Which Industry is Greener? Empirical Study for Nine Industries in OECD Countries

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Abstract

This study analyzed the relationship between CO_2 *emissions of different industries and economic growth in OECD countries from 1970 to 2005. We tested an environmental Kuznets curve (EKC) hypothesis and found that total* CO_2 *emissions from nine industries show an N-shaped trend instead of an inverted U or monotonic increasing trend with increasing income. The EKC hypothesis for sector-level* CO_2 *emissions was supported in (1) paper, pulp and printing industry, (2) wood and wood products industry, and (3) construction industry. We also found that emissions from coal and oil increase with economic growth in steel and construction industries. Meanwhile, non-metallic minerals, machinery, and transport equipment industries tend to have increased emissions from oil and electricity with increased economic development. Finally, the EKC turning point and the relationship between GDP per capita and sectoral* CO_2 *emissions differ among industries according to the fuel type used. Therefore, the environmental policies for* CO_2 *reduction need to consider these differences in industrial characteristics.*

Keywords: environmental Kuznets curve, CO_2 emission, industrial sector, OECD
JEL Classification: Q53, Q40, L60

1. Introduction

Clarification of the relationship between environmental emissions and economic growth has been a crucial issue for several decades (Stern 2004; Azomahou et al. 2006; Kijima et al. 2010) because the ability to forecast emissions due to economic growth could be helpful in estimating the potential magnitude of environmental problems (Riahi et al. 2011). If we could detect conditions where economic growth leads to increased environmental burdens, we might be able to treat the source of environmental emissions earlier and at a lower cost (Kuosmanen et al. 2009). More specifically, climate change is currently the one of the most important environmental problems, and it must be dealt with adequately (Organization for Economic Cooperation and Development (OECD) 2009).

Although activities within an industrial sector lead to economic growth, they often create significant carbon dioxide (CO_2) emissions. However, the structure of CO_2 emissions for an entire country is unclear. For example, emissions from the manufacturing sector might not be strongly correlated with population size because the sector produces products for the domestic market as well as for the global market through exportation (Perkins and Neumayer 2012).

The environmental Kuznets curve (EKC) hypothesis has been applied empirically and theoretically to identify the relationship between environmental emissions and economic growth (Kijima et al. 2010)[1]. Numerous studies have analyzed the relationship between CO_2 emissions and economic growth. In most studies, the applied data are cross-country (regional) or are from entire industrial sector within one country, which does not comprehensively consider individual industrial characteristics or fuel choices. Cross-country EKC analysis intends to show the close relationship between environmental emissions and gross domestic product (GDP) or related policy variables (Azomahou et al. 2006; Farzin and Bond 2006; Wagner 2008; Galeotti et al. 2009; Tsurumi and Managi 2010). However, as Grossman and Krueger (1995) suggested, economic scale, technology level, and industrial composition effects are keys to understanding the shape of the EKC. The industrial composition effect is especially difficult to interpret with respect to EKC (Tsurumi and Managi 2010). Previous studies have controlled for the composition effect using the capital-labor ratio (Managi et al. 2009). They assume that capital-intensive industries discharge more CO_2 emissions than labor-intensive industries because capital equipment requires the use of more fossil fuel. However, a limitation of this assumption is that it fails to capture detailed industrial characteristics, such as intermediate fuel inputs and energy substitution tendencies.

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[1] Cases of local environmental problems (e.g., acid rain or river pollution) often support the EKC. However, it is difficult to support an inverted U-shaped curve for emissions related to global environmental problems (e.g., CO_2 for climate change) (Dinda, 2004).

To solve this problem, we propose an estimation of the EKC relationship by separately controlling for economic scale and technology according to the type of industry and type of fuel. Then we discuss the EKC relationship considering the detailed composition differences in the industrial characteristics and fuel type.

In addition to previous studies in multiple countries, data from all industries in a single country were analyzed to test the EKC[2]. When the data were analyzed by country or entire industrial sector, the characteristics of the industrial structure largely affected the relationship between CO_2 emissions and economic performance because the technical difficulty of reducing CO_2 emissions differs across each industry. The capital equipment and labor requirements for reducing CO_2 emissions differ across industries because the types of fuel consumed as intermediate fuel materials also differ (Table 1).

Table 1. CO_2 emission ratio by fuel combustion in 2006 in OECD country

Industry type	Coal/peat	Oil/petroleum product	Natural gas	Electricity
Manufacturing industries and construction	14%	19%	18%	48%
Food and tobacco	8%	11%	37%	45%
Wood and wood products	1%	16%	17%	66%
Chemical and petrochemical	7%	15%	28%	51%
Paper, pulp and printing	8%	11%	17%	65%
Non-metallic minerals	3%	4%	31%	62%
Steel and metal	32%	3%	33%	33%
Machinery	1%	6%	20%	73%
Transport equipment	1%	4%	45%	50%
Construction	11%	47%	26%	15%

Source: International Energy Association, CO_2 emission fuel from combustion.

Note: Machinery and transport equipment are categorized as downstream industry.

Additionally, the manufacturing sector can be divided into upstream and downstream industries[3]. In general, upstream industries tend to demand more energy, especially fossil fuels including coal and petroleum. However, downstream industries generally consume more electricity

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[2] The EKC hypothesis has been tested in many countries, including the U.S. (Franklin and Ruth 2012), Canada (He and Richard 2010), France (Iwata et al. 2010), Scotland (Turner and Hanley 2011), Korea (Kim et al. 2010), Turkey (Akbostanci et al. 2009), and Israel (Yanai et al. 2010). Recently, several studies have targeted developing countries (Auffhammer and Carson 2008; Jalil 2009).

[3] Upstream industry is industrial firms that process the basic or raw material into an intermediary product that is converted into finished product by the downstream industries. Downstream industry is industrial firms that process the output of other firms into a finished or different product.

and natural gas than coal and oil because most downstream industries use automated production systems fueled by electricity and natural gas. From Table 1, natural gas and electricity have a share of more than 90% in total energy use in machinery and transport equipment industries categorized as downstream industry. In the meantime, chemical and steel industries categorized as upstream industries use coal and oil more than downstream industry[4].

We hypothesized that the EKC relationship between CO_2 emissions and economic growth would not be observed in entire industrial sector. This is because (1) unclear responsibility of environmental problems by CO_2 emissions, and (2) limited available technology to treat CO_2 emissions. Because the purposes of fuel use differ among industries, the relationships between technological progress and economic growth also differ (Appendix 1). Therefore, we hypothesized limited support for the EKC across industries for two reasons. First, when an industry uses fossil fuels as main intermediate fuels, it is difficult to support the EKC because the intermediate fuel input increases proportionally with production growth. Therefore, we expected limited support for the EKC relationship between CO_2 emissions and economic growth from the steel and metal industry, which use coal as their main intermediate fuels.

Second, we focused on the global and domestic market sizes of products. If product demand is highly dependent on the global market, the domestic market size does not strongly affect the amount of production (Suri and Chapman 1998). In general, the incentives to trade products with low value per weight across the country are weak because of high transportation costs. Thus, there is decoupling relationship between national GDP and sectoral CO2 emission from industry which produces low value per weight product (e.g. wood product) if country increases GDP through trade high value per weight products (e.g. electric device). Therefore, we hypothesized that the EKC relationship would be supported by specific industries, such as the wood and wood products industry, and paper, pulp and printing industry, which do not use fossil fuels as intermediate fuels and product value per weight is lower than others.

Based on these backgrounds, we hypothesized that the EKC relationship observed in previous studies was mainly caused by industrial structural changes. To test this hypothesis, we analyzed CO_2 emissions data by industrial sector. No previous studies that have tested the EKC hypothesis have focused on the relationship between sectoral CO_2 emissions per capita and economic growth. We also analyzed the data by energy type because technological progress in energy

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[4] Non-metallic minerals industry is categorized as upstream industry and it highly depend on the electricity usage. This is because electricity is consumed at electric cement mill in cement production process.

consumption differs for different fuel types. Thus, we controlled for fuel characteristics to confirm the EKC relationship by energy type in each industry.

The main objective of this study is to examine the possibility of EKC relationship between CO_2 emission and economic growth under controlling industrial structure composition effect. Another objective is to find which industries have decreased CO_2 emissions with increasing GDP (i.e., identification of “greener” industries). The novelty of study is empirically focuses on the relationship between sectoral CO_2 emissions and economic growth.

Additionally, some previous researches on EKC focus on the multiple factors behind the relationship between pollution and economic growth (e.g. Seldan et al., 1999; Bruvoll and Medin, 2003; Stern, 2004). One advantage of decomposition analysis is to identify the contribution effect of each factor to emission change (Fujii and Managi, forthcoming). In this study, we apply the decomposition analysis to clarify the contribution to CO_2 emissions change for understanding the factors behind the relationship between CO_2 emissions per capita and economic growth.

2. Analytical Framework and Methodology

The mechanism of EKC relationship between sectoral CO_2 emission and GDP per capita is explained by change of people’s environmental preference including pressure to manufacturing firms and requirement of climate change policy to government (Kijima et al. 2010). To correspond these external pressures about CO_2 emission reduction, manufacturing firms try to reduce their CO_2 emissions. However, firm would not prefer to start decrease CO_2 emissions if other firm does not change their behavior. This is because they lose the market competitiveness. Meanwhile, it is more acceptable situation if all of the member firms of industry group start simultaneously to reduce CO_2 emission. According to Southworth (2009), corporate voluntary action is more acceptable with economic growth. Thus, corporate activity plays a key role in balancing environmental protection and economic growth (Barros and Managi, forthcoming). Then, we consider the degree of economic growth reflects that strength of incentive for CO_2 emission reduction for manufacturing firms.

We applied a panel regression analysis in this study to examine the relationship between CO_2 per capita (*CO2per*) and GDP per capita (*GDPper*); we considered the following specifications in equation (1) and (2). The relationships are assumed to be quadratic or cubic.

$$CO2\,per_{ijk}^{t} = \beta_1 \cdot GDPper_k^t + \beta_2 \cdot (GDPper_k^t)^2 + \mathbf{X\beta} + \eta_k + \mu^t + \varepsilon_k^t \tag{1}$$

$$CO2\,per_{ijk}^{t} = \beta_1 \cdot GDPper_k^t + \beta_2 \cdot (GDPper_k^t)^2 + \beta_3 \cdot (GDPper_k^t)^3 + \mathbf{X\beta} + \eta_k + \mu^t + \varepsilon_k^t \qquad (2)$$

where i is energy type, j is industry, k is country, and t is year. To capture the country characteristics that influence *GDPper*, the control variable vector $\mathbf{X}$ was incorporated into the models. η and μ are unobserved country- and time-specific fixed effects, respectively. ε is an idiosyncratic error term. β is the estimated coefficients.

We used two control variables which are energy efficiency (EE) and share of each industry in GDP ($\mathrm{SHARE}_{\mathrm{GDP}}$) to capture the standard EKC determinants of scale and technique effects. Firstly, technique effect can be controlled by energy efficiency (EE). We define the *EE* indicator, which indicates the productive efficiency of energy use, is calculated as the total energy use per sale. This indicator can be reduced by decreasing the energy use per sale due to technological improvements in energy use. *EE* indicator reflects the energy use technology, which is highly depend on the technological level of equipment of energy combustion and production.

Next, scale effect is explained by $SHARE_{GDP}$ indicator. We use $SHARE_{GDP}$ indicator is calculated by dividing each industrial sector's value added by the GDP, yielding each industrial sector's share of value added in the total GDP. This indicator (e.g., $SHARE_{GDP,k}$) decreases if the value added of industry k decreases more quickly than GDP decreases or if the value added of industry k increases more slowly than GDP increases. $SHARE_{GDP}$ indicator captures the production scale of each industrial sector.

All control variables are expected to be positively related to *CO2per*. To analyze the EKC relationship according to fuel type, we calculated quadratic and cubic models using CO_2 emissions from each fuel type separately as dependent variables.

3. Data

The sector-level CO_2 emissions and energy consumption data were obtained from three databases published by the International Energy Agency: (1) CO_2 Emissions from Fuel Combustion, (2) Energy Balances of OECD countries, and (3) Energy Statistics of OECD countries. Total revenue and value added data by industrial sectors were obtained from EU-KLEMS[5]. GDP and population data were obtained from World Development Indicators published by World Bank. All financial data were deflated to 1995 prices. These data cover the 36 years from 1970 to 2005. Table 2 provides a

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[5] The EU-KLEMS is financial database published by the Groningen Growth and Development Centre. EU KLEMS stands for EU level analysis of capital (K), labour (L), energy (E), materials (M) and service inputs(S) (http://www.euklems.net/).

description of the data[6]. The current dataset is composed of unbalanced panel data because of missing data; the number of total observations is 61,068. We categorized energy data into four groups: coal/peat, oil/petroleum products, natural gas, and electricity (see Appendix 2). The CO_2 emissions data from coal/peat, oil/petroleum products, and natural gas were obtained directly from the CO_2 Emissions from Fuel Combustion database. However, this database does not include electricity-derived CO_2 emissions; therefore, we estimated electricity-derived CO_2 emissions as the sectoral electricity consumption amount (kWh) multiplied by the CO_2 coefficient (ton-CO_2/kWh) for each country[7].

Table 2. Data sample description

Time period	1970-2005
Country (23)	Australia, Austria, Belgium, Canada, Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Japan, Korea, Netherlands, Poland, Portugal, Slovak Republic, Spain, Sweden, United Kingdom, United States
Industry type	(1) Manufacturing industry and construction, (2) Food and tabaco, (3) Wood and wood products, (4) Chemical, (5) Paper, pulp and printing, (6) Non-metallic minerals, (7) Steel and Metal, (8) Machinery, (9) Transport equipment, (10) Construction
Energy type	(1) Coal/Peat, (2) Oil/Petroleum product, (3) Natural gas, (4) Electricity

There are two reasons of selection of the industries in our analysis. Firstly, industries for our analysis have large share of CO_2 emissions. The other reason is these nine industries have advantage in matching dataset between financial data from EU-KLEMS and CO_2 emissions and energy data from International Energy Agency dataset.

Table 3 shows the average value of each variable by industry type from 1970 to 2005[8]. There are differences in values among industries. CO2per is high in the chemical industry and steel and metal industry. These two industries account for 36.6% of CO_2 emissions in the manufacturing and construction sectors. EE is diverse among the industries. The non-metallic minerals, steel and metal industries have high energy consumption per sale ratios. These industries produce energy intensive products from raw materials such as iron ore. While, downstream industries and construction

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[6] Chemical industry includes coal chemical and petro chemical industries. Non-metallic minerals industry includes cement industry and ceramic industry.

[7] Because we have difficulty to distinguish the electric power production source by type of industry, we apply the each country's overall average CO_2 coefficient score to estimate electricity-derived CO_2 emissions from industrial sectors. CO_2 coefficient depends on the power generation technology and portfolio of electricity power generation (see Appendix 2).

[8] Average of *GDPper* is different by type of industry because of missing data.

industries tend to have lower energy consumption per sale. These industries use energy-embodied intermediate material made by upstream industries.

Table 3. Average score of each variable during 1970-2005 by type of industry

	CO2per (ton-CO_2/person)	EE (toe/ million dollar)	$SHARE_{GDP}$ (dollar/dollar)	GDPper (thousand dollar/person)
Manufacturing industries and construction	0.846	16.790	0.256	19.106
Food and tabaco	0.067	11.183	0.026	19.423
Wood and wood products	0.016	14.460	0.006	18.215
Chemical	0.125	24.040	0.027	19.429
Paper, pulp and printing	0.080	23.504	0.021	19.439
Non-metallic minerals	0.064	46.221	0.009	19.975
Steel and metal	0.174	26.266	0.026	19.349
Machinery	0.052	4.960	0.061	19.227
Transport equipment	0.025	7.156	0.017	18.627
Construction	0.028	3.403	0.059	18.243

4. Results

4-1. Environmental Kuznets curve estimation

We conducted a model specification F-test to assess the quadratic and cubic effects of GDP per capita (see Appendixes 3 to 6 for specification results). Then, to estimate the sectoral CO_2 emissions per person, we applied the most preferable functional form following the results of the F-test. Additionally, we select preferable specification from fixed effects or random effects by Hausman test results. The results are shown in Figures 1 and Table 4[9]. The empirical results are summarized as follows: first, the EKC hypothesis was supported by three sectors, (1) wood and wood products industry, (2) paper, pulp and printing industry, and (3) construction industry. Second, from the results in right side (named “Total”) in Table 4, the food and tobacco, chemical, steel and metal, and machinery industries have two turning points (TPs). Because the cubic term of GDP per capita was positive[10], we found that the relationship is represented by an N-shaped curve in four industries. Finally, we did not observe these TPs in non-metallic minerals and transport equipment industries, although the cubic term of GDP per capita was positive. These results show that in two industries, the relationship

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[9] Detailed results by type of industry are described at Appendix 7 to Appendix 16.

[10] The cubic terms of GDPper coefficient of machine in Appendix 3, chemical industry and machine industry in Appendix 5 are not significant. The cubic terms of GDPper coefficient are significantly positive in Appendix 4 and Appendix 6.

between GDP per capita and sectoral CO_2 emissions per capita is described by an increasing monotonic trend.

Based on the results regarding CO_2 emissions from the four fuel types by each industries, we estimate the projection of CO_2 emissions (see Figure 1). CO_2 emissions across four fuel types increase with economic growth until *GDPper* is approximately $32,000. Up to this level, CO_2 emissions for all industries increase with economic growth as a function of the industrialization stage. We also find the CO_2 emission from oil and electricity rapidly expand (see Appendix 7 to Appendix 16). In the meantime, CO_2 emission from coal tends to be stable to with other three fuels in this stage except steel and metal industry. Therefore, share of CO_2 emission from coal consumption in total CO_2 emission decreases with increasing *GDPper*. This result can be explained by change of secondary energy supply capacity.

Electric power interruption frequently occurs in low-income countries due to the lack of electrical supply capacity. Therefore, industrial sectors often generate electricity themselves using coal and oil because they have limited access to a stable supply of electricity. However, electricity supply capacity and distribution technology improve with economic growth, resulting in a declining dependency on self-generation equipment in the industrial sector. Furthermore, high-quality petroleum products can be made in the petrochemical industry using modern electricity-consuming production equipment. These developments in the external environment permit manufacturing sectors, especially downstream industries, to increase production with electricity and petroleum products.

Overall CO_2 emissions levels are stable until GDP reaches approximately $47,000 because changes in CO_2 emissions are offset by changes in emissions from industries with inverted U-shaped, N-shaped, and monotonic increases relationship. CO_2 emissions from coal and oil consumption tend to decrease while emission from electricity use increases in upstream industries. However, CO_2 emissions from oil and electricity in downstream industries increase rapidly, which is the main reason for the monotonic increase of CO_2 emissions accompanying economic growth.

After *GDPper* exceeds $47,000, CO_2 emissions start to increase. In this stage, CO_2 emissions from industries with an N-shape relationship increase again, especially in downstream industries. In this stage, focus of manufacturing companies tends to shift from the domestic market to the global market, including developing countries. Because developing countries have huge market demands and low technological standards for domestic companies, manufacturing firms in developed countries gain market competitiveness more easily than in saturated domestic markets.

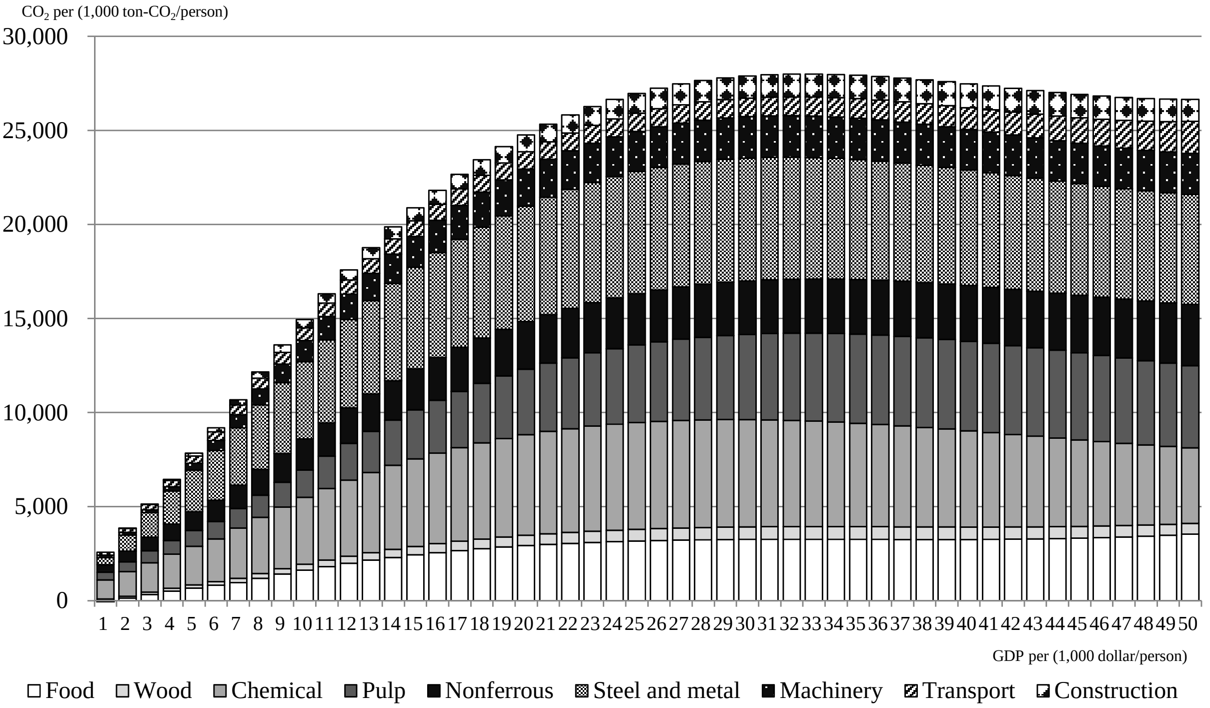

Figure 1. CO_2 emission projection in nine industries

As seen in Table 4, CO_2 emissions increase until GDP per capita is approximately $32,000, especially as CO_2 emission from oil and electricity expands in manufacturing industries and construction sector (first row in Table 4). Meanwhile, CO_2 emissions from coal tend to remain stable because CO_2 emissions from coal increase in the steel and metal industries but decrease in many other sectors.

Table 4 shows the EKC relationship is observed in wood, paper, and construction industries. However, the cause of the EKC relationship is different. From Table 4, we find that TPs of the GDP per capita score of oil and natural gas are greater than that of total (right side row in Table 4) in wood and wood product. Additionally, GDP per capita scores are similar between total and two fuels. These results imply that energy substitution may not be happened after total CO2 per capita start to decrease. Because the TP is not related to the choice of fuel, we suspect that the EKC relationship in the wood and wood products industry is caused by changes in the production scale because the market size of wood and wood products in developed countries tends to decrease with economic growth due to the increasing substitution of goods for growth in the construction and housing sectors. Furthermore, developing countries with rich forest resources expand their low-cost exportation of wood products. In other words, developing countries easily catch up with developed countries in the wood and wood products sector because wood products require relatively lower levels of technology to process than products from other manufacturing sectors.

Additionally, GDP per capita of the TP differs across fuel type in the pulp, paper and printing industry (see Table 4). TP due to coal, oil, and, natural gas occurred earlier than that of electricity in pulp and paper industry. These results imply that the EKC relationship is caused by substituting energy from coal, oil, and natural gas for energy from electricity as part of the production process in the pulp, paper, and printing industry. Our result is consistent with previous study. Lindmark et al. (2011) shows paper and pulp industry in Sweden reduce oil consumption due to oil price increase and expand electricity consumption generated by biofuels. This energy transition makes achieve both economic output growth and CO_2 emissions reduction.

However, the relationship between CO_2 emissions from oil and economic growth is characterized by an N-shaped curve because it has two TPs. The second TP can be explained by industrial characteristics. The printing industry uses petroleum products for ink, and the paper and pulp industry consumes a petroleum product as an intermediate product. It is difficult to change intermediate materials because this change requires the development and use of alternative technologies. Furthermore, paper products are inexpensive, which provides little incentive to export; therefore, paper products are mainly consumed within domestic markets. Paper consumption within a country increases with an increase in economic growth. We consider that these industrial characteristics are reflected in the results for this industry.

We also observed EKC relationship in construction industry. CO_2 emission from oil consumption is large comparing to other three fuels (see Appendix 16). CO_2 emission increased until the point GDP per capita equal $40,000. After this point, CO_2 emissions start to decrease due to reduction of CO_2 emission from oil consumption with income growth. This EKC relationship can be explained by equipment energy efficiency improvement. Main consumed oil product in construction industry is diesel oil, which is mainly use for construction equipment (e.g., hydraulic shovel, crane car) and truck for conveying materials. These are produced by machinery and transport equipment sector which achieve rapid technological progress in our research period, especially fuel efficiency of diesel truck was dramatically improved[11]. This rapid fuel efficiency improvement allow construction sector to reduce energy consumption, cost of energy use, and CO_2 emission. Today, new technology is also invented for truck and construction equipment (e.g. hybrid construction equipment and

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[11] According to IEA (2011b), average fuel efficiency of heavy truck has steadily improved by 0.8 – 1% per year over the last 40 years. Light truck, which is trucks with a gross vehicle weight of less than 3.5 tonnes, has been fallen average energy intensity from around 13.8MJ/tkm in 1995 to around 12.2 MJ/tkm in 2005 (IEA 2011a).

biodiesel truck (U.S. EPA 2009)). Thus, CO_2 emission from oil consumption can be expected to continue to decrease in future by adoption of new technology.

CO_2 emissions from electricity are high in the non-metallic minerals industry, and CO_2 emissions from coal are high in the steel and metal industry (see Appendix 12 and Appendix 13). These two industries are highly dependent on the use of a single type of fuel. This reliance on a single fuel source is due to the industrial characteristics of the production process and intermediate materials. The non-metallic minerals industry consumes a large amount of electricity in electric cement mills and electric arc furnaces, which are used for creating ceramic products. Steel and metal industry use coal both as a fuel and as an intermediate material. It is difficult to reduce the amount of fossil fuels used as intermediate materials without changing the production process.

While, we observed N-shape curve relationship instead of monotonic increase relationship in steel and metal industry. One interpretation of this result is substitution of steel production from shaft furnace to electric arc furnace. Steel and metal industry uses coal both as a fuel and for oxidation-reduction reactions in shaft furnaces. In this case, without technological innovation of the intermediate material technology, it is difficult to reduce coal consumption while maintaining the same level of production. Alternatively, electric arc furnaces, which use scrap steel as an intermediate material, can be used to make steel, thereby saving energy. Shifting the steel production process to electric arc furnaces allows the steel industry to reduce the consumption of coal as an intermediate fuel. However, electric arc furnaces require a large stock of steel scrap (e.g., scrap cars) which is more generated with economic growth. Thus, economic growth indirectly operates to reduce CO_2 emissions from coal consumption through a change in the production process from shaft furnaces to electric arc furnaces.

With regard to downstream industries, CO_2 emissions from natural gas and electricity increased more than the coal. One interpretation of this result is that the production process became more capital intensive and automated in the manufacturing sector, especially in the downstream sector. The power sources of new production processes also shifted from coal to oil, natural gas and electricity.

Finally, as seen in Table 4, the total CO_2 emissions in the chemical industry started to decrease when the GDP per capita reached approximately $28,000. The main contributor of this decrease was CO_2 emissions from electricity; concurrently, CO_2 emissions from coal and oil did not decrease by a large amount because the chemical industry produces petroleum products and coal products using coal and oil as intermediate materials (see Appendix 1 and Appendix 10). CO_2 emissions from natural gas increase with economic growth in food industry. Because oil and coal fuels are mainly used for the heating process in the food industry, the fuel source used in the heating process can be substituted by natural gas, which is inexpensive and low in carbon intensity.

Table 4. Turning point between GDP per capita and sectoral CO_2 emission per capita.

	Coal/Peat	Oil/petroleum product	Natural gas	Electricity	Total
	(GDPper, CO2per)	(GDPper, CO2per)	(GDPper, CO2per)	(GDPper, CO2per)	(GDPper, CO2per)
Manufacturing industries and construction	(26.5, 674.1) (60.7, 534.8)	(35.7, 1291.6) (57.5, 1182.7)	(26.1, 682.8) (41.7, 631.5)	(30.7, 1251.0) (64.8, 976.9)	(32, 3863.80) (52, 3549.38)
Food and tabaco	(25.1, 25.9) (57.0, 20.3)	(34.5, 129.1) (57.7, 111.7)	N.A. (monotonic)	(25.6, 103.3) (68.0, 49.6)	(32, 326.24) (39, 324.93)
Wood and wood products	(23.8, 4.9)	(38.9, 27.3)	(36.8, 10.3)	(28.1, 26.2) (65.3, 19.0)	(35, 67.28)
Chemical	(24.2, 49.4) (58.7, 25.0)	(35.5, 165.6) (62.7, 139.3)	(25.1, 140.6)	(23.6, 228.5) (58.3, 147.6)	(28, 572.80) (74, 209.09)
Paper, pulp and printing	(30.8, 57.6)	(39.2, 153.6) (59.6, 141.0)	(38.3, 90.5)	(49.5, 188.2)	(38, 477.18)
Non-metallic minerals	N.A. (monotonic)	N.A. (monotonic)	(25.0, 35.6) (31.4, 35.3)	(29.2, 154.5) (49.2, 144.7)	N.A. (monotonic)
Steel and metal	(27.2, 388.5) (58.9, 274.5)	N.A. (monotonic)	(24.8, 63.1) (32.7, 62.1)	(27.9, 127.1) (59.1. 101.4)	(28, 653.81) (50, 584.48)
Machinery	(7.7, 14.6) (53.6, 3.1)	N.A. (monotonic)	(29.3, 41.1)	(29.0, 117.0) (59.8, 81.0)	(32, 220.60) (44, 214.73)
Transport equipment	(11.9, 17.9) (31.7, 7.8)	N.A. (monotonic)	(35.8, 24.2)	(28.9, 42.7) (62.2, 32.3)	N.A. (monotonic)
Construction	(3.7, -2.3) (36.5, 12.5)	(40.2, 92.0)	N.A. (monotonic)	(26.6, 10.5)	(40, 126.78)

* Unit of GDPper is 1,000 dollar /person, Unit of CO2per is 1,000 ton-CO_2/person.

** Single turning point shows that quadratic functional form is preferable than cubic functional form. Double turning point shows that cubic functional form is preferable than quadratic functional form.

4-2. Factor decomposition analysis of CO2 per capita

We apply decomposition analysis for two manufacturing sectors which are wood and wood product, and pulp and paper industry. We consider that these two industries have different factors of EKC relationship because of the differences of turning point location. We propose the decomposition of sectoral CO_2 emission per capita (*CO2per*) as follows:

$$\mathrm{CO2_{ij}/Pop} = (\mathrm{CO2_{ij}/E_{ij}}) \times (\mathrm{E_{ij}}/\textstyle\sum_i E_{ij}) \times (\textstyle\sum_i E_{ij}/\mathrm{Value_j}) \times (\mathrm{Value_j/GDP}) \times (\mathrm{GDP/Pop}) \quad (3)$$

where i is the fuel type (i.e. coal, oil, natural gas, and electricity), j is the industry type, CO2 is CO_2 emissions, Pop is the population, E is the energy use, Value is the value added, and GDP is the gross domestic product. In this estimation, we use aggregated data of 23 countries shown in Table 2 as OECD country data.

This equation shows that sector-level CO_2 per capita (*CO2per*) can be decomposed into five factors: carbon intensity (*CI*, first term), energy share ($SHARE_E$, second term), energy intensity (*EI*, third term), GDP share ($SHARE_{GDP}$, fourth term), and scale effect (*SCALE*, fifth term). Because the definition of GDP share is shown in section 2, we explain other four factors here.

We define the *CI* indicator, the carbon intensity of energy use, as the CO_2 emissions per energy use. This indicator can be decreased by applying more efficient fuel combustion, which decreases carbon emissions per energy use. This reduction can be achieved through low carbon energy use. Second, the $SHARE_E$ indicator, the share of energy use for each fuel type, is calculated as the amount of energy consumed per total energy use. This indicator (e.g., $SHARE_{E,i}$) can be reduced by decreasing the energy share i in total energy. Third, the *EI* indicator, which indicates the energy use efficiency, is calculated as the total energy use per value added. This indicator can be reduced by decreasing the total energy use per value added due to energy saving activities. Finally, we use *GDPper* as SCALE indicator following Stern (2004).We summarized the result of decomposition analysis in Table 5 to Table 6[12].

Comparing two tables, we find carbon intensity contributes to reduce CO_2 per capita from electricity in both sectors. One interpretation is that low carbon electricity generation using nuclear power plant and renewable power plant increased from 1970 to 2005. Another point we find commonly in two tables is energy share contribute to decrease CO_2 emissions from coal and oil. We consider that this result is caused by oil price increase due to oil crisis in 1973 and 1979. This rapid oil price increase gave an incentive for industrial firms to decrease oil dependency.

From Table 5, we find wood and wood product industry decrease CO2 per capita by reducing carbon intensity and structural change. These results imply that EKC relationship between wood and wood product are caused by carbon intensity decrease and scale down of production.

From Table 6, Pulp, paper, and printing industry reduce CO2 per capita by carbon intensity and structural change effect. Additionally, CO2 per capita from coal and oil was decreased by change of energy share. This result implies that energy substitution from coal and oil to natural gas to electricity is occurred in pulp, paper, and printing industry. From Table 5 and Table 6, we confirm that the results of decomposition analysis are consistent with our consideration about EKC relationship.

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[12] We describe detail decomposition methodology part in Appendix 17.

Table 5. Contributions to change of CO_2 emissions from 1970 to 2005 in Wood and wood products

Unit (ton CO_2 per capita)	⊿CO2per	CI	$SHARE_E$	EI	$SHARE_{GDP}$	SCALE
Coal/Peat	-0.51	-0.05	-1.63	1.02	-0.21	0.36
Oil/petroleum product	4.01	-0.17	-4.88	7.86	-1.60	2.79
Natural gas	5.60	-0.08	4.05	1.41	-0.29	0.50
Electricity	22.75	-3.09	5.91	17.30	-3.51	6.15
Total	31.85	-3.39	3.45	27.59	-5.61	9.8

Table 6. Contributions to change of CO_2 emissions from 1970 to 2005 in Pulp, paper and printing industry

Unit (ton CO_2 per capita)	⊿CO2per	CI	$SHARE_E$	EI	$SHARE_{GDP}$	SCALE
Coal/Peat	12.91	-0.09	-7.76	11.03	-0.12	9.85
Oil/petroleum product	-17.56	-0.53	-59.93	22.80	-0.25	20.35
Natural gas	50.91	-0.02	36.26	7.80	-0.09	6.96
Electricity	112.55	-11.31	45.40	41.71	-0.46	37.21
Total	158.81	-11.95	13.97	83.34	-0.92	74.37

5. Conclusions

This study investigated how differences in industry and energy use affect CO_2 emissions in the OECD. First, we found that overall CO_2 emissions show an N-shaped trend instead of an inverted U or monotonic increasing trend with respect to income. Second, the EKC hypothesis for sector-level CO_2 emissions was supported in the (1) wood and wood products, (2) paper, pulp and printing, and (3) construction industries. Thus, these three industries were found to be greener industries than the other industries analyzed. The EKC relationship was not observed in other industries. These results imply that current climate energy and resource policy is not sufficient to prevent increases in CO_2 emissions due to economic growth.

Third, CO_2 emissions from coal and oil increased with economic growth in upstream industries. Because they use coal and petroleum products as intermediate materials, energy consumption grew as production increased. On one hand, improvements in production technology and changes in intermediate materials would reduce CO_2 emissions in upstream industries. On the other hand, downstream industries increased CO_2 emissions from oil and electricity with increased economic growth. Therefore, future development of a more efficient automation production system would decrease CO_2 emissions in downstream industries. Some previous EKC studies concluded that the EKC relationship is supported by country- or sector-level data. However, our study demonstrates that the EKC relationship is supported only within three sectors, i.e., those industrial sectors with smaller GDP shares in OECD countries beginning in the 1990s. Furthermore, downstream industries that have monotonic increases and N-shaped relationships between sectoral CO_2 emissions and economic growth have developed more rapidly than paper, pulp and printing, wood and wood products, and construction industries. Thus, the EKC relationship is not supported at the country level or entire industry level among different countries. Therefore, past technological changes would not result in reduced emissions, so more drastic changes are required to reduce CO_2 emissions.

Finally, the relationship and turning point between the GDP per capita and sectoral CO_2 emissions per capita are different among industries according to the fuel type. From our study, we find that under the current environmental policy and economic system, the paper, wood, and construction industries reduces CO_2 emissions with increasing economic growth. Meanwhile, the other six industries analyzed do not support the EKC relationship. Therefore, the environmental policies for CO_2 reduction need to consider these differences in industrial characteristics, which are a function of intermediate materials used and the export sales ratio. CO_2 reduction with minimizing economic loss is important to achieve sustainable development (Tavoni, et al. 2012). Thus, decision makers need to consider the industrial characteristics (greener or not greener) of CO_2 emissions to set the emissions cap for an industry (e.g., with a treaty such as the Kyoto protocol).

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Appendix 1. Main purpose of energy use by type of industry

	Coal / peat	Oil/petroleum products	Natural gas	Electricity
Food and tabaco	Private power generation, Fuel for boiler	Fuel for equipment, Packaging materials, Private power generation,	Fuel for equipment, Private power generation	Fuel for automation production equipment
Wood and wood products	Private power generation, Fuel for boiler	Fuel for equipment, Private power generation	Fuel for equipment,	Fuel for automation production equipment
Chemical and petro-chemical	Material for coal product, Private power generation, Fuel for boiler	Material for petroleum product, Petroleum solvent, Private power generation, Industrial steam generation	Fuel for equipment, Private power generation	Fuel for automation production equipment
Paper, pulp and printing	Private power generation, Fuel for boiler	Ink for printing, Fuel for equipment, Petroleum solvent	Fuel for equipment, Private power generation	Fuel for automation production equipment
Non-metallic minerals	Material for cement, Fuel for boiler	Material for cement, Fuel for equipment, Thermal source	Fuel for equipment, Private power generation	Fuel for equipment, (e.g. Electric cement mill)
Steel and metal	Material for cokes product, Fuel for equipment, Private power generation	Fuel for equipment, Private power generation, Thermal source	Fuel for equipment, Private power generation	Fuel for equipment, (e.g. Electric arc furnaces)
Machinery	Private power generation	Fuel for equipment, Petroleum product for painting, Grease, Petroleum solvent,	Fuel for equipment, Private power generation	Fuel for automation production equipment
Transport equipment	Private power generation	Fuel for equipment, Petroleum product for painting, Grease, Petroleum solvent,	Fuel for equipment, Private power generation	Fuel for automation production equipment
Construction	Material for coal tar	Fuel for construction equipment, Material for asphalt, Fuel for truck	Fuel for equipment, Private power generation	Fuel for equipment

Appendix 2. Definition of fuel data.

Coal/peat

hard coal	brown coal	anthracite	coking coal	other bituminous coal
sub-bituminous coal	lignite/brown coal	oil shale	peat	patent fuel
coke oven coke and lignite coke	gas coke	coal tar	brown coal briquettes /peat briquettes	gas works gas
coke oven gas	blast furnace gas	oxygen steel furnace gas		

Oil/petroleum product

crude oil	oil natural gas	liquids oil	refinery feedstocks oil	additives/blending components oil
orimulsion oil	refinery gas oil	ethane oil	liquefied petroleum gases (LPG)	motor gasoline oil
aviation gasoline oil	gasoline type jet fuel oil	kerosene type jet fuel oil	other kerosene oil	gas/diesel oil
heavy fuel oil	naphtha oil	lubricants oil	petroleum coke oil	non-specified petroleum products oil

Natural gas

Natural gas

Electricity

coal-fired thermal power	oil-fired thermal power	Natural gas-fired thermal power	Hydro power generation
biomass power generation	renewable energy	Waste-to-energy	Nuclear power generation

Appendix 3. Result of panel analysis with sectoral CO$_2$ emission from coal and peat

Quadratic model	Industry	Food	Wood	Chemical	Paper	Minerals	Steel	Machine	Transport	Construction
EE	21.49 ***	2.86 ***	0.31 ***	2.59 ***	2.15 ***	0.90 ***	4.11 ***	3.13 ***	1.15 ***	2.30 ***
SHARE$_{GDP}$	2.66 ***	0.40 ***	0.23 **	0.53 **	3.41 ***	1.77 ***	5.82 ***	0.04	0.52 ***	0.05 *
GDPper	0.09 ***	0.00	0.00	0.01 **	0.06 ***	0.00 ***	0.08 ***	-0.01 ***	-0.01	0.01 ***
GDPper^2	-0.01 ***	-0.00	-0.00	-0.00 *	-0.01 ***	0.00 ***	-0.01 ***	0.00 ***	0.00	-0.00 **
Const.	-0.44 ***	-0.00	-0.00	-0.01	-0.14 ***	-0.02 ***	-0.12 ***	0.01 ***	0.01	-0.01 ***
Within	0.598	0.601	0.622	0.610	0.376	0.748	0.553	0.482	0.513	0.759
Between	0.368	0.793	0.328	0.672	0.624	0.843	0.424	0.434	0.668	0.474
Overall	0.472	0.640	0.562	0.661	0.572	0.879	0.514	0.433	0.552	0.600
model	*fixed*	*fixed*	*fixed*	*random*	*random*	*random*	*fixed*	*fixed*	*fixed*	*fixed*

Cubic model	Industry	Food	Wood	Chemical	Paper	Minerals	Steel	Machine	Transport	Construction
EE	22.47 ***	2.89 ***	0.32 ***	2.67 ***	2.38 ***	0.90 ***	4.35 ***	3.17 ***	1.16 ***	2.23 ***
SHARE$_{GDP}$	2.53 ***	0.40 ***	0.26 ***	0.43 **	3.44 ***	1.83 ***	5.67 ***	0.05 *	0.51 ***	0.06 **
GDPper	0.34 ***	0.01 ***	0.00	0.05 ***	0.07 *	0.02 ***	0.35 ***	0.00	0.03 **	-0.00
GDPper^2	-0.09 ***	-0.00 **	-0.00	-0.01 ***	-0.01	-0.00 ***	-0.09 ***	-0.00	-0.02 ***	0.01 *
GDPper^3	0.01 ***	0.00 **	0.00	0.00 ***	0.00	0.00 ***	0.01 ***	0.00	0.00 ***	-0.00 **
Const.	-0.62 ***	-0.01 **	-0.00	-0.04 ***	-0.15 ***	-0.03 ***	-0.38 ***	0.01	-0.01	-0.01 *
Within	0.608	0.606	0.623	0.617	0.378	0.753	0.571	0.485	0.560	0.790
Between	0.407	0.803	0.318	0.701	0.597	0.856	0.500	0.443	0.608	0.200
Overall	0.517	0.655	0.556	0.685	0.564	0.885	0.580	0.449	0.567	0.466
Model	*fixed*	*fixed*	*random*	*random*	*fixed*	*random*	*random*	*fixed*	*fixed*	*fixed*
F-test	*reject*	*reject*		*reject*		*reject*	*reject*		*reject*	*reject*

Note: *, **, and *** indicate statistical significance at the 10%, 5%, and 1% levels, respectively.

We use the F-test to evaluate hypotheses that coefficient of GDP3 equal to zero. “Reject” represents that coefficient of GDP3 does not equal to zero at the 95% confidence level.

Appendix 4. Result of panel analysis with sectoral CO_2 emission from oil and petroleum product

Quadratic model	Industry	Food	Wood	Chemical	Paper	Minerals	Steel	Machine	Transport	Construction
EE	29.77 ***	5.51 ***	1.41 ***	3.85 ***	4.61 ***	1.28 ***	3.16 ***	6.26 ***	2.20 ***	7.62 ***
$SHARE_{GDP}$	3.30 ***	1.81 ***	2.04 ***	0.65 ***	1.21 **	2.59 ***	1.22 ***	0.00	0.80 ***	0.40 ***
GDPper	0.51 ***	0.06 ***	0.02 ***	0.08 ***	0.10 ***	0.03 ***	0.03 ***	0.03 ***	0.01 ***	0.05 ***
$GDPper^2$	-0.05 ***	-0.01 ***	-0.00 ***	-0.01 ***	-0.01 ***	-0.00 ***	-0.00 ***	-0.00 ***	-0.00	-0.01 ***
Const.	-1.30 ***	-0.14 ***	-0.04 ***	-0.13 ***	-0.21 ***	-0.08 ***	-0.07 ***	-0.04 ***	-0.03 ***	-0.09 ***
Within	0.737	0.811	0.719	0.715	0.617	0.542	0.764	0.714	0.583	0.794
Between	0.759	0.818	0.777	0.588	0.653	0.934	0.787	0.770	0.723	0.861
Overall	0.704	0.828	0.755	0.687	0.667	0.866	0.760	0.743	0.643	0.851
model	*fixed*	*random*	*fixed*	*random*	*fixed*	*fixed*	*random*	*fixed*	*fixed*	*random*

Cubic model	Industry	Food	Wood	Chemical	Paper	Minerals	Steel	Machine	Transport	Construction
EE	32.45 ***	5.85 ***	1.41 ***	3.92 ***	4.76 ***	1.29 ***	3.23 ***	6.20 ***	2.19 ***	7.64 ***
$SHARE_{GDP}$	2.99 ***	1.70 ***	2.01 ***	0.53 ***	0.64	2.65 ***	1.19 ***	-0.00	0.71 ***	0.39 ***
GDPper	1.29 ***	0.17 ***	0.03 ***	0.17 ***	0.21 ***	0.06 ***	0.07 ***	0.07 ***	0.03 **	0.07 ***
$GDPper^2$	-0.29 ***	-0.04 ***	-0.01 **	-0.04 ***	-0.04 ***	-0.01 ***	-0.02 ***	-0.02 ***	-0.01 ***	-0.01 **
$GDPper^3$	0.02 ***	0.00 ***	0.00	0.00 ***	0.00 ***	0.00 ***	0.00 ***	0.00 ***	0.00 ***	0.00
Const.	-1.92 ***	-0.23 ***	-0.05 ***	-0.19 ***	-0.29 ***	-0.11 ***	-0.10 ***	-0.06 ***	-0.04 ***	-0.10 ***
Within	0.776	0.846	0.721	0.731	0.633	0.553	0.770	0.722	0.591	0.200
Between	0.771	0.739	0.771	0.565	0.523	0.917	0.726	0.667	0.634	0.695
Overall	0.705	0.798	0.752	0.664	0.589	0.862	0.751	0.700	0.612	0.580
model	*fixed*	*fixed*	*fixed*	*random*	*fixed*	*fixed*	*fixed*	*fixed*	*fixed*	*random*
F-test	*reject*	*reject*		*reject*	*reject*	*reject*	*reject*	*reject*	*reject*	

Note: *, **, and *** indicate statistical significance at the 10%, 5%, and 1% levels, respectively.

We use the F-test to evaluate hypotheses that coefficient of GDP3 equal to zero. “Reject” represents that coefficient of GDP3 does not equal to zero at the 95% confidence level.

Appendix 5. Result of panel analysis with sectoral CO$_2$ emission from natural gas

Quadratic model	Industry	Food	Wood	Chemical	Paper	Minerals	Steel	Machine	Transport	Construction
EE	17.70 ***	1.92 ***	0.33 ***	1.86 ***	1.70 ***	0.74 ***	1.61 ***	3.24 ***	0.70 ***	2.67 ***
SHARE$_{GDP}$	-0.13	-0.31	-0.28 **	0.61 ***	3.83 ***	0.39 *	0.13 ***	0.13 ***	0.59 ***	0.07 ***
GDPper	0.54 ***	0.05 ***	0.01 ***	0.09 ***	0.06 ***	0.02 ***	0.05 ***	0.04 ***	0.01 ***	0.01 ***
GDPper^2	-0.10 ***	-0.01 ***	-0.00 ***	-0.02 ***	-0.01 ***	-0.00 ***	-0.01 ***	-0.01 ***	-0.00 ***	-0.00 ***
Const.	-0.33 ***	-0.03 ***	-0.01 ***	-0.07 ***	-0.13 ***	-0.03 ***	-0.04 ***	-0.04 ***	-0.02 ***	-0.01 ***
Within	0.571	0.546	0.589	0.503	0.506	0.882	0.519	0.568	0.510	0.570
Between	0.856	0.582	0.385	0.743	0.761	0.921	0.654	0.443	0.423	0.666
Overall	0.853	0.584	0.357	0.697	0.778	0.927	0.656	0.554	0.430	0.671
model	*fixed*	*fixed*	*fixed*	*fixed*	*random*	*fixed*	*random*	*random*	*random*	*random*

Cubic model	Industry	Food	Wood	Chemical	Paper	Minerals	Steel	Machine	Transport	Construction
EE	17.48 ***	2.01 ***	0.34 ***	1.90 ***	1.70 ***	0.74 ***	1.60 ***	3.26 ***	0.71 ***	2.80 ***
SHARE$_{GDP}$	-0.17	-0.29	-0.29 **	0.63 ***	3.83 ***	0.36 *	0.12 **	0.13 ***	0.59 ***	0.08 ***
GDPper	0.89 ***	0.14 ***	0.01 ***	0.15 ***	0.06 ***	0.06 ***	0.11 ***	0.03 ***	0.01 **	0.02 ***
GDPper^2	-0.28 ***	-0.05 ***	-0.00 **	-0.04 ***	-0.01	-0.02 ***	-0.04 ***	-0.00	-0.00	-0.01 ***
GDPper^3	0.03 ***	0.01 ***	0.00	0.00	0.00	0.00 ***	0.00 ***	-0.00	-0.00	0.00 ***
Const.	-0.51 ***	-0.08 ***	-0.01 ***	-0.11 ***	-0.14 ***	-0.05 ***	-0.07 ***	-0.04 ***	-0.01 ***	-0.02 ***
Within	0.582	0.569	0.599	0.506	0.507	0.885	0.538	0.568	0.511	0.587
Between	0.856	0.552	0.260	0.730	0.748	0.920	0.722	0.442	0.421	0.660
Overall	0.853	0.574	0.255	0.693	0.768	0.928	0.691	0.555	0.427	0.667
model	*fixed*	*fixed*	*fixed*	*random*	*random*	*fixed*	*random*	*random*	*random*	*random*
F-test	*reject*	*reject*				*reject*	*reject*			*reject*

Note: *, **, and *** indicate statistical significance at the 10%, 5%, and 1% levels, respectively.

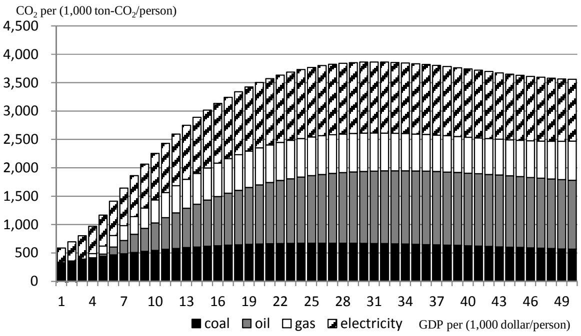
We use the F-test to evaluate hypotheses that coefficient of GDP3 equal to zero. “Reject” represents that coefficient of GDP3 does not equal to zero at the 95% confidence level.

Appendix 6. Result of panel analysis with sectoral CO_2 emission from electricity consumption

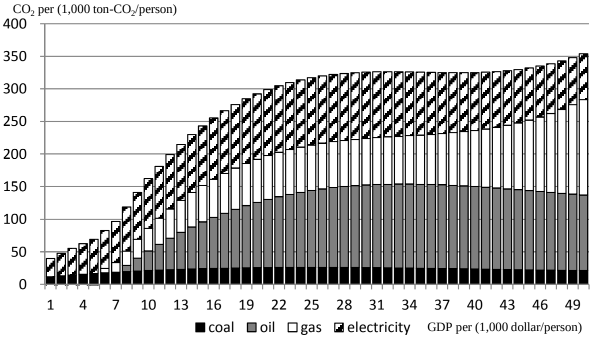
Quadratic model	Industry	Food	Wood	Chemical	Paper	Minerals	Steel	Machine	Transport	Construction
EE	38.69 ***	3.26 ***	0.62 ***	2.58 ***	2.68 ***	1.47 ***	3.84 ***	7.57 ***	1.74 ***	4.46 ***
SHARE_{GDP}	2.87 ***	0.12	0.87 ***	1.33 ***	6.39 ***	5.14 ***	2.15 ***	0.80 ***	1.09 ***	0.05 ***
GDPper	0.35 ***	0.03 ***	0.01 ***	0.02 **	0.06 ***	0.02	0.02 ***	0.04 ***	0.01 ***	0.00 ***
GDPper^2	-0.04 ***	-0.00 ***	-0.00 ***	-0.00 **	-0.01 ***	-0.00	-0.00 ***	-0.00 ***	-0.00 ***	-0.00 ***
Const.	-0.88 ***	0.02 *	-0.00	0.06 *	-0.17 ***	-0.08	-0.05 ***	-0.08 ***	-0.01 **	-0.00 *
Within	0.410	0.317	0.278	0.263	0.281	0.412	0.484	0.586	0.203	0.312
Between	0.093	0.021	0.285	0.103	0.672	0.302	0.154	0.215	0.476	0.285
Overall	0.157	0.095	0.325	0.155	0.630	0.332	0.249	0.322	0.407	0.207
model	*fixed*	*fixed*	*fixed*	*random*	*random*	*random*	*fixed*	*random*	*fixed*	*random*

Cubic model	Industry	Food	Wood	Chemical	Paper	Minerals	Steel	Machine	Transport	Construction
EE	38.58 ***	3.30 ***	0.62 ***	2.80 ***	2.68 ***	1.48 ***	3.88 ***	7.97 ***	1.76 ***	4.50 ***
SHARE_{GDP}	2.74 ***	0.16	0.94 ***	1.09 ***	6.44 ***	5.54 ***	2.12 ***	0.79 ***	1.06 ***	0.05 ***
GDPper	0.83 ***	0.07 ***	0.02 ***	0.16 ***	0.05 **	0.11 **	0.08 ***	0.13 ***	0.03 ***	0.01 ***
GDPper^2	-0.20 ***	-0.02 ***	-0.00 ***	-0.05 ***	-0.00	-0.03 **	-0.02 ***	-0.03 ***	-0.01 ***	-0.00 **
GDPper^3	0.01 ***	0.00 ***	0.00 ***	0.00 ***	-0.00	0.00 **	0.00 ***	0.00 ***	0.00 ***	0.00 *
Const.	-1.23 ***	-0.02	-0.01 **	-0.05	-0.16 ***	-0.14 **	-0.10 ***	-0.14 ***	-0.03 ***	-0.01 **
Within	0.429	0.437	0.290	0.297	0.281	0.416	0.498	0.626	0.229	0.315
Between	0.124	0.475	0.368	0.137	0.668	0.322	0.167	0.216	0.510	0.294
Overall	0.182	0.525	0.359	0.170	0.628	0.340	0.266	0.318	0.426	0.212
model	*random*	*fixed*	*random*	*random*	*random*	*random*	*random*	*fixed*	*fixed*	*random*
F-test	*reject*	*reject*	*reject*	*reject*		*reject*	*reject*	*reject*	*reject*	

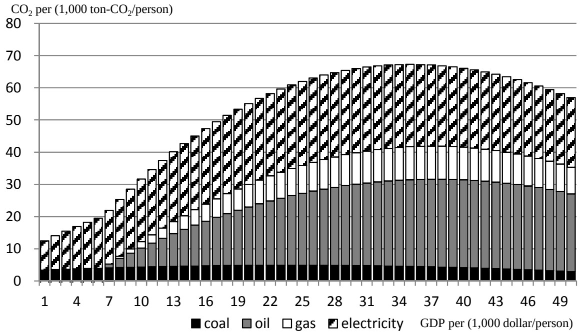
Note: *, **, and *** indicate statistical significance at the 10%, 5%, and 1% levels, respectively.
We use the F-test to evaluate hypotheses that coefficient of GDP3 equal to zero. “Reject” represents that coefficient of GDP3 does not equal to zero at the 95% confidence level.



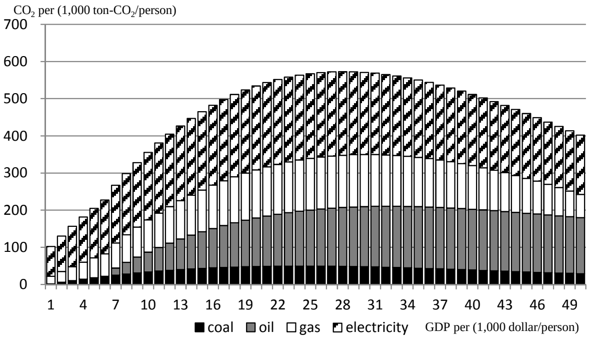
Appendix 7. Manufacturing industries and construction



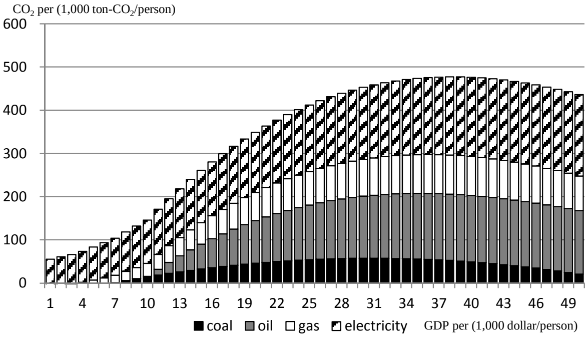
Appendix 8. Food and tabaco industry



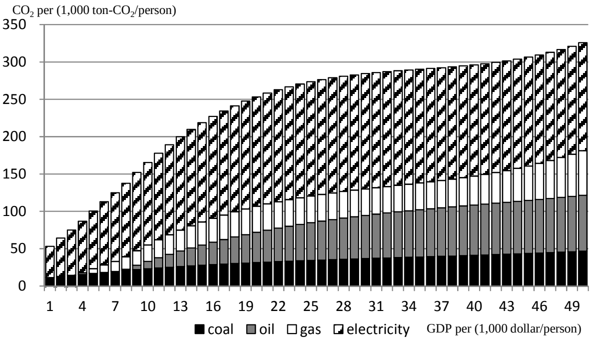
Appendix 9. Wood and wood products industry



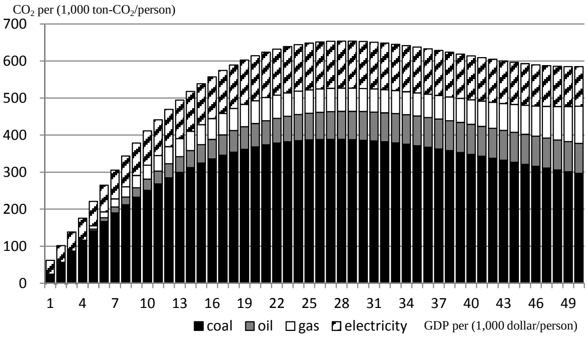
Appendix 10. Chemical industry



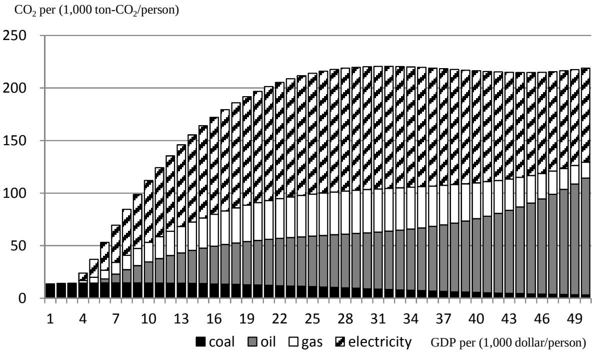
Appendix 11. Paper, pulp and printing industry



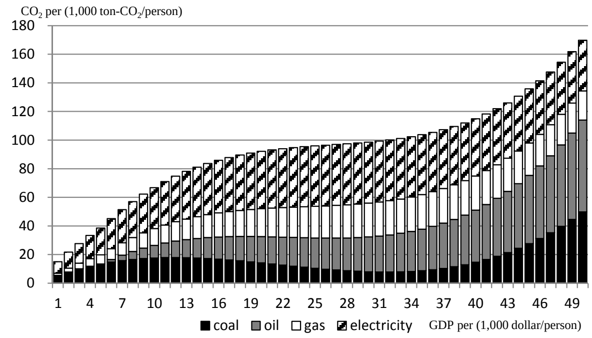
Appendix 12. Non-metallic minerals industry



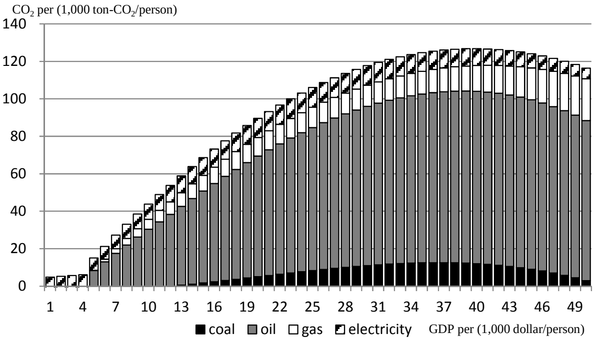
Appendix 13. Steel and metal industry



Appendix 14. Machinery industry



Appendix 15. Transport equipment industry



Appendix 16. Construction industry

Appendix17: Decomposition analysis methodology.

Here, the CO2 emission per capita from fuel type *i* in industry *j* is decomposed as equation (A1).

$$\mathrm{CO2per}_{ij} = \mathrm{CI}_{ij} \times \mathrm{SHARE}_{Eij} \times \mathrm{EI}_{j} \times \mathrm{SHARE}_{GDPj} \times \mathrm{SCALE} \tag{A1}$$

We consider the CO2 emission change from 1970 year ($\mathrm{CO2per}_{ij}^{1970}$) to 2005 year ($\mathrm{CO2per}_{ij}^{2005}$). By using equation (A1), growth ratio of CO$_2$ emission per capita can be represented as follows.

$$\frac{\mathrm{CO2per}_{ij}^{2005}}{\mathrm{CO2per}_{ij}^{1970}} = \frac{\mathrm{CI}_{ij}^{2005}}{\mathrm{CI}_{ij}^{1970}} \times \frac{\mathrm{SHARE}_{Eij}^{2005}}{\mathrm{SHARE}_{Eij}^{1970}} \times \frac{\mathrm{EI}_{j}^{2005}}{\mathrm{EI}_{j}^{1970}} \times \frac{\mathrm{SHARE}_{GDPj}^{2005}}{\mathrm{SHARE}_{GDPj}^{1970}} \times \frac{SCALE^{2005}}{SCALE^{1970}} \tag{A2}$$

We transform equation (A2) to natural logarithmic function, then equation (A3) is obtained[13].

$$\mathrm{lnCO2per}_{ij}^{2005} - \mathrm{lnCO2per}_{ij}^{1970} = \ln\left(\frac{\mathrm{CI}_{ij}^{2005}}{\mathrm{CI}_{ij}^{1970}}\right) + \ln\left(\frac{\mathrm{SHARE}_{Eij}^{2005}}{\mathrm{SHARE}_{Eij}^{1970}}\right) + \ln\left(\frac{\mathrm{EI}_{j}^{2005}}{\mathrm{EI}_{j}^{1970}}\right) + \ln\left(\frac{\mathrm{SHARE}_{GDPj}^{2005}}{\mathrm{SHARE}_{GDPj}^{1970}}\right) + \ln\left(\frac{SCALE^{2005}}{SCALE^{1970}}\right) \tag{A3}$$

Multiplying both sides of equation (A3) by $\omega_{ij} = (\mathrm{CO2per}_{ij}^{2005} - \mathrm{CO2per}_{ij}^{1970})/(\mathrm{lnCO2per}_{ij}^{2005} - \mathrm{lnCO2per}_{ij}^{1970})$, we have equation (A4) as follows[14].

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[13] If there is a case of zero value in the dataset, which cause problem in the formulation of the decomposition because of the properties of logarithmic function. In order to solve this problem, the literature on the LMDI suggests replacing the zero value by a small positive number (Ang and Liu, 2007).

[14] $\omega_i^t = 0$ if $\mathrm{E}_i^t = \mathrm{E}_i^{t-1}$

$$\mathrm{CO2per}_{ij}^{2005} - \mathrm{CO2per}_{ij}^{1970} = \triangle\mathrm{CO2per}_{ij}^{1970,2005}$$
$$= \omega_{ij}\ln\left(\frac{\mathrm{CI}_{ij}^{2005}}{\mathrm{CI}_{ij}^{1970}}\right) + \omega_{ij}\ln\left(\frac{\mathrm{SHARE}_{Eij}^{2005}}{\mathrm{SHARE}_{Eij}^{1970}}\right) + \omega_{ij}\ln\left(\frac{\mathrm{EI}_{j}^{2005}}{\mathrm{EI}_{j}^{1970}}\right) + \omega_{ij}\ln\left(\frac{\mathrm{SHARE}_{GDPj}^{2005}}{\mathrm{SHARE}_{GDPj}^{1970}}\right) + \omega_{ij}\ln\left(\frac{SCALE^{2005}}{SCALE^{1970}}\right) \tag{A4}$$

Therefore, changes in the CO_2 emission per capita from fuel i ($\triangle\mathrm{CO2per}_{ij}$) is decomposed of the changes in CI (first term), SHARE_E (second term), EI (third term), SHARE_{GDP} (fourth term,), and SCALE (fifth term). This decomposition technique of emission change factor is called logarithmic mean Divisia index (LMDI) developed by Ang et al. (1998). The term ω_i^t operates as additive weight estimated within LMDI framework. The LMDI approach has been applied to energy studies and toxic chemical pollution research (e.g. Fujii and Managi, forthcoming). Ang (2004) pointed out that the LMDI is the preferred method for decomposition analysis because of its theoretical foundation, adaptability, ease of use and result interpretation, and the lack of a residual term, which is generated by Laspeyres-type methodology.

Reference:

Ang, B. W., F. Q. Zhang, and K. H. Choi. 1998. Factorizing changes in energy and environmental indicators through decomposition. *Energy* 23(6): 489–495.

Ang, B. W. and N. Liu. 2007. Handling zero values in the logarithmic mean Divisia index decomposition approach. *Energy Policy* 35(1): 238–246.

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Fujii, H., Managi, S., forthcoming. Decomposition of toxic chemical substance management in three U.S. manufacturing sectors from 1991 to 2008. Journal of Industrial Ecology.

Stern, D.I., 2004. The rise and fall of the environmental Kuznets curve. World Development 32(8), 1419-1439.