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Anthropogenic Drivers of Carbon Emissions: Scale and Counteracting Effects

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Abstract This paper assesses the achievement and the limitation of our path to the stabilization of anthropogenic carbon emissions with economic growth using a stochastic Kaya model. The elasticity of carbon dioxide emissions with respect to anthropogenic drivers such as population, affluence, energy efficiency, fossil-fuel dependence, and emission factor is estimated using panel data of 132 countries from 1960 to 2010. Then the stochastic Kaya model is used for index decomposition analysis. Investigating the scale and the counteracting effects, I find that except a few countries like Germany, most countries have not achieved the goal of carbon reductions with economic growth. In addition, the current path of each nation does not guarantee the achievement of a global long-term goal of emissions reductions, say 50% by 2050 compared to the 1990 level. This is because the scale effect (the sum of the population and affluence effects) is so large that the current level of the technology effects can rarely offset carbon emissions. Should we achieve the global target for carbon reductions a significant amount of technology effects through stringent policy interventions need to be accompanied.

1. Introduction

Two decades have passed since the advent of the United Nations Framework Convention on Climate Change (UNFCCC), which initiated the international climate-policy regime. Are we approaching "the stabilization of greenhouse gas concentrations in the atmosphere" in a manner to "enable economic development" (UNFCCC, 1992: Article 2: Objective)?[1] Among others we here focus on the changes of anthropogenic carbon emissions.[2]

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[1] Broadly speaking, this objective can be rephrased as "sustainable development" or "ecological modernization". For more discussion on the notions see Brutland (1987), Hajer (1995), Langhelle (2000), Mol and Sonnenfeld (2000) and Jänicke (2008), among others.

[2] The reasons are that 1) anthropogenic CO_2 is the most important greenhouse gas in terms of its magnitude of emissions (Canadell et al., 2007; Solomon et al., 2007; Le Quéré et al., 2009) and that 2) data for CO_2 emissions

One thing to note for such an evaluation is that looking at the changes of carbon emissions between two periods of interest alone may mislead policy implications. The reason is that there are so many drivers of carbon emissions that they cannot be represented in just one dimension like the change of emissions.[3] For instance, carbon reductions of the Economies in Transition (EIT) during the early 1990s and those of member countries of the Organization for Economic Cooperation and Development (OECD) during the recent financial crisis are never the signs that show the current path is sustainable. During such economic recessions, carbon emissions decrease even without technological improvements (e.g., improvements in energy efficiency or the propagation of renewable energy) or behavioral changes (e.g., consuming less carbon intensive materials) because economic downturn itself reduces the demand for energy. Furthermore, this is not what we hope for - or UNFCCC aims for - when we say "the stabilization of GHG emissions" along with "economic development".

The IPAT identity (Commoner et al., 1971; Ehrlich and Holdren, 1971) and its variants such as the Kaya identity (Kaya, 1990), the I=PBAT identity (Schulze, 2002) and the ImPACT identity (Waggoner and Ausubel, 2002) have been widely used for analyzing anthropogenic drivers of environmental impacts since the early 1970s (Chertow, 2001; Rosa and Dietz, 2012). Such methods assume that the relation between an environmental impact and its driving forces can be represented as a mathematical identity. For instance, the IPAT identity defines that human impacts are equivalent to the product of population, affluence and technology.

Beside its simplicity, the IPAT and its variants have an advantage that the acquisition of data is less demanding. For instance, indicators for an IPAT analysis such as population, affluence (e.g., gross world output), and environmental impacts (e.g. pollutants) have been developed by each country or by some international organizations (e.g., United Nations, World Bank, International Energy Agency) and they are usually open for research purposes. As a result we can find a huge number of applications of the IPAT and its variants.[4] The index decomposition analysis (IDA) in energy literature is one of such examples (Ang and Zhang, 2000; Ang and Zhou, 2010).[5] The changes of environmental impacts such as carbon

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are relatively well documented compared to the other greenhouse gases such as methane, nitrous oxide and F-gases and that 3) anthropogenic CO_2 emissions are directly related to economic activities (e.g., energy use) and thus they are better suited for the purpose of the current paper and that 4) anthropogenic CO_2 emissions are less uncertain than the other gases (Penman et al., 2000).

[3] For a comprehensive review on various kinds of driving forces of carbon emissions see Rosa and Dietz (2012).

[4] Main areas of applications are industrial ecology and energy economics. Some examples of international comparisons on carbon emissions are Dietz and Rosa (1997), Hoffert et al. (1998), Greening et al. (1998), Shi (2003), Bacon and Bhattacharya (2007), Raupach et al. (2007), Agnolucci et al. (2009), Jorgenson and Clark (2010) and Jotzo et al. (2012).

[5] Ang and Zhang (2000) reported that there were over a hundred of papers applying IDA in energy literature.

emissions between two periods of interest can be quantitatively attributed to each driving force from IDA.[6]

One of the critics on IPAT and its variants is that statistical tests are not available for them because they use a mathematical identity (York et al., 2003). In addition, IPAT and its variants assume the unit elasticity of environmental impacts with respect to each driving force, which is not supported by empirical data (Rosa and Dietz, 2012). Accounting for these drawbacks Dietz and Rosa (1994) developed a stochastic IPAT model, namely the Stochastic Impacts by Regression on Population, Affluence and Technology (STIRPAT). The STIRPAT model includes an error term and the elasticity of an environmental impact with respect to each driving force is estimated from empirical data.

The current paper extends STIRPAT by constructing a stochastic Kaya model, whereas STIRPAT uses IPAT. In addition, I apply IDA derived from the stochastic Kaya model, whereas the existing literature use IDA derived from (deterministic) IPAT or its variants. For the calibration of the model I use panel data for all countries of the world where data are available. In specific, I use data including population, gross domestic output, the total primary energy, fossil-fuel dependence and CO_2 emissions from energy use and cement manufacturing for 132 countries from 1960 to 2010.

From the model and IDA, this paper investigates how each country has offset or increased its CO_2 emissions and then projects future CO_2 emissions to 2050. The main findings of the this paper are that 1) except a few countries like Germany, most countries have not achieved the goal of CO_2 reductions with economic growth and that 2) the current path of each nation does not guarantee the achievement of a global long-term goal of carbon reductions, say 50% by 2050 compared to the 1990 level (van Vuuren, 2012).[7] This is because the scale effect (the sum of population and affluence effects) is so large that the current level of the technology effects can rarely offset carbon emissions. Should we achieve the global target for carbon reductions, a significant amount of the technology effects through stringent policy interventions need to be accompanied.

The current paper proceeds as follows. Section 2 presents the stochastic Kaya model and the IDA equations. Section 3 illustrates the panel data used in this paper and the results for statistical tests. The results of IDA are discussed in Section 4. The scenario analysis for future

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[6] The structural decomposition analysis (SDA) is another stream of research on quantifying driving forces of human impacts. See Hoekstra and van den Bergh (2003) for a comparison of the two methods in detail.

[7] The exact amount of reductions and the due time are not yet made as the global target, although the consensus that 50% or more reductions by 2050 are inevitable if we hope to avoid climate catastrophe is growing. A global goal expressed as an emissions level (e.g., Kyoto target) is subject to critics, however. Since greenhouse gas (GHG) has a stock effect (note that the half-life of each GHG is well beyond hundreds of years) (Solomon et al., 2007), the goal should account for a time-path of emissions. An alternative is a goal for temperature increases.

emissions is presented in Section 5. Section 6 concludes.

2. Model and Methods

2.1. Stochastic Kaya Model

A stochastic modification of the Kaya identity is as follows. Compared to the Kaya model, the carbon intensity effect is further decomposed into the effect of fossil-fuel dependence and the effect of emission factor, following Bacon and Bhattacharya (2007).[8] In addition, an error term is added and the elasticity of each driving force needs not to be unity.

$$\begin{aligned} CO_{2,i,t} &= \alpha P_{i,t}^{\beta_P} G_{i,t}^{\beta_A} T_{i,t}^{\beta_T} F_{i,t}^{\beta_F} C_{i,t}^{\beta_C} \varepsilon_{i,t} \\ &= \alpha\left(POP_{i,t}\right)^{\beta_P} \left(\frac{GDP_{i,t}}{POP_{i,t}}\right)^{\beta_G} \left(\frac{TPE_{i,t}}{GDP_{i,t}}\right)^{\beta_T} \left(\frac{FF_{i,t}}{TPE_{i,t}}\right)^{\beta_F} \left(\frac{CO_{2,i,t}}{FF_{i,t}}\right)^{\beta_C} \varepsilon_{i,t} \end{aligned} \tag{1}$$

where i and t denote country and time period, P, G, T, F and C are population, per capita GDP, energy intensity, fossil-fuel dependence and the total emission factor,[9] respectively, CO_2, POP, GDP, TPE and FF are CO_2 emissions, population, gross domestic product, the total primary energy and fossil fuel, respectively, α is a constant, β is the elasticity of CO_2 emissions with respect to each driving force, and ε is the error term. See Waggoner and Ausubel (2002) and Bacon and Bhattacharya (2007) for more discussions on each driving force and its policy implications.

Taking natural logarithm on each side of Equation (1):

$$ln\left(CO_{2,t}\right) = \beta_0 + \beta_P ln(P_t) + \beta_G ln(G_t) + \beta_T ln(T_t) + \beta_F ln(F_t) + u_t \tag{2}$$

where $\beta_0 = ln(\alpha)$ and u is the residual. Note that we drop i for simplicity and the term for emission factor is included in the residual term for statistical tests (York et al., 2003).[10]

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[8] The original Kaya model decomposes carbon emissions into population, affluence, energy intensity (the reciprocal of energy efficiency), and carbon intensity.

[9] Note that the total emission factor is different from an emission factor of a certain fossil fuel. Mathematically it is calculated as $C_{i,t} = CO_{2,i,t}/FF_{i,t} = \left(\sum_j FF_{i,t,j}\, C_{i,j,t}\right)/\sum_j FF_{i,t,j}$, where j is each fossil fuel (e.g., coal, oil, natural gas). Therefore, the effect of fuel mix is reflected in the emission-factor effect in Equation (1).

[10] Although there are independent data for the emission factor of each fossil fuel (Eggleston et al., 2006), it is not easy to calculate the total emission factor (see endnote 9). This is because the disaggregated data for energy

Following the convention of IPAT literature, the residual term captures all remaining factors not included in Equation (2).

For scenario analysis in Section 5, the residual is further decomposed into the emission-factor effect and remaining errors using the following model.

$$u_t = \beta_{0,r} + \beta_C ln(C_t) + v_t \tag{3}$$

where $\beta_{0,r}$ is a constant and v is the remaining error.

2.2. IDA Equations

For the derivation of equations for IDA, I follow the method of logarithmic mean Divisia index (LMDI) decomposition. For the method in detail and comparisons with other methods, see Ang (2004, 2005) and Ang et al. (2009). Whereas the usual LMDI derives the IDA equations from a mathematical identity such as IPAT, I here derive the equations from the stochastic model (2).

Since Equation (2) holds for each time period, the difference between equations for t_1 and t_2 reads:

$$ln\left(\frac{CO_{2,t_2}}{CO_{2,t_1}}\right) = \beta_P ln\left(\frac{P_{t_2}}{P_{t_1}}\right) + \beta_G ln\left(\frac{G_{t_2}}{G_{t_1}}\right) + \beta_T ln\left(\frac{T_{t_2}}{T_{t_1}}\right) + \beta_F ln\left(\frac{F_{t_2}}{F_{t_1}}\right) + R_1 \tag{4}$$

where t_1 and t_2 are time periods of interest, respectively, and $R_1 = u_{t_2} - u_{t_1}$.

Multiplying $A_{t_1,t_2} \equiv (CO_{2,t_2} - CO_{2,t_1})/ln(CO_{2,t_2}/CO_{2,t_1})$ to the both side of Equation (4), the change of CO_2 emissions between the two periods is decomposed into each driving force as follows.

$$CO_{2,t_2} - CO_{2,t_1} = P_{eff} + G_{eff} + T_{eff} + F_{eff} + R_2 \tag{5}$$

where $P_{eff} = A_{t_1,t_2}\beta_P ln(P_{t_2}/P_{t_1})$, $G_{eff} = A_{t_1,t_2}\beta_G ln(G_{t_2}/G_{t_1})$, $T_{eff} = A_{t_1,t_2}\beta_T ln(T_{t_2}/T_{t_1})$ and

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use (on each fuel basis: e.g., gasoline, diesel etc.) are not easily accessible. Thus it is beyond the scope of this paper to include independent data for the total emission factor.

$F_{eff} = A_{t_1,t_2}\beta_T ln(T_{t_2}/T_{t_1})$ refer to the effects of population, affluence, energy-efficiency and fossil-fuel dependence, respectively on CO_2 emissions, and $R_2 = A_{t_1,t_2}R_1$.

Substituting Equation (3) into Equation (2) and following the same procedure leads to:

$$CO_{2,t_2} = CO_{2,t_1} + P_{eff} + G_{eff} + T_{eff} + F_{eff} + C_{eff} + R_3 \tag{6}$$

where $C_{eff} = A_{t_1,t_2}\beta_C ln(C_{t_2}/C_{t_1})$ is the effect of emission factor on CO_2 emissions and R_3 is the residual.

3. Calibration

3.1. Data

For estimating the elasticity of each driving force, the data on population, GDP (PPP, 2005 constant US$), the total primary energy, fossil-fuel dependence (%) and CO_2 emissions of each country are collected from the world development indicator (WDI) dataset of the World Bank.[11] The dataset covers all countries of the world from 1960 to 2011. The number of countries that have all the above-mentioned data are 132 and the total number of observations for each variable (e.g., population) is 4,416, which is less than 6,732 (=132 countries × 51 years) because the data-availability is different from country to country. The WDI data for population and energy use are based on national statistics, the estimates of the United Nations Population Division, and the estimates of the international energy agency (IEA), respectively. Carbon dioxide data of the WDI dataset include emissions from energy consumption and cement manufacturing.[12]

3.2. The Elasticity of CO_2 Emissions

Since this paper uses panel data, the ordinary least square (OLS) regression applied to Equation (2) may be subject to statistical problems such as serial correlation or multi-collinearity (Davidson and MacKinnon, 2009). Thus I apply Equation (4) for OLS to estimate the elasticity of CO_2 emissions with respect to each driving force. Equation (4) compares the

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[11] Data can be downloaded at http://data.worldbank.org/data-catalog/world-development-indicators (The World Development Indicators 2013).

[12] Note that the dataset provides production-based CO_2 emissions. For the consumption-based calculations see Davis and Caldeira (2010).

differences of the variables between two time periods of interest of the same country. Therefore some possible fixed effects of each country and some possible lagged effects of the time series are less severe for Equation (4) than for the static model of Equation (2).[13] The similar method (the first-difference model) is used by Jorgenson and Clark (2010). As Table 1 illustrates, this method performs well. Serial correlation (see Durbin-Watson statistics) and multi-collinearity (see VIF statistics) are not serious problems for the model and all the coefficients are statistically significant (see p-value).[14]

Table 1 The results for model (4)

	β	Standard error	VIF
(Constant)	$-.00637^{**}$	.00186	
Population	1.030^{***}	.017	1.372
per capita GDP	1.049^{***}	.020	2.274
Energy intensity	$.670^{***}$	.020	1.507
Fossil-fuel dependence	$.575^{***}$	.024	1.438

Note: ** p-value < .05, *** p-value < .001, Number of observations: 4,416, adjusted R^2: .617, Durbin-Watson: 2.346

As Table 1 shows, a 1% increase in population, per capita GDP, energy intensity and fossil-fuel dependence results in 1.03%, 1.05%, 0.67% and 0.58% increase in CO_2 emissions, respectively. These results are generally consistent with the estimates of the literature (Rosa and Dietz, 2012).[15]

Table 2 is the results for Equation (3). It illustrates that statistical problems do not pose a significant problem to the model and the coefficient is statistically significant. A 1% increase

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[13] Of course the data for initial year are lost when Equation (4) is applied instead of Equation (2).

[14] From residual plots and some test statistics (Wooldridge, 2002), it is also found that heteroskedasticity is not a significant problem to the model (results not shown).

[15] These results are comparable to the estimates of the literature. Since the existing literature applies different specifications to their models, I only present the results comparable to the model of this paper below. York et al. (2003), with cross-sectional data for 146 countries in 1996, estimated that the elasticity of CO_2 emissions with respect to population is 1.019. Brizga et al. (2013) performed regression for the time period of 1990-2010 for the 15 former Soviet Union countries. Their estimates for population and affluence are 1.003 and 0.864, respectively. The estimates of Jorgenson and Clark (2010) for population and affluence are 1.43 and 0.65, respectively. They used the data for the time period of 1960-2005 for 86 countries.

in emission factor results in 0.875% increase in CO_2 emissions.[16]

Table 2 The results for model (3)

	β	Standard error	VIF
(Constant)	.00296***	.00063	
Emission factor	.875***	.005	1.000

Note: *** p-value < .001, Number of observations: 4,416, and the adjusted R^2: .874, Durbin-Watson: 2.114

4. Driving Forces of CO_2 Emissions

4.1. CO_2 Emissions

This section focuses on the changes of emissions from 1990 since it is the basis year for the current international climate-policy regime. To this end the UNFCCC dataset (in specific, energy related CO_2 emissions) is used for UNFCCC-Annex 1 countries, while the WDI dataset is used for non-Annex 1 countries.[17] This is because, for the periods of interest, CO_2 emissions data of WDI are not complete for Annex 1 countries. For instance, the emissions data for Germany are reported from 1991 in the WDI dataset. Many EIT countries have the similar problem. The UNFCCC dataset, however, covers complete emissions data for Annex 1 countries from 1990, but the data for non-Annex1 countries are rare (if any, sporadic) since it is based on a national inventory report (NIR) of each party.[18] The results of this paper, however, do not change much even if we use the WDI dataset for Annex 1 countries (results not shown).

Table 3 shows CO_2 emissions of major countries and groups. Since we have data for over a hundred of countries I should select some of them for presentation. The selection is arbitrary but it includes major CO_2 emitters. The Kyoto target of each country is also presented in the last column for comparison. Although the Kyoto target is about the aggregate greenhouse gas (GHG) emissions, it can be served as a proxy for a measure on how each country approaches the target.

CO_2 emissions of Germany, UK, France and Italy in 2010 were less than their own levels

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[16] Note that emission factor discussed in this paper can be changed according to the fuel mix of any country. For instance change from coal to natural gas decreases the emission factor.

[17] Data can be downloaded at http://unfccc.int/di/DetailedByParty.do (Greenhouse Gas Inventory Data).

[18] Note that the obligation of NIR-submission applies only to Annex 1 parties.

in 1990. In addition, the amount of their reductions exceeded the Kyoto target, except Italy.[19] As a group the European Union (EU) and the UNFCCC Annex 1 (but only Annex 1-EIT) emit less CO_2 in 2010 than in 1990. The other countries and groups presented in Table 3 increased their levels of CO_2 emissions in 2010 compared to those in 1990. Especially CO_2 emissions of South Korea and emerging markets including China, Brazil and India doubled or more during the past two decades. In a global scale, annual CO_2 emissions increased by 51% from 1990.

Table 3 CO_2 emissions

Country/ Group	CO_2 emission (1990)		CO_2 emission (2010)		Change of emissions (1990-2010)		Kyoto target
	$MtCO_2$	% World emissions	$MtCO_2$	% World emissions	$MtCO_2$	% 1990 emissions	% 1990 emissions
France	371	1.7	370	1.1	-1	-0.4	0.0
Germany	979	4.4	772	2.3	-207	-21.2	-21.0
Italy	404	1.8	404	1.2	-1	-0.1	-6.5
Spain	206	0.9	261	0.8	56	27.0	15.0
UK	573	2.6	493	1.5	-80	-14.0	-12.5
EU	4,109	18.5	3,655	10.9	-454	-11.1	-8.0
Australia	260	1.2	385	1.1	125	48.3	8.0
Canada	425	1.9	511	1.5	85	20.0	-6.0
Japan	1,068	4.8	1,137	3.4	69	6.4	-6.0
US	4,912	22.1	5,586	16.6	674	13.7	n.a.
Annex1	14,054	63.2	13,440	40.0	-614	-4.4	-5.2
Annex1-EIT	3,999	18.0	2,431	7.2	-1,567	-39.2	n.a.
Annex1-nonEIT	10,055	45.2	11,009	32.7	953	9.5	n.a.
Mexico	314	1.4	444	1.3	129	41.1	n.a.
South Korea	247	1.1	568	1.7	321	129.8	n.a.
OECD	11,282	50.8	12,592	37.5	1,309	11.6	n.a.
Brazil	209	0.9	420	1.2	211	100.9	n.a.
China	2,461	11.1	8,287	24.7	5,826	236.8	n.a.
India	691	3.1	2,009	6.0	1,318	190.9	n.a.
World	22,223	100.0	33,615	100.0	11,393	51.3	n.a.

Note: The shaded cells highlight countries or groups where their CO_2 emissions were reduced during the past two decades. n.a.: not applicable.

4.2. Driving Forces of CO_2 Emissions

IDA gives quantitative information about the effect of each driving force on the changes of CO_2 emissions between the time periods of interest. The driving forces of CO_2 emissions between 1990 and 2010 are presented in Table A1 of Appendix A. The results like Table A1

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[19] Strictly speaking, the Kyoto target should be met for the first commitment period (2010-2012).

of Appendix A for the other time periods are obtained but I here present only the results for 2010 for the purpose of illustration. As Table A1 of Appendix A shows, the main drivers of CO_2 emissions for almost all countries were the affluence effect and the population effect, whereas energy efficiency, fossil-fuel dependence and others (mainly, emission factor) played a role in (partially) offsetting CO_2 emissions. The relative magnitude of each driving force was different from country to country.

The results in Table 3 and Table A1 are sensitive to the choice of the time period. Thus the results themselves may mislead policy implications. For instance, from Table 3 and Table A1 Annex1-EIT countries seem to have performed well in terms of CO_2 reductions. However, is it consistent with the objective of UNFCCC (see Section 1)? In order to answer the question we need a chained decomposition analysis, a series of decomposition analyses applying time-series data (Ang and Zhou, 2010).

4.3. The Scale and Technology Effects

Instead of investigating the results case by case in detail, I will focus on the aggregate effect - the scale and the counteracting (or technology) effects - for the purpose of this paper.[20] The scale effect is the sum of the population and affluence effects and the technology effect is the sum of the energy efficiency, fossil-fuel dependence and other effects. The ratio of the technology effect to the scale effect is defined as the offsetting ratio, following Bacon and Bhattacharya (2007). Therefore the offsetting ratio above 100% means that CO_2 emissions from the scale effect were fully offset by the technology effect.

Figure 1 is the results for all countries where data are available.[21] It shows how the scale and technology effects evolve over time for all countries where all the required data are available. Before going on the details, the way of interpretation for the figure is worth mentioning. The positive (negative, respectively) scale effect means that the economy has grown economically (undergone economic recession, resp.) and thus scale played a role in increasing (reducing, resp.) emissions. On the other hand, the positive (negative, respectively) technology effect implies that abatement-related technology has deteriorated (improved, resp.) and thus technology played a role in increasing (reducing, resp.) emissions. The point below (above, respectively) the diagonal implies that the economy has fully (partly, resp.) offset the scale effect. If a country achieved the objective of UNFCCC illustrated in Section 1, the

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[20] As I noted, it is hard to enumerate all the literature investigating the driving forces of carbon emissions. Among the recent papers are Mahony et al. (2012), Brizga et al. (2013) and Rafaj et al. (2013). Interested readers are referred to references therein.

[21] The number of countries analyzed is 111. It is less than the one in Section 3 since some countries having incomplete data for 1990-2010 are dropped.

country would be located in the 2nd quadrant and below the diagonal in the figure. Finally, if the magnitude of the scale (or technology) effect is higher in a country than in the other, the point of the country with a higher effect is located far away from the origin.

As Figure 1 shows, most countries did not achieve the goal of the stabilization of CO_2 emissions with economic development during the past two decades. Moreover many countries have deteriorated CO_2 technology. This may include one (or some) of the followings: decreasing energy-efficiency, increasing dependence on fossil fuels, more use of CO_2 intensive fuels (e.g., coal) than others (e.g., natural gas). Some countries underwent economic recession especially during the early 1990s. This pulled down the points of the countries below the diagonal but this is never what we hoped for.

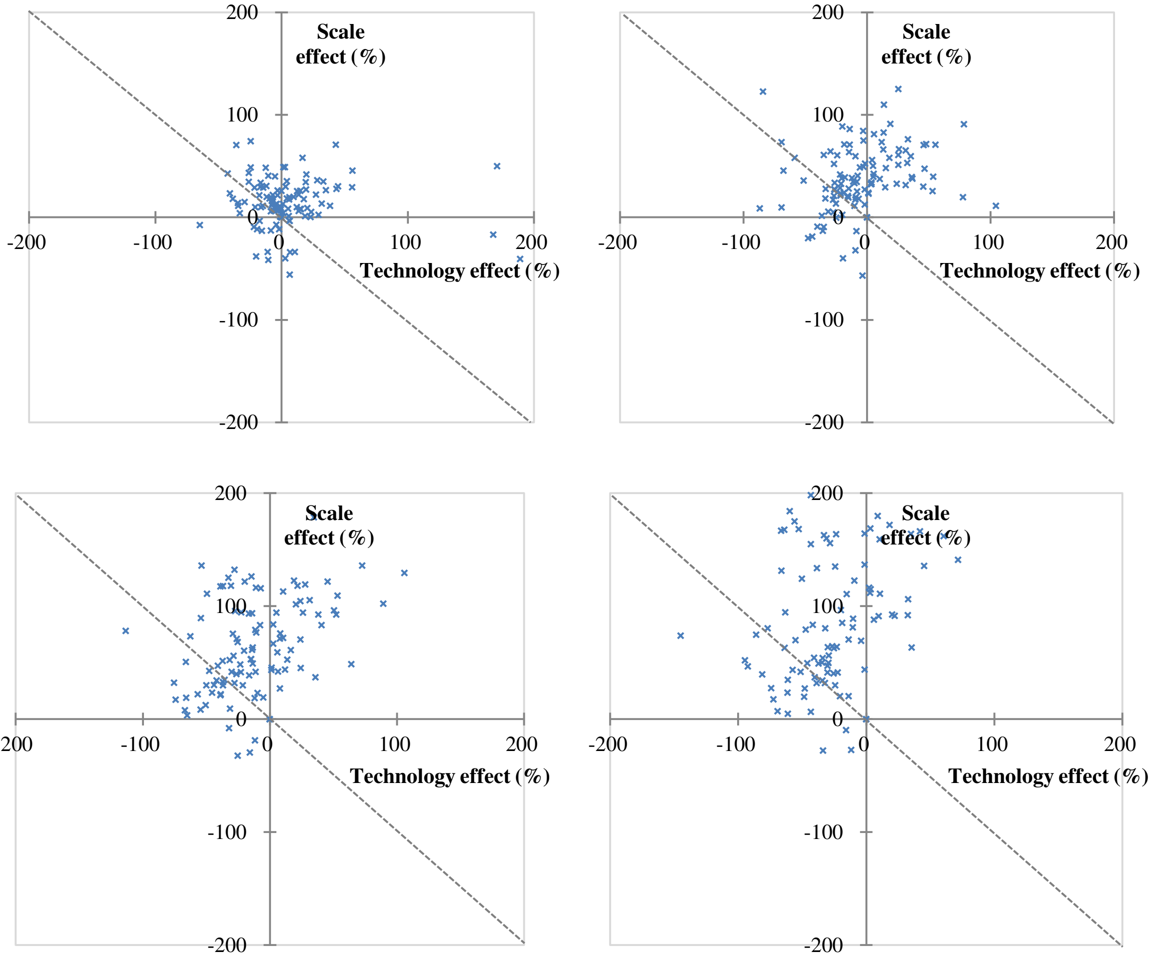

Figure 1 IDA Results. (Top left panel): 1990-1995. **(Top right panel):** 1990-2000. **(Bottom left panel):** 1990-2005. **(Bottom right panel):** 1990-2010.

In order to get more insight I present the results for some major economies and groups. Figure 2 shows the results. The top left panel is the results for some non-EIT European Union countries. Germany and the UK have followed good paths relative to the other countries in terms of the stabilization of CO_2 emissions with economic development. Note that the farther the point is away from the diagonal (to the first quadrant), the more the country emitted in total. By the symmetry, this sentence holds if we replace the terms "first quadrant" and "higher" to the terms "3rd quadrant" and "less". The recent global economic recession led the path of each nation in the top left panel in Figure 2 to lower-left parts of the figure, which means that emissions are reduced. This is one of the main reasons why Italy and France have reduced their emissions in 2010 below the level in 1990.

The top right panel is the results for some non-EU OECD member states. The US, Japan, Australia and Canada show a similar pattern, although the magnitude is different from country to country. Technological improvements have partially offset the scale effect but they were not enough to achieve their national goals. The scale effect was great in South Korea but the technology effect further increased CO_2 emissions during 1990s unlike the other nations.

The bottom left panel is the results for Russia, emerging markets including China, India and Brazil and least developed countries (LDC) as a group following UN classification. Russia suffered from economic downturn in early 1990s and the emissions-reduction during the period constitutes almost all reductions that Russia has achieved for the past two decades. Since then emissions have increased steadily. Brazil and LDC deteriorated technology and these further increased CO_2 emissions. Although there was a progress in CO_2 technology in China and India, the technology effects were not enough for offsetting the huge scale effects. Even worse is the recent trend of China: decreasing rate of technological improvements since 2000. Considering its magnitude in CO_2 emissions, the Chinese path is one of the main contributors to the global trend in CO_2 emissions.

The bottom right panel shows the results for the world total, EU, Annex 1, EIT Annex 1, non-EIT Annex 1 and OECD. As a group EU has followed a path of almost offsetting the scale effect by technology. Annex 1 has undergone the similar path, but this is almost due to EIT Annex 1 during early 1990s. Non-EIT Annex 1 steadily increased CO_2 emissions except the period of current recession. The path of OECD was similar to non-EIT Annex 1. The global situation became worse since 2000 as China did. The counteracting effect of technology has reduced since the early 2000s.

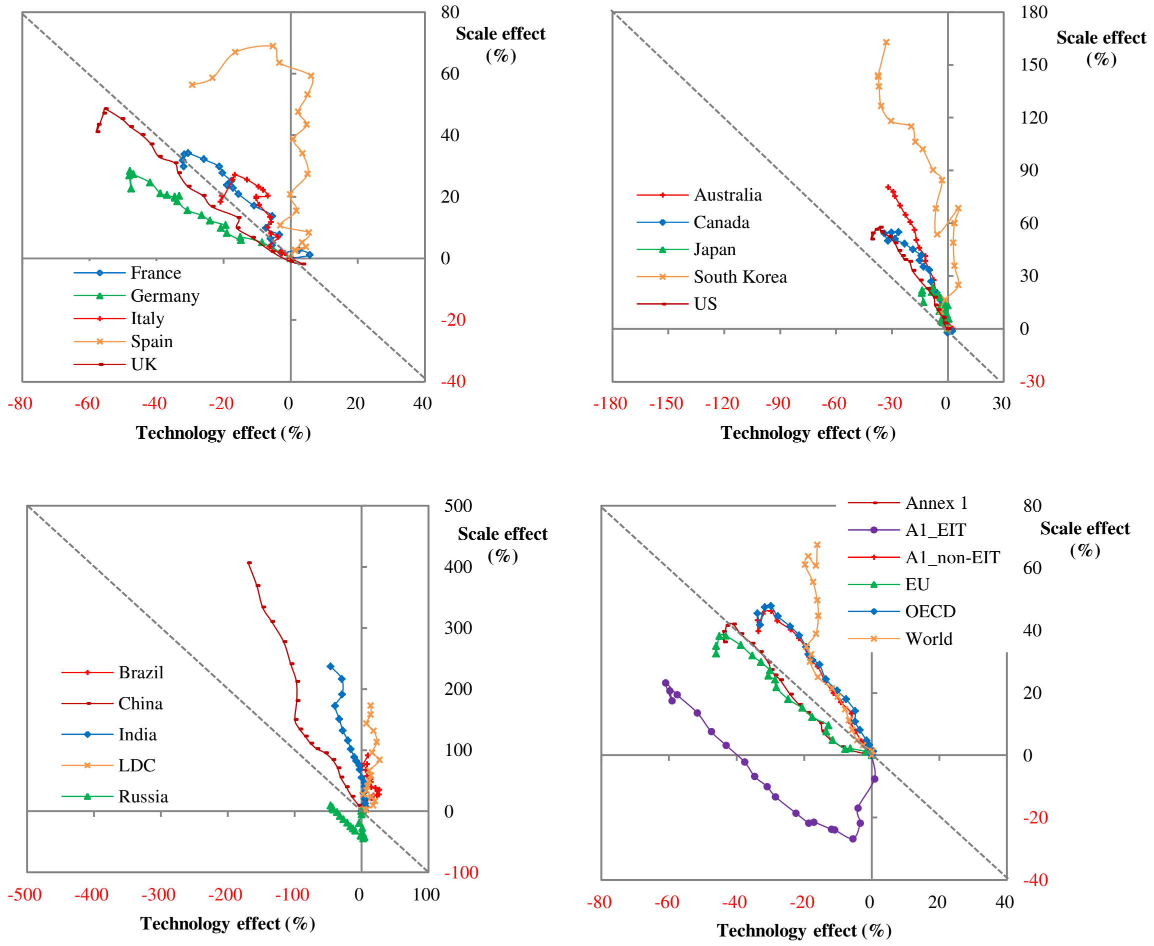

Figure 2 Chained IDA results for selected countries: 1990-2010. (Top left panel): non-EIT European countries. **(Top right panel):** non-EU OECD members. **(Bottom left panel):** Emerging economies, Russia and LDC (least developed countries: UN classification). **(Bottom right panel):** Group.

5. Future CO_2 emissions prospects

In this section I project the future global CO_2 emissions. To this end Equation (6) is applied with the coefficients in Section 3. For the world population prospects the no-change scenario of the United Nations Population Division is used.[22] The growth rate of per capita GDP is assumed to be 2%/yr for a reference scenario.

For technology prospects the trend of each indicator in Equation (6) from 1960 to 2010 is investigated (see Figure A1 in Appendix A). There is a tendency to decrease in energy

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[22] For the scenario the global population will be about 10,210 billion in 2050. The data can be downloaded at http://www.un.org/en/development/desa/population/publications/index.shtml (The World Population Prospects: The 2012 Revision).

intensity and fossil-fuel dependence over time (except China: increasing fossil-fuel dependence). The trend of emission factor is not as transparent as the other two indicators, but we can observe that emission factor has slightly increased after the early 2000s. One of the reasons is the transition of fuels from oil to coal on account of high prices of oil. It is also found that the technology indicators of the world total have not reached (although it becomes close to) the 1970 level of EU for the past 40 years. A simple thought says that if the world total indicators follow the historical EU path from now on with the same speed, the global indicators in 2050 (another 40 years ahead from now) would not be better than the current EU level (in 2010).[23] This constitutes a reference scenario for CO_2 technology prospects. Based on various levels of technological improvements, I formulate more scenarios. For instance, the 'EU2010×0.5' scenario refers to the case where each technology indicator in Equation (6) decreases to 50% of 2010 EU level by 2050. Note that decreasing indicator means technological improvement (see Equation (1)).

This construction of scenarios, especially high technological improvements scenarios, may not be realistic because each technology indicator has an upper bound for improvements. For instance, there is a lower bound for emission factor because this effect refers to substitution between fossil fuels. Even if we substitute coal for natural gas perfectly, the total emission factor cannot be less than the one of natural gas (see endnote 9). The fossil-fuel dependence effect also has a lower bound since the propagation of renewables is constrained by natural environments. However I do not refine the scenarios further. This is because 1) this paper does not aim for robust CO_2 projections, and 2) if the main points of this paper (i.e., the current path and its extension to the future do not guarantee the achievement of our goal) hold under the above scenarios, the fact that there may be a limit for technological improvements supports the points further.

Figure 3 shows the global CO_2 emissions trajectory according to each scenario.[24] Since the reference scenarios for population and affluence are used (the rate of economic growth: 2%/yr, population: about 10.2 billion in 2050), the differences between projected values are originated from technological improvements scenarios. Following the reference scenario of technological improvements (labelled as 'EU2010': approaching the current EU level by 2050), the global CO_2 emissions will increase more than 250% by 2050 relative to the 1990

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[23] Taken at face value, this observation can be rephrased as a statement that there is about 40 years of technology gap.

[24] According to the scenario there is a target for technology improvement in 2050 and we have the current level of technology indicators. For simplicity, I assume a linear trend for the future technology improvements between 2010 and 2050.

level. This shows that such technological improvements are not enough for offsetting the scale effect. If we aim for decreasing CO_2 emissions by 50% by 2050, we need to improve each technology indicator by more than 50% relative to the current EU level (labelled as 'EU2010*0.5'). Note that this number is not about the level of technological frontiers such as Germany or Japan but about the world-averaged level.

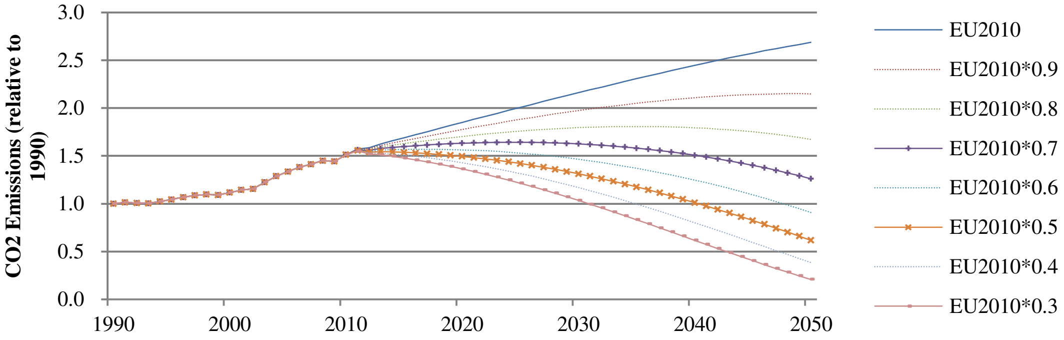

Figure 3 Global CO_2 emissions trajectory: 1990-2050. EU2010 refers to the reference scenario where the world average technology in 2050 reaches the level of EU in 2010. EU2010*x refer to the scenario where the world average technology in 2050 reaches the level of EU times x in 2010. The growth rate of per capita GDP is assumed to be 2%/yr.

CO_2 emissions trajectory is sensitive to the assumed scale effect. For instance if the growth rate of per capita GDP is assumed to be 1%/yr (3%/yr, respectively), with the reference scenarios on population and technological improvements, the global CO_2 emissions will be less than double (almost quadruple, resp.) with respect to the 1990 level (see the top panel in Figure 4).

Even if the emissions-reduction target is the same and it is achieved, the cumulative emissions are sensitive to the speed of technological improvements. For instance, a 10 year faster improvement in technology (that is, reaching the technology target by 2040 and then constant thereafter) decreases the cumulated emissions by 6.9% for the reference scenarios of population, affluence, and technology. If we assume that each technology indicator improves 50% ('EU2010*0.5', resp.), with the reference scenarios on population and affluence, a 10 year faster improvements reduce the amount of total emissions by 15.4%. See the bottom panel in Figure 4.

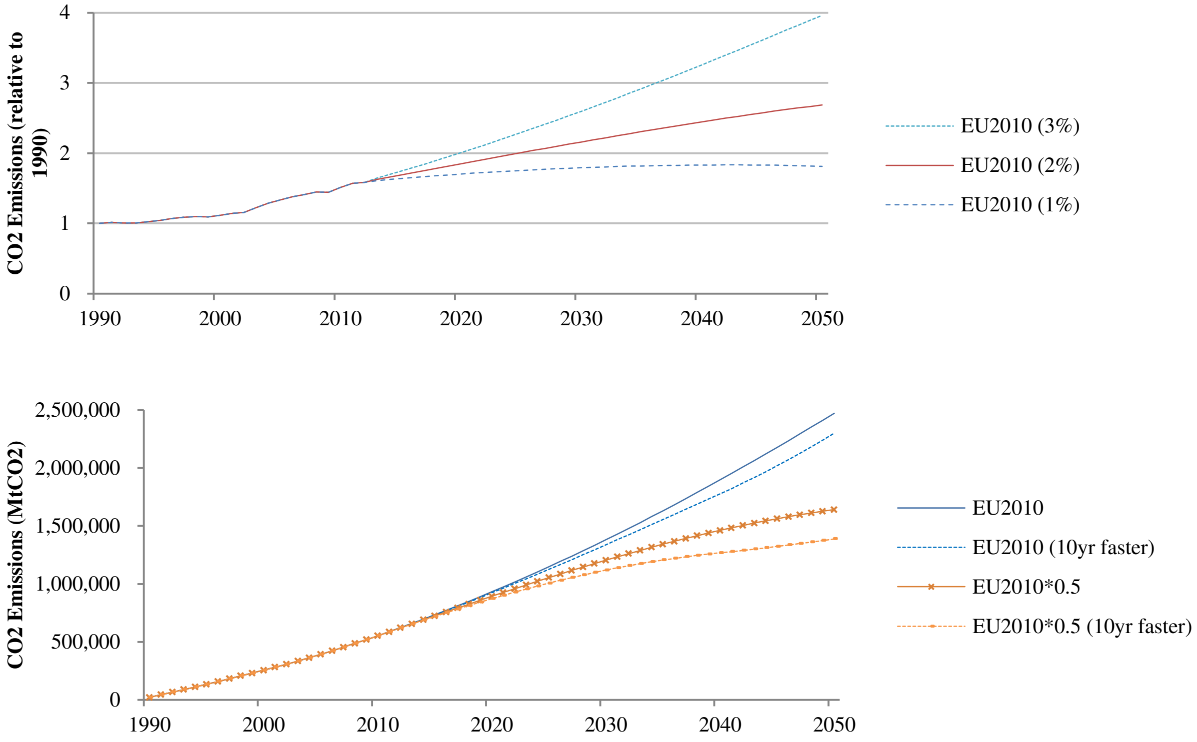

Figure 4 Global CO_2 emissions trajectory: 1990-2050 (sensitivity analysis). (Top panel): Sensitivity to the growth rate of per capita GDP (3%/yr, 2%/yr, 1%/yr). **(Bottom panel):** Sensitivity to the rate of technological improvements. The growth rate of per capita GDP is assumed to be 2%/yr. The meaning of the label EU2010*x is the same as in Figure 3.

6. Concluding Remarks

This paper has assessed the achievements and the limitations of our path to the stabilization of anthropogenic CO_2 emissions with economic growth using the stochastic Kaya model. To this end, the elasticity of CO_2 emissions with respect to each anthropogenic driver such as population, affluence, energy intensity and fossil-fuel dependence was estimated using the panel data of 132 countries from 1960 to 2010. From the analysis, I have found that except a few countries like Germany, most countries have not achieved the goal of carbon reductions with economic growth. In addition, the current path of each nation does not guarantee the achievement of a long-term goal of carbon reductions. If we try to achieve the target, a significant increase of the technology effect through stringent policy interventions should be accompanied. This is not an easy task of course because by the technology level I mean not the level of most advanced countries but the world-averaged level. How can we achieve the required technological improvements? Technology transfer from advanced countries to less developed countries and huge investments in research and development will be an answer. For the answer to be useful and practical, however, we need to enumerate all possible options and then identify the cost and benefit of each option. These are the future works to be done.

The analysis of this paper can be applied to the other measures of environmental impacts such as temperature increases. Of course this is much more demanding than the analysis of this paper because there are many things to consider for such an analysis, including other GHGs, carbon emissions from land-use changes, efficiency of natural sinks (Canadell et al., 2007; Le Quéré et al., 2009), and so on. However such an analysis has value. For instance, once driving forces of temperature increases are enumerated and their magnitudes are quantified as was done in this paper, the model and its parameters can be applied into an integrated assessment model (IAM). This would give another perspective on the understanding of the relationship between climate and the economy.

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Appendix A: Supplementary results

Table A1 Driving forces of CO_2 emissions: 1990-2010

Country/ Group	Driving forces of CO_2 emissions (% 1990 emissions)					Scale (% 1990 emissions)	Technology (% 1990 emissions)	Offsetting ratio (%)
	Population	GDP per capita	Energy intensity	Renewables	Emission factor			
France	11.0	20.8	-10.2	-8.8	-13.2	31.8	-32.2	101.2
Germany	2.7	24.3	-21.0	-5.3	-21.8	26.9	-48.1	178.6
Italy	6.6	13.8	-3.1	-4.4	-13.1	20.4	-20.5	100.6
Spain	19.8	36.5	-9.8	-1.1	-18.4	56.3	-29.3	52.0
UK	8.0	35.4	-29.1	-1.4	-27.0	43.4	-57.5	132.3
EU	5.7	29.3	-19.5	-5.0	-21.6	35.0	-46.1	131.5
Australia	32.4	47.8	-22.8	0.9	-10.1	80.3	-32.0	39.9
Canada	23.2	30.8	-21.2	-0.2	-12.6	54.1	-34.0	62.9
Japan	3.3	17.0	-4.2	-2.6	-7.1	20.3	-13.9	68.3
US	23.6	30.8	-24.6	-1.6	-14.4	54.4	-40.7	74.8
Annex1	9.2	30.4	-22.2	-2.9	-18.8	39.6	-43.9	111.0
Annex1-EIT	-4.4	25.0	-28.4	-2.7	-28.8	20.6	-59.8	290.1
Annex1-nonEIT	15.2	28.0	-17.2	-2.4	-14.1	43.2	-33.7	78.1
Mexico	38.7	25.3	-11.0	1.7	-13.6	64.0	-22.9	35.8
S. Korea	22.8	140.0	-1.0	-1.0	-31.0	162.8	-33.0	20.3
OECD	16.4	29.0	-16.6	-2.3	-15.0	45.5	-33.9	74.5
Brazil	39.6	51.6	3.3	3.6	2.9	91.2	9.8	-10.7
China	33.0	373.1	-121.1	16.5	-64.7	406.0	-169.3	41.7
India	60.3	176.7	-53.1	27.7	-20.7	237.0	-46.1	19.5
World	33.9	33.5	-12.1	0.1	-4.2	67.4	-16.2	24.0

Note: The shaded cells highlight the countries or groups in which CO_2 emissions are reduced compared to the

1990 levels. The negative offsetting ratios for some countries were originated from technological deterioration.

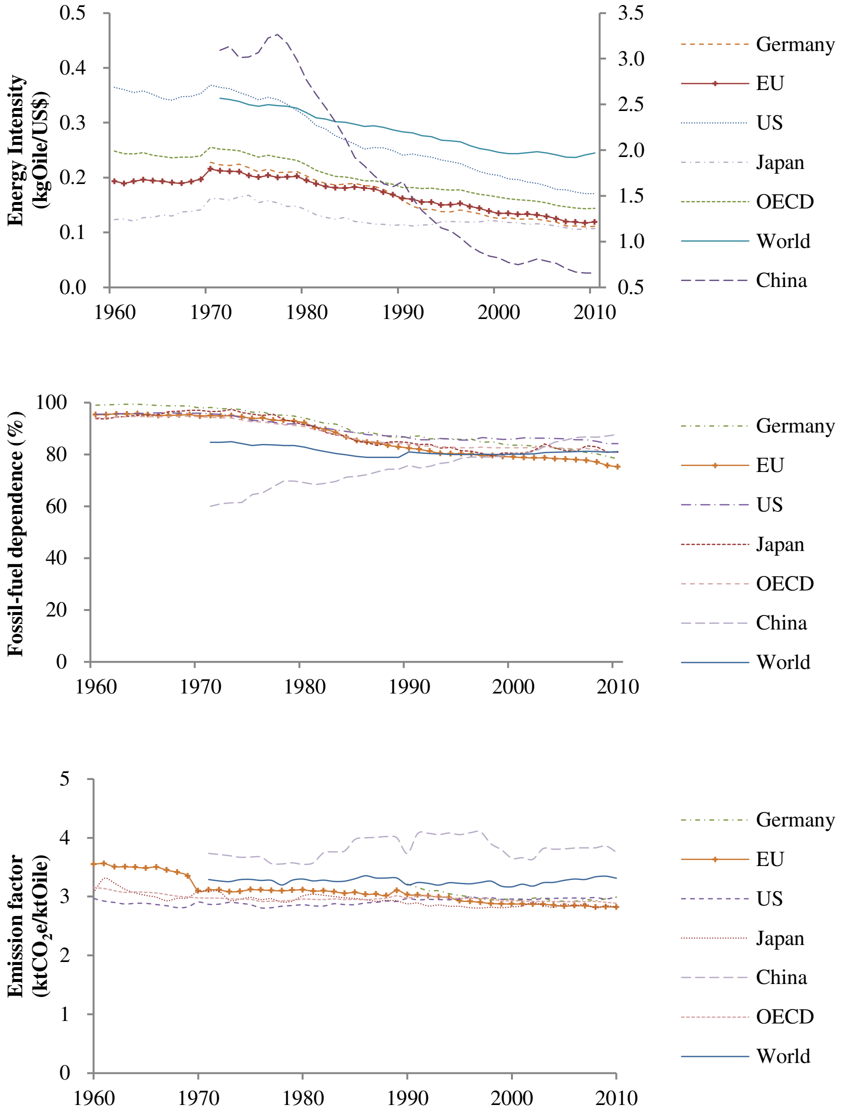

Figure A1 Trend of technology indicators for some selected countries: 1960-2010. (Top panel): Energy intensity. The right axis is for China. **(Middle panel):** Fossil-fuel dependence. **(Bottom panel):** Emission factor. For data source see Section 2.

References

Ang, B. W.: 2004, ‘Decomposition analysis for policymaking in energy: Which is the preferred method?’, *Energy Policy* **32**, 1131-1139.

Ang, B. W.: 2005, ‘The LMDI approach to decomposition analysis: A practical guide’, *Energy Policy* **33**, 867-871.

Ang, B. W., Huang, H. C., and Mu, A. R.: 2009, 'Properties and linkages of some index decomposition analysis methods', *Energy Policy* **37**, 4624-4632.

Ang, B. W. and Zhang, F. Q.: 2000, 'A survey of index decomposition analysis in energy and environmental studies', *Energy* **25**, 1149-1176.

Agnolucci, P., Ekins, P., Iacopini, G., Anderson, K., Bows, A., Mander, S., and Shackley, S.: 2009, 'Different scenarios for achieving radical reduction in carbon emissions: A decomposition analysis', *Ecological Economics* **68**, 1652-1666.

Brizga, J., Feng, K., and Hubacek, K.: 2013. 'Drivers of CO2 emissions in the former Soviet Union: A country level IPAT analysis from 1990 to 2010', *Energy* **59**, 743-753.

Bruntland, G.: 1987, *Our common future: The world commission on environment and development*, Oxford University Press, Oxford.

Canadell, J. G., Le Quere, C., Raupach, M. R., Field, C. B., Buitenhuis, E. T., Ciais, P., Conway, T. J., Gillett, N. P., Houghton, R. A., and Marland, G.: 2007, 'Contributions to accelerating atmospheric CO2 growth from economic activity, carbon intensity, and efficiency of natural sinks', in *Proceedings of the national academy of sciences 104*, pp. 18866-18870.

Chertow, M. R.: 2000, 'The IPAT equation and its variants', *Journal of Industrial Ecology* **4**, 13-29.

Commoner, B., Corr, M., and Stamler, P. J.; 1971, *The closing circle: nature, man, and technology*, Knopf, New York.

Davidson, R. and MacKinnon, J. G.: 2009, *Econometric Theory and Methods* Oxford University Press, New York and Oxford.

Davis, S. J. and Caldeira, K.: 2010, 'Consumption-based accounting of CO2 emissions', in *Proceedings of the National Academy of Sciences 107*, pp. 5687-5692.

Daily, G. C. and Ehrlich, P. R.: 1992, 'Population, sustainability, and Earth's carrying capacity', *BioScience* **42**, 761-771.

Dietz, T. and Rosa, E. A.: 1994, 'Rethinking the environmental impacts of population, affluence and technology', *Human Ecology Review* **1**, 277-300.

Dietz, T. and Rosa, E. A.: 1997, 'Effects of population and affluence on CO2 emissions', in *Proceedings of the National Academy of Sciences 94*, pp. 175-179.

Eggleston, S., Buendia, L., Miwa, K., Todd, N., and Tanabe, K.: 2006, *2006 IPCC guidelines for national greenhouse gas inventories*, Institute for Global Environmental Strategies: Hayama, Japan.

Ehrlich, P. R. and Holdren, J. P.: 1971, 'Impact of population growth', *Science* **171**, 1212-1217.

Greening, L. A., Davis, W. B., and Schipper, L.: 1998, 'Decomposition of aggregate carbon intensity for the manufacturing sector: Comparison of declining trends from 10 OECD countries for the period 1971-1991', *Energy Economics* **20**, 43-65.

Hajer, M. A.: 1995, *The politics of environmental discourse: ecological modernization and the policy process*, Clarendon Press, Oxford.

Hoffert, M. I., Caldeira, K., Jain, A. K., Haites, E. F., Harvey, L. D., Potter, S. D., Schlesinger, M. E., Schneider, S. H., Watts, R. G., and Wigley, T. M.: 1998, 'Energy implications of future stabilization of atmospheric CO2 content', *Nature* **395**, 881-884.

Hoekstra, R. and van den Bergh, J. C.: 2003, 'Comparing structural decomposition analysis and index', *Energy Economics* **25**, 39-64.

Janicke, M.: 2008, 'Ecological modernisation: new perspectives', *Journal of Cleaner Production* **16**, 557-565.

Jorgenson, A. K. and Clark, B.: 2010, 'Assessing the temporal stability of the population/environment relationship in comparative perspective: A cross-national panel study of carbon dioxide emissions, 1960-2005', *Population and Environment* **32**, 27-41.

Jotzo, F., Burke, P. J., Wood, P. J., Macintosh, A., and Stern, D. I.: 2012, 'Decomposing the 2010 global carbon dioxide emissions rebound', *Nature Climate Change* **2**, 213-214.

Kaya, Y.: 1990, 'Impact of carbon dioxide emission control on GNP growth: Interpretation of proposed scenarios', IPCC Energy and Industry Subgroup, Response Strategies Working Group, Paris 76.

Langhelle, O.: 2000, 'Why ecological modernization and sustainable development should not be conflated', *Journal of Environmental Policy and Planning* **2**, 303-322.

Le Quéré, C., Raupach, M. R., Canadell, J. G., and Marland, G.: 2009, 'Trends in the sources and sinks of carbon dioxide', *Nature Geoscience* **2**, 831-836.

Mahony, T. O., Zhou P., Sweeney, J.: 2012, 'The driving forces of change in energy-related CO2 emissions in Ireland: A multi-sectoral decomposition from 1990-2007', *Energy Policy* **44**, 256-267.

Mol, A. P. and Sonnenfeld, D. A.: 2000, 'Ecological modernisation around the world: an introduction', *Environmental Politics* **9(1)**, 1-14.

Morgan, M. G. and Keith, D. W.: 2008, 'Improving the way we think about projecting future energy use and emissions of carbon dioxide', *Climatic Change* **90**, 189-215.

Penman, J., Kruger, D., Galbally, I., Hiraishi, T., Nyenzi, B., Emmanuel, S., Buendia, L., Hoppaus, R., Martinsen, T., and Meijer, J.: 2000, *Good practice guidance and uncertainty management in national greenhouse gas inventories*, IPCC National Greenhouse Cost Inventories programme, Technical Support Unit.

Rafaj, P., Amann, M., Siri, J., and Wuester, J.: 2013, 'Changes in European greenhouse gas and air pollutant emissions 1960-2010: decomposition of determining factors', *Climatic Change* DOI 10.1007/s10584-013-0826-0.

Raupach, M. R., Marland, G., Ciais, P., Le Quere, C., Canadell, J. G., Klepper, G., and Field, C. B.: 2007, 'Global and regional drivers of accelerating CO2 emissions', in *Proceedings of the National Academy of Sciences 104*, pp. 10288-10293.

Rosa, E. A. and Dietz, T.: 2012, 'Human drivers of national greenhouse-gas emissions', *Nature Climate Change* **2**, 581-586.

Schulze, P. C.: 2002, 'I= PBAT', *Ecological Economics* **40**, 149-150.

Shi, A.: 2003, 'The impact of population pressure on global carbon dioxide emissions, 1975-1996: Evidence from pooled cross-country data', *Ecological Economics* **44**, 29-42.

Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M., and Miller, H. L.: 2007, *The physical science basis*, Contribution of working group I to the fourth assessment report of the intergovernmental panel on climate change.

van Vuuren, D. P.: 2012, *The Emissions Gap Report 2012*, United Nations Environment Planning.

Waggoner, P. E. and Ausubel, J. H.: 2002, 'A framework for sustainability science: A renovated IPAT identity', in *Proceedings of the National Academy of Sciences 99*, pp. 7860-7865.

Wooldridge, J. M.: 2002, *Econometric Analysis of Cross Section and Panel Data*, The MIT Press, Cambridge, MA.

York, R., Rosa, E. A., and Dietz, T.: 2003, 'STIRPAT, IPAT and ImPACT: Analytic tools for unpacking the driving forces of environmental impacts', *Ecological economics* **46**, 351-365.