterioration with a shift from Zone V to Zone I. In general, whether the energy intensity effect or the carbon factor effect was the larger contributor to changes in the aggregate carbon intensity was country-specific and time-dependent. The activity structure effect consistently contributed to an increase in the aggregate carbon intensity but the extent of the impact reduced over time. There was no evidence of a specific effect dominating the changes that took place. For passenger transportation, the plot shows a clear long-term trend where the cases of most countries were placed in Zone III, i.e. only the carbon factor effect contributing to a lower aggregate carbon intensity. The short-term performance was country-specific, where all the countries experienced improvement initially, followed by deterioration either in the energy intensity or carbon factor. Also, activity structure change had mixed contributions to changes in the aggregate carbon intensity and no distinct temporal trend was observed.

For “The rest of Europe”, the plot for freight transportation shows shifts from the left half to the right half of Fig. 6. This indicates worsening over time in energy intensity. Shifts over time from Zone V to Zone I were observed for Italy and the United Kingdom, while from Zone VII to Zone III for France and Germany. The long-term performance was country-specific. Energy intensity change led to reduction in the aggregate carbon intensity in the long term and the level of impact generally declined over time. In contrast, activity structure change generally contributed to an increase in the aggregate carbon intensity and the level of impact increased over time. For passenger transportation, the plot shows a clear convergence of cases to Zone V, an indication of improved performance arising from energy intensity change. Although the situation in earlier periods was country-specific, this transition took place over time. Among the three effects, the impact of energy intensity change was the largest for most short-term periods. The activity structure effect consistently contributed to increases in the aggregate carbon intensity.

In summary, the following temporal features were observed for the transportation sector based on the countries studied. First, energy intensity change was the main effect that helped to reduce the aggregate carbon intensities for both passenger and freight transportation. Second, activity structure change was the main contributor to increases in the aggregate carbon intensities in both sectors from a long-term perspective. In the short terms, its impacts were country-specific. Third, the transportation sector did not exhibit regional consistency features. The developments tend to vary among countries within a region in one way or another. Finally, although the non-temporal features of passenger transportation and freight transportation were very similar as revealed in Section 5, there were differences between them in terms of temporal features.

6.4. Residential Sector

There was improvement in the performance for the residential sector over time as increase in the aggregate carbon intensity came to a halt in some countries. This development was fairly consistent for the countries in the same region. All the cases for the United States were placed in Zone VII, which indicates a positive contribution from the energy intensity effect and the carbon factor effect, but a negative contribution from the activity structure, over time. Apparently, higher income and changing lifestyle led to more energy-intensive consumption behaviors. For “Northern Europe”, both energy intensity change and carbon factor change contributed to reduction in the aggregate carbon intensity in most periods. The impact of the energy intensity effect declined, while that of carbon factor effect increased, over time. Conversely, activity structure change generally contributed to an increase in the aggregate carbon intensity. For “The rest of Europe”, there were shifts, though not very strong ones, from Zone V to Zone VII and then to Zone III. These shifts indicate improvement in performance arising from fuel mix change, but deterioration in performance arising from energy efficiency change.

7. The Electricity Generation Sector

As pointed out earlier, the electricity generation sector has attracted special interest in emission IDA studies. Treating it as a source of emissions, the sector accounted for 41% of global energy-related CO_2 emissions in 2010 (IEA, 2012). The IDA decomposition identity for the sector is different from that for other sectors and it therefore deserves special attention. The various identities that have been reported in the literature for the sector can be consolidated into a standard form in which the aggregate carbon intensity of electricity generation (CI^{elec}) is expressed in terms of generation mix (GM), generation intensity (GI) and emission coefficient of primary energy sources (U)[14]:

$$CI^{elec} = \frac{C}{G} = \sum_j \frac{G_j}{G}\frac{E_j}{G_j}\frac{C_j}{E_j} = \sum_i GM_j \times GI_j \times U_j \tag{5}$$

where G is the total electricity generation, and G_j and E_j are respectively the electricity generation and primary energy consumption for energy source j. The emission coefficient of primary energy sources can be assumed to remain unchanged in relative short time periods, and its impact on the aggregate carbon intensity may be assumed to be nil. A change in the aggregate carbon intensity for electricity can then be

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[14] The generation mix effect includes the impact of changes the shares of electricity generation from all energy sources including both fossil and non-fossil fuels.

Table 7
Relative impacts of generation mix change and generation intensity change on the aggregate carbon intensity change of electricity generation.

Country/ economy	Type	I	II	III	IV	V	VI	VII	VIII	No. of cases
	Aggregate carbon intensity	↑	↑	↑	↑	↓	↓	↓	↓	
	Generation mix	+ +	+ +	+	−	− −	− −	−	+	
	Generation intensity	−	+	+ +	+ +	+	−	− −	− −	
A: Industrial economies	1990 GDP/capita (US $)									
Japan	24,754	1			1		1	3		6
USA	23,038			1					1	2
Canada	20,968	2					1	1		4
Australia	19,431			1	1	1			1	4
Hong Kong	13,478								1	1
New Zealand	12,907			1	2					3
Singapore	12,745						1		1	2
Sub-total		3	0	3	4	1	3	4	4	22
B: Developing economies										
Korea	6153	1			2		2	2	2	9
Turkey	2784				2					2
Malaysia	2418				1	1	1			3
Thailand	1,495			2					1	3
Philippines	719			1			1	1		3
Indonesia	621			1	1		2			4
Sri Lanka	463			1	1			1		3
India	374	3	1	2	2			4	5	17
Pakistan	358			1	1				1	3
China	314			1		2		1	6	10
Bangladesh	286				1	1				2
Vietnam	98					2		1		3
Sub-total		4	1	9	11	6	6	10	15	62
No. of cases		7	1	12	15	7	9	14	19	82
Country counts		4	1	10	11	5	7	8	9	55*

Note: Nine cases are not included in this table due to missing information in the source or one of the decomposition effects was found to be insignificant. See "Note" in Table 1 for the meanings of the numbers shown.

expressed in terms of the generation mix effect and the generation intensity effect.

All the decomposition cases for the electricity generation sector compiled in Section 4 can be classified under one of the eight combinations of changes in the aggregate electricity carbon intensity and the two effects as shown on the top of Table 7. The symbols "↑" and "↓" respectively denote an increase or decrease in the aggregate electricity carbon intensity, while the meanings of symbols "+" and "−" are the same as those defined in Section 5. In addition, the symbols "+ +" and "− −" denote effects which are relatively large in absolute terms.

From Table 7, there are more decomposition cases dealing with the electricity generation sector for the developing countries (74%) than for the industrial countries (26%). There were more cases distributed in the last four combination types (58%), meaning that the number of cases with a decrease in the aggregate electricity carbon intensity is higher than that with an increase. The same feature applied to the impact of generation intensity change. As to generation mix change, the cases were fairly evenly divided. All these features were applicable to both Group A and Group B countries. The results in Table 7 also provide information as to whether the generation mix effect or the generation intensity effect was larger in absolute terms. Cases placed in Types I, II, V, VI are those having a greater absolute terms for the generation mix effect, while the converse is true for cases placed in the other four types. Cases placed in Types III, IV, VII, VIII add up to 68% of the total number of cases in Group A, and the corresponding number is 73% for Group B. Hence, there is no question that the impact of generation intensity change has been greater than that of generation mix change. Changes in electricity generation mix, such as a switch from coal generation to nuclear energy or hydroelectricity, can have a significant impact on the aggregate carbon intensity for electricity generation. The evidence from the past, however, suggests that the contribution of generation mix change to the lowering of the aggregate carbon intensity of electricity generation fell far short of what was technically feasible in most countries.

8. Conclusions

Index decomposition analysis applied to CO_2 emissions is an extension of that applied to energy. The number of such emission studies has increased rapidly since the first study was reported in 1991. Our literature survey, which includes 80 journal publications, reveals the developments in IDA models and methods, as well as findings, in this IDA application area. The publications reviewed cover all major sectors of emissions and a wide spectrum of countries. From the survey, it can be concluded that IDA has been recognized by researchers and analysts as a useful analytical tool for studying the drivers of changes in CO_2 emissions. Through quantifying these drivers, the mechanisms of change in CO_2 emissions in a sector and hence in a country can be better understood. Among the various applications of the results obtained, the effectiveness of measures taken in the past to reduce growth in emissions can be assessed, comparisons of performance can be made among sectors or countries, and appropriate measures can be taken to reduce future emissions.

In terms of IDA methodology, decomposition models for analyzing emission changes are slightly more complex than those for studying energy consumption changes. More factors are normally included in the IDA identity and a larger dataset is generally needed. For some factors, such as fuel mix, zero values in the data set are more likely to appear. This has implication of the use of IDA methods. Over the years, a development in this study area has been the switch from using the traditional Laspeyres method to ideal decomposition methods. In addition, due to the need to include more factors in the IDA identity, there has been a strong preference for the LMDI method. This development is in line with that observed in energy decomposition studies. As energy production, conversion and consumption systems become increasingly more complex, further refinement may be made to the methodology. This includes, for example, how carbon capture and storage, and combined heat and power can be appropriately handled in an IDA framework. These are methodological issues that deserve further study.

We also investigated the relative contributions of various drivers to changes in the aggregate carbon intensity as reported in the literature for different emission sectors and countries. We compiled and adjusted these reported empirical results and presented them in a coherent manner in tabular and graphical forms. Among the results obtained, it is found that energy intensity change was generally the key driver of changes in the aggregate carbon intensity in most sectors and countries. In most cases, it contributed to decreases in the aggregate carbon intensity. If we take energy intensity as a proxy for energy efficiency, this means improvements in energy efficiency have been the main driver of decreases in the aggregate carbon intensity for most sectors in most countries. In comparison, the contribution of activity structure change and that of carbon factor change have been less significant.

Furthermore, activity structure change in the transportation and residential sectors generally led to increases in the aggregate carbon intensity both in the industrial and developing countries. Carbon factor change contributed more often to decreases in the aggregate carbon intensity in the industrial countries than the developing countries. At the same time, diversities in the emission patterns and drivers were also found among different sectors and among countries. This shows that while there were some uniform patterns among countries with respect to the underlying developments of the aggregate carbon intensity, there were also diversities which led to different development paths among countries. This has implications on future CO_2 emissions, especially of the developing countries. It means that what occurred in the industrial countries may not be a good indication of future developments in the developing countries. The findings also indicate that to reduce growth in future CO_2 emissions, countries should focus more on activity structure and carbon factor as compared to the past.

Our survey study does not include an evaluation of the impact of overall activity level change. In IDA, emissions and overall activity level are positively correlated and this applies to all sectors. As such, in all IDA studies, increases in overall activity level will invariably lead to increases in emissions, and vice versa. In the context of our study, analyzing the overall activity effect on emissions is of lesser relevance, compared to studying the activity structure, energy intensity, and carbon factor effects. For studies which are more specific than the present comprehensive survey, it may be useful to include the overall activity level effect as well. Examples of such studies are analyzing the actual growth in emissions in a specific country, a specific group of countries, or a specific emission sector. The focus of these specific studies would be different from the present study as actual numerical results, rather than the direction of and relative impacts, which are the primary focus of the present study, are of greater interest to the researcher or analyst.

In terms of IDA application, a main difference between energy decomposition analysis and emission decomposition analysis is the greater focus on the electricity generation sector in the latter. Studies related to the latter show that, to a large extent, decreases in the aggregate carbon intensity of the electricity generation sector in most countries in the past was driven primarily by improvements in electricity generation intensity. In contrast, the generation mix effect led to either increases or decreases in the aggregate carbon intensity. In absolute terms, the impact of the generation mix effect was generally smaller than the generation intensity effect. How far this development will continue into the future and to what extent this would lead to, especially in the industrial countries, is an area in which further research is needed.

Appendix A. List of IDA studies applied to emissions

Columns 1 and 2 give the basic information of the studies, including the country or geographical region studied. Columns 3 to 6 are methodology-related, i.e. the emission aggregate considered, whether it is in absolute change or in the form of per unit output change, whether additive or multiplicative decomposition approach is adopted, the decomposition method used, and the activity indicator and the factors included in the IDA identity. Columns 7 to 9 provide information on application, i.e. the emission sector and time period studied, and the number of specific cases for which decomposition was performed and the results were presented. Each of these cases will be referred to as a decomposition case or simply a case. In Column 9 only those decomposition cases dealing with CO_2 emissions are considered. Publications with no numerical analysis or dealing with other GHG emissions are excluded and denoted with “N.A.”. More details about decomposition cases and their selection are described in Section 4.

Table A.1
A summary of the main features of IDA studies applied to emissions, 1991–2012.

	1. Publication	2. Country/region	3. Indicator type[1]		4. Decomposition approach[2]			5. Activity indicator[3]		
			C	I	Add	Mul	Method	$	B	Pop
1	Torvanger (1991)	OECD-9	×			×	AMDI	×		
2	Golove and Schipper (1996)	USA	×			×	LASP	×		
3	Lin and Chang (1996)	Taiwan	×		×		Divisia	×		
4	Scholl et al. (1996)	OECD-9	×			×	LASP		×	
5	Shrestha and Timilsina (1996)	12 Asia countries		×	×		AMDI		×	
6	Ang and Choi (1997)	Korea		×		×	LMDI	×		
7	Ang and Pandiyan (1997)	China, Korea, Taiwan		×		×	Divisia, LASP	×		
8	Golove and Schipper (1997)	USA	×		×		LASP	×		
9	Lakshmanan and Han (1997)	USA	×		×		LASP		×	
10	Schipper et al. (1997)	OECD-10	×			×	LASP		×	
11	Sheinbaum and Rodríguez (1997)	Mexico	×		×		LASP	×		
12	Ang et al. (1998)	Korea	×		×		AMDI, LMDI, LASP		×	
13	Greening et al. (1998)	OECD-10		×		×	AWD	×		
14	Krackeler et al. (1998)	OECD-13	×			×	LASP	×		
15	Shrestha and Timilsina (1998)	Tailand, Korea		×	×		AMDI		×	
16	Sun and Malaska (1998)	Developed countries		×	×		S/S	×		
17	Greening et al. (1999)	OECD-10		×		×	AWD		×	
18	Sun (1999)	OECD-24 aggregate	×		×		S/S	×		
19	Viguier (1999)	Hungary, Poland, USA, France, UK, Russia		×		×	AMDI	×		
20	Liaskas et al. (2000)	EU	×		×		LASP	×		
21	Mazzarino (2000)	Italy	×		×		LASP			×
22	Nag and Kulshreshtha (2000)	India		×		×	AMDI	×		
23	Nag and Parikh (2000)	India		×		×	AMDI	×		
24	Greening et al. (2001)	OECD-10		×		×	AWD			×
25	Hammar and Lofgren (2001)	Sweden	×		×		AMDI	×		
26	Murtishaw et al. (2001)	IEA-8		×		×	AWD	×		
27	Schipper et al. (2001)	IEA-13	×			×	AWD	×		
28	Albrecht et al. (2002)	Belgium, UK France, Germany	×		×		S/S			×
29	Ang and Choi (2002)	Korea		×	×		LMDI		×	
30	Kim and Worrell (2002a)	7 countries	×		×		Divisia	×		
31	Kim and Worrell (2002b)	Brazil, China, Korea, USA	×	×	×		Divisia		×	
32	Ozawa et al. (2002)	Mexico	×		×		Divisia	×		
33	Bhattacharyya and Ussanarassamee (2004)	Thailand		×		×	LMDI	×		
34	Greening (2004)	OECD-10		×		×	AWD		×	
35	Paul and Bhattacharya (2004)	India	×		×		S/S	×		
36	Nag and Parikh (2000)	India		×		×	Divisia		×	
37	Wu et al. (2005)	China	×			×	LMDI	×		
38	Ebohon and Ikeme (2006)	SSA region		×	×		S/S	×		
39	Lise (2006)	Turkey		×	×		S/S			×
40	Steenhof et al. (2006)	Canada	×			×	LASP		×	
41	Diakoulaki and Mandaraka (2007)	EU-14	×		×		S/S	×		
42	Fan et al. (2007)	China		×		×	AWD	×		
43	Liu (2007)	Taiwan	×			×	LMDI			×
44	Liu et al. (2007)	China	×		×		LMDI	×		
45	Steenhof (2007)	China		×		×	LASP		×	
46	İpek Tunç et al. (2009)	Turkey	×		×		LMDI	×		
47	Malla (2009)	Asia-Pacific and North Amercia	×		×		LMDI		×	
48	Papagiannaki and Diakoulaki (2009)	Greece, Denmark	×		×		LMDI			×
49	Shrestha et al. (2009)	Asia-Pacific	×		×		LMDI	×		
50	Steenhof (2009)	China		×		×	LASP			
51	Timilsina and Shrestha (2009a)	12 Asia countries	×			×	LMDI			×
52	Timilsina and Shrestha (2009b)	20 Latin American & Caribbean countries	×			×	LMDI			×
53	Tol et al. (2009)	USA	×			×	AMDI			×

Table A.1 (*continued*)

6. Decomposition identity [4]							7. Sector[5]						8. Time period studied	9. No. of cases
act	str	int	fmx	emi	oth	Total	Ind	Tra	R/S	Ele	Ew	Oth		
×	×	×	×	×		6	×						1973–1987	18
×	×	×	×			4	×						1958–1991	3
×	×	×	×	×		5	×	×	×		×		1980–1992	1
×	×	×	×			4		×					1973–1992	9
		×	×	×		3				×			1980–1990	12
	×	×	×	×		4	×						1981–1993	1
	×	×	×	×		4	×						1980–1993	3
×	×	×	×	×		5					×		1960–1993	3
×	×	×	×		×	5		×					1970–1991	N.A
×	×	×	×	×		5	×	×	×		×		1973–1991	50
×	×	×	×	×		5	×						1987–1993	1
×		×	×	×		4				×			1985–1990	1
	×	×	×	×		4	×						1971–1991	30
×	×	×	×	×		5			×				1973–1995	13
	×	×	×	×		4				×			1985–1995	N.A
	×	×	×			3					×		1980–1994	48
	×	×	×	×		4		×					1970–1993	30
×	×	×	×			4						×	1960–1995	N.A
	×	×	×	×		4					×		1971–1994	N.A
×	×	×	×			4	×						1973–1993	26
×	×	×	×		×	6		×					1980–1995	N.A
	×	×	×	×	×	3 vs. 6				×	×		1974–1994	6
	×	×	×	×		4				×	×		1970–1995	5
	×	×	×	×		4			×				1970–1993	30
×	×	×	×	×	×	6	×						1976–1995	N.A
	×	×	×	×		4	×						1973–1994	N.A
×	×	×	×	×		5	×						1973–1994	13
×	×	×	×		×	5					×		1960–1996	4
	×		×		×	3				×			1970–1998	2
×	×	×	×	×		5	×						1986–1994	N.A
×	×	×	×	×	×	6	×						1988–1995	N.A
×	×	×	×	×		5	×						1970–1996	N.A
	×	×	×			3	×						1981–2000	3
	×	×	×	×	×	4 vs. 5		×					1970–1993	30
×	×	×	×			4					×		1980–1996	3
	×	×	×		×	5				×			1974–1998	4
×	×	×	×	×	×	12					×		1996–1999	3
	×	×	×			3						×	1971–1998	N.A
	×	×	×	×	4					×			1980–2003	2
×	×	×	×			4		×					1990–2003	1
×	×	×	×	×		5	×						1990–2003	28
	×	×	×	×		4	×						1980–2003	2
×	×	×	×		×	5					×		1989–2004	N.A
×	×	×	×	×		5	×						1998–2005	1
	×	×	×		×	5				×			1980–2002	2
×	×	×	×	×		5					×		1970–2006	4
×		×	×	×		4				×			1990–2005	14
×	×	×	×	×	×	8		×					1990–2005	N.A
×		×	×	×	×	5				×			1980–2004	45
	×	×	×	×	×	5				×			1980–2002	N.A
×	×	×	×	×	×	6		×					1980–2005	N.A
×	×	×	×	×	×	6		×					1980–2005	N.A
×	×	×	×		×	6					×		1850–2002	N.A

(continued on next page)

Table A.1 (*continued*)

	1. Publication	2. Country/region	3. Indicator type[1]		4. Decomposition approach[2]			5. Activity indicator[3]		
			C	I	Add	Mul	Method	$	B	Pop
54	Zhang et al. (2009a)	China	×	×	×		S/S	×		
55	Zhang et al. (2009b, 2011)	China	×		×		S/S	×		
56	Bhattacharyya and Matsumura (2010)	EU-15		×		×	LMDI	×		
57	Löfgren and Muller (2010)	Sweden	×		×		LMDI	×		
58	Oh et al. (2010)	Korea	×		×		LMDI	×		
59	Sheinbaum et al. (2010)	Mexico	×		×		LMDI	×		
60	Vinuya et al. (2010)	USA	×		×		LMDI			×
61	Zhao et al. (2010)	Shanghai	×		×		LMDI	×		
62	Chen (2011)	China		×		×	LMDI	×		
63	de Freitas and Kaneko (2011a)	Brazil	×		×		LMDI			×
64	de Freitas and Kaneko (2011b)	Brazil	×			×	LMDI			×
65	Kumbaroğlu (2011)	Turkey	×		×		S/S		×	
66	Liu (2007, 2011)	China	×		×		LMDI			×
67	Mendiluce and Schipper (2011)	Spain	×			×	LMDI		×	
68	Schipper et al. (2011)	USA	×		×		LASP, LMDI		×	
69	Sheinbaum et al. (2011)	5 Latin countries	×			×	LMDI	×		
70	Steenhof and Weber (2011)	Canada	×			×	LASP		×	
71	Tan et al. (2011)	China		×	×		LMDI	×		
72	Wang et al. (2011)	China	×		×		LMDI			×
73	Yang and Chen (2011)	China	×		×		LMDI	×		
74	Zhang et al. (2011)	China	×		×		LMDI	×		
75	Chong et al. (2012)	China	×		×	×	LMDI			×
76	Hammond and Norman (2012)	UK	×		×		LMDI	×		
77	Liu et al. (2012)	China	×		×		LMDI	×		
78	Lu et al. (2012)	USA	×		×		LMDI	×		
79	O'Mahony et al. (2012)	Ireland	×			×	LMDI		×	
80	Zhang et al. (2013)	China	×		×		LMDI	×		

Note:

1. The letters “C” and “I” stand for aggregate emission change and aggregate emission intensity change respectively.
2. The abbreviations “Add” and “Mul” stand for additive and multiplicative decomposition schemes respectively.
3. The symbol “$” and abbreviation “Pop” indicate that a monetary indicator and the population are used as the activity indicator respectively, while the letter “B” indicates that the best or most appropriate activity indicator for the application area is employed as is generally agreed. For example, this means passenger-km is used for passenger transportation, tonne-km for freight transportation, and kWh of electricity generation for the electricity generation sector.
4. The abbreviations “act”, “str”, “int”, “fmx”, and “emi” refer to the various effects in the decomposition identity, i.e. activity, structure, energy intensity, fuel mix, and emission coefficient effects, respectively. Other effects used are treated as “oth”.
5. The abbreviations “Ind”, “Tra”, “R/S”, “Ele”, and “Ew” respectively refer to the following sectors: industry, transportation, residential and service, electricity generation, and economy-wide. The abbreviation “Oth” includes some other sectors such as agriculture.

Table A.1 (*continued*)

6. Decomposition identity [4]							7. Sector[5]						8. Time period studied	9. No. of cases
act	str	int	fmx	emi	oth	Total	Ind	Tra	R/S	Ele	Ew	Oth		
×	×	×	×			4					×		1991–2006	1
×	×	×	×			4					×		1991–2006	3
	×	×	×			3					×		1990–2007	N.A
×	×	×	×			4					×		1993–2006	1
×	×	×	×			4					×		1990–2005	2
×	×	×	×		×	6	×						1970–2006	N.A
×		×	×		×	4					×		1990–2004	N.A
×	×	×	×			4	×						1996–2007	N.A
×	×	×	×	×		5	×						1980–2008	3
×	×	×	×	×	×	10					×		1970–2009	4
×	×	×	×	×	×	6					×		1980–1994 2004–2009	2
×	×	×	×			4	×	×	×	×		×	1990–2007	4
×	×	×	×	×	×	6						×	1999–2004	N.A
×	×	×	×			4		×					1990–2008	4
×	×	×	×	×	×	6		×					1960–2008	8
×	×	×	×			4					×		1990–2006	5
×	×	×	×	×	×	6				×			1990–2008	2
	×	×	×		×	5				×			1998–2008	N.A
×	×		×		×	6		×					1985–2009	N.A
×	×	×	×			4	×						2004–2008	N.A
×	×	×	×			4					×		1995–2009	1
×	×	×	×		×	5					×		1995–2007	1
×	×	×	×	×		5	×						1990–2007	2
×	×	×				3					×		1995–2009	N.A
×	×			×		3				×			2008–2009	N.A
×	×	×	×	×	×	9					×		1990–2007	N.A
×	×	×	×	×	×	6				×			1991–2009	2

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