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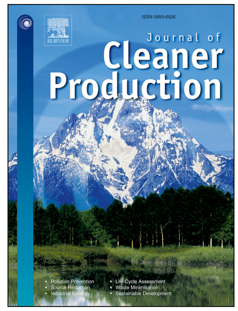

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Decarbonization under Green Growth Strategies? The case of South Korea

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Abstract

The win-win opportunities connected to green growth are appealing to academics and policy makers alike, but empirical evaluations about the effectiveness of green growth policies are still scattered. Taking South Korea as case study, which set up a highly ambitious green growth program in 2009, our research casts light on the extent to which the Korean Green Growth Strategy has been effective in decarbonizing the economy. Our methodology combines decomposition analysis and econometrics with a review of energy and climate policies, including related structural changes. On the short term (2008-2012), most of the drivers displayed an enhancing effect on CO_2 emissions from fuel combustion, with GDP per capita being the strongest driver. From a historical perspective (1971-2012), findings reveal that important drivers, such as energy and CO_2 intensity even worsened their effects during the first years under the Green Growth Strategy. Regression statistics revealed that GDP per capita was in fact the driver with the most explanatory power for CO_2 emissions, followed by energy intensity. The Korean policy mix of modest government support to low-carbon energy technologies and a lack of complementary pricing policies did not deliver the targeted emissions reduction, at least in the short-term. Despite recent policy developments, i.e. the introduction of a renewable portfolio standard in 2012 and an emissions trading system in 2015, several key policy challenges for decarbonization remain.

Keywords: climate change, decomposition analysis, energy, green growth, policy evaluation, South Korea

8.900 words

1. Introduction

The 2008 - 2009 global financial crisis triggered fiscal stimulus packages around the world. While the main purpose of the stimulus was to get economies back on the economic growth path, several environmental organizations, environmental economists, and policy makers saw this crisis as an opportunity to achieve economic recovery with low environmental impact. UNEP pointed out the "unique opportunity presented by the multiple crises and the ensuing global recession" (UNEP, 2009, p. 4). Moreover, it was argued that "a Global Green New Deal, if implemented effectively and swiftly, has the potential to revive the world economy and reduce its vulnerability to repeated fuel and food crises as well as climate-induced risks." (Barbier, 2010, p. 20). Within this framework, economic stimulus packages were portrayed as a golden opportunity and entry point into a new green economy, with the low-carbon energy technology sector playing a critical role (IEA, 2009). In many countries (e.g. USA, China, South Korea) clean energy was heavily targeted (UNEP & GEI, 2009). While the opportunities connected to green growth strategies are appealing, there are few studies about their actual success in delivering the aspired win-win outcome. The literature regarding the effectiveness of green growth strategies and supportive policies is scattered. This case study of decarbonization in South Korea in a Green Economy context finds that, mainly due to a lack of ambitious supplementary reforms, public spending under a green growth strategy seems insufficient to offset economic growth effects on CO_2 emissions.

The case of South Korea (hereafter Korea) is sticking out in the green growth debate as, together with China, it became the world leader in green growth spending. With 80% the share of green investments in Korea's 2009 economic recovery package of USD 45 billion[1] (representing 3% of GDP) was the largest worldwide (UNEP, 2010). The green stimulus package was already under the impression of President Lee Myung-bak's 2008 announcement of "Low carbon, green growth" as the new development vision for the country. This vision inspired the "National Green Growth Strategy", which was published in 2009. The strategy had "Mitigation of climate change & energy independence" as the first of three objectives. The other two objectives were "Securing new growth engines" and "Improving living standards and enhancing national status", which included only the improvement of water and flood management and the construction of railways as further actions with direct relation to environmental goals (Presidential Commission on Green Growth, 2009). The Green Growth Strategy and its primary focus on climate change mitigation are reflected in several policies, above all the Five Year Plan for Green Growth (2009-2013), which emerged from and overlapped with above mentioned stimulus package, and had a total volume of USD 98.8 billion (OECD, 2012).

There were several reasons for Korea to give a strong push towards the decarbonization of its energy economy. First, Korea is 97% dependent on imports for its primary energy supply (U.S. Energy Information Administration, 2014), which means that energy security and reduced import costs are important co-benefits of climate change mitigation. Second, Korea is an OECD country with consistent and rapid economic growth over several decades (OECD, 2012), but it is one of only three OECD countries that do not have any emissions reduction obligations under the Kyoto Protocol. Third, Korea is a heavily industrialized country with a high share of energy intensive industry, in which a significant part of Korea's economic capacity and welfare is rooted (Jeong & Kim, 2013). Fourth, renewable energy has only a marginal share in both primary energy supply and power generation, which also means that there

[1] When we refer to GDP in the text, we assume an exchange rate of 1,100 KRW per USD, which reflects the rate at the time of writing (January 2015) and is close to the average exchange rate over the last five years.

is no strong domestic market for renewable energy technology, yet (N.-B. Park, Yun, & Jeon, 2013). Finally, and most importantly, Korea's CO_2 emissions from fuel combustion increased by 125% from 229Mt in 1990 to 516Mt in 2009 (IEA, 2014b).

The Korean commitment towards decarbonization has not only been expressed in the National Green Growth Strategy but also in quantitative targets: Korea committed itself to reducing GHG emissions by 30% till 2020 as compared to a business as usual (BAU) scenario, representing a decrease of 4% compared to 2005 levels. This is the most demanding pledge of any non-Annex I country under the Kyoto Protocol. Furthermore, the First Energy Basic Plan contained targets for the energy intensity of the economy (46% reduction by 2030 as compared to 2006) and renewable energy (increase from 2.4% of total primary energy supply in 2006 to 11% in 2030) (W. J. Chung, 2014).

Despite all these relevant drivers and policy commitments, there is a lack of assessment regarding the actual performance of Korea's Green Growth Strategy, in particular from the empirical point of view. Earlier quantitative studies in the context of decarbonizing the Korean energy system have researched: the drivers of CO_2 emission from industry between 1990 and 2009 (Jeong & Kim, 2013), the energy and GHG emissions intensity of 96 economic sectors between 1990 and 2004 (W.-S. Chung, Tohno, & Shim, 2009), the role of eco-industrial parks in reducing CO_2 emissions in Korea (Jung, An, Dodbiba, & Fujita, 2012), the sector-specific drivers of CO_2 emissions in Korea between 1990 and 2005 (Oh, Wehrmeyer, & Mulugetta, 2010), and the drivers of power sector CO_2 emissions in a scenario analysis for the period 2008-2050 (N.-B. Park et al., 2013). While these analyses provide valuable quantitative insights about some drivers of energy-related CO_2 emissions, they do not relate their findings to green growth policy programs. On the other hand, recent research on Korean climate and energy policy is scattered. Duffield (2014) provides a qualitative analysis of Korea's first National Energy Plan without putting much stress on its environmental effectiveness. The only explicit attempt we found in the literature is the report "Korea's Green Growth based on OECD Green Growth Indicators" by Statistics Korea. The report provides an interesting summary of several green growth statistics, but neither analyzes these statistics nor assesses the impact of green growth policy on the included indicators (Statistics Korea, 2012). The lack of evaluations of green growth policy programs is likely to explain why there is a discrepancy between the political optimism about the win-win potential of green growth policies on one side, and academic skepticism about the environmental effectiveness of green growth policies on the other side (cf. Antal & Van Den Bergh, 2014; Brahmbhatt, 2014).

Given the lack of knowledge, our research aims to cast light on the extent to which the Korean Green Growth Strategy has been a suitable policy tool for short to mid-term decarbonization of the economy. Our analysis quantitatively unravels key drivers and identifies the extent to which policy efforts have, or not, facilitated decarbonization. The paper combines decomposition analysis and econometrics with a review of energy and climate change mitigation policies; including related structural changes.

The analysis is undertaken in two steps. We first take the Korean National Green Growth Strategy (2009-2013) as a point of departure to analyze recent (2008 onwards) policy efforts to reduce CO_2 emissions. We do this by carrying out an additive decomposition analysis that attributes CO_2 emissions to various drivers, since the indicator CO_2 emissions alone does not have enough resolution to unveil the dynamics that were potentially triggered by policy intervention (methodological details in the next section). Second, and building upon the decomposition approach, we take a longer-term perspective by analyzing Korea's CO_2 emissions using an econometric model with time series data from 1971 to 2012. Questions that guided our analysis included: What have been the most significant drivers of CO_2 emission levels in the short and long term? Which policies (if any) have facilitated the decarbonization of the economy? What can be said about the environmental effectiveness of Korea's Green Growth Strategy? Is Korea on track to reach its 2020 emissions reduction target? And finally, are economic growth and decarbonization compatible? As a whole, our research aims to learn from Korea's experience with using green growth policies to encourage a low-carbon energy system.

The paper is structured as follows. Section 2 outlines the methodology of this study. The results from the short-term decomposition analysis are presented and analyzed in section 3.1. These findings are put into the context of the long-term development of CO_2 emissions drivers, which were analyzed with econometric tools (section 3.2). The findings from both parts of the analysis are discussed in the context of structural changes of the Korean economy and its energy system in section 3.3. Key policy aspects are further analyzed in section 3.4. Section 4 summarizes implications of our analysis for short to mid-term decarbonization policies. Conclusions are drawn in section 5.

2. Methodology

The methodology is based on a top-down empirical approach. Building upon the Kaya Identity (Kaya, 1990), our research deploys two complementary analytical tools, namely additive decomposition analysis and an econometric assessment. This study gives emphasis on *environmental effectiveness*, which is primarily assessed by analyzing CO_2 emissions from fuel combustion.

2.1. Decomposition analysis

Decomposition analysis is a useful tool to further the understanding of interactions between CO_2 emissions and socio-economic activities. This understanding can be used as the basis for policies that address the most relevant drivers of CO_2 emissions (IEA, 2014a). The Kaya Identity is a macroeconomic decomposition equation for energy-economy-environment indicators that quantitatively estimate CO_2 emission levels (Kaya, 1990). The equation typically reads as follows:

$$C = Pop * GDPpc * E\_int * C\_int \qquad (1)$$

where *C* represents the level of CO_2 emissions from fuel combustion and industrial processes. *C* is the product of four driving factors: *Pop* is population, *GDPpc* is the per-capita GDP, *E_int* is the energy supply intensity of GDP, and *C_int* is the *CO_2* intensity of total primary energy supply (*TPES*) (see Table 1 for definitions of indicators and data sources).

Taking the Kaya Identity as point of departure, we decompose CO_2 emissions based on the Logarithmic Mean Divisia Index (LMDI). The advantages of the LMDI method are the ease of using it, the achievement of complete decomposition without residual, the option to carry out both additive and multiplicative decomposition, and the applicability for short time series (Su & Ang, 2012). The LMDI additive decomposition starts off from the basic Kaya Identity:

$$\Delta C = C^T - C^0 = \Delta C_{Pop} + \Delta C_{GDPpc} + \Delta C_{E\_int} + \Delta C_{C\_int} \qquad (2)$$

where C^0 are CO_2 emissions from fuel combustion in the base year and C^T are CO_2 emissions *T* years later. The change in CO_2 emissions (ΔC) is split into the respective effects of changes in population (ΔC_{Pop}), economic activity (ΔC_{GDPpc}), energy intensity (ΔC_{E_int}) and carbon intensity of energy (ΔC_{C_int}).

Table 1: Parameters and data sources for both decomposition and econometric analysis (full data in Table 6)

Parameter	Definition	Data source
C	Emissions from fuel combustion (in $MtCO_2$), excluding emissions from marine and aviation bunkers, following the IPCC Sectoral Approach	(IEA, 2014)
$TPES$	Total primary energy supply = production + imports − exports − international marine bunkers − international aviation bunkers ± stock changes (in Mtoe)	(IEA, 2014)
TFC	Total final consumption of energy = sum of consumption by the different end-use sectors, excluding international marine and aviation bunkers (in Mtoe)	(IEA, 2014)
GDP	Total annual output adjusted by purchasing power parities (ppp) (valued in billion 2005 US$)	(OECD, 2014b)
Pop	All residents regardless of legal status or citizenship, midyear (in millions)	(Statistics Korea, 2014)

Equation (2) is further disaggregated into equation (3) by separating the transformation effect from the energy intensity effect and by separating the energy mix effect from the carbon intensity of energy effect. This results in:

$$\Delta C = C^T - C^0 = \Delta C_{Pop} + \Delta C_{GDPpc} + \Delta C_{E\_int\_fc} + \Delta C_{E\_transf} + \Delta C_{E\_mix} + \Delta C_{C\_factor} \quad (3)$$

where ΔC_{E_transf} is the change in CO_2 emissions that can be attributed the energy transformation effect[2], which is driven by changes in the ratio of TPES and TFC. Accordingly, $\Delta C_{E\_int\_fc}$ is now based on the TFC of energy. ΔC_{E_mix} refers to the changes in CO_2 emissions driven by the composition of the energy mix, and ΔC_{C_factor} reflects changes in the respective implied emission factors of oil, coal and natural gas. These changes occur as for this analysis *implied* emission factors are used which are not based on the specific carbon content of a fuel. They reflect the ratio between total CO_2 emissions from combustion and the TPES of that fuel. The LMDI formulae for the individual drivers in the additive decomposition equations (2) and (3) are presented in Table 2. The index *i* stands for the different fuel types, such as oil, coal, natural gas and non-carbon energy.

Table 2: LMDI formulae for various decomposition parameters

Parameter	LMDI formulae	
Pop	$\Delta C_{Pop} = \frac{C^T - C^0}{\ln C^T - \ln C^0} \ln\left(\frac{P^T}{P^0}\right)$	$P = Pop$
$GDPpc$	$\Delta C_{GDPpc} = \frac{C^T - C^0}{\ln C^T - \ln C^0} \ln\left(\frac{G^T}{G^0}\right)$	$G = \frac{GDP}{Pop}$
E_int	$\Delta C_{E\_int} = \frac{C^T - C^0}{\ln C^T - \ln C^0} \ln\left(\frac{I^T}{I^0}\right)$	$I = \frac{TPES}{GDP}$
E_int_fc	$\Delta C_{E\_int\_fc} = \frac{C^T - C^0}{\ln C^T - \ln C^0} \ln\left(\frac{U^T}{U^0}\right)$	$U = \frac{TFC}{GDP}$

[2] The name "energy transformation effect" is slightly misleading as it merely reflects the ratio between two different metrics of capturing the economy-wide energy, namely TPES and TFC. Between supply and final consumption some transformation takes place (e.g. in power generation), while for other energy products like transportation fuels no transformation happens.

E_transf	$\Delta C_{E\_int} = \frac{C^T - C^0}{\ln C^T - \ln C^0} \ln\left(\frac{T^T}{T^0}\right)$	$T = \frac{TPES}{TFC}$
C_int	$\Delta C_{C\_int} = \frac{C^T - C^0}{\ln C^T - \ln C^0} \ln\left(\frac{F^T}{F^0}\right)$	$F = \frac{CO2}{TPES}$
C_factor	$\Delta C_{C\_int} = \sum_i \frac{C_i^T - C_i^0}{\ln C_i^T - \ln C_i^T} \ln\left(\frac{F_i^T}{F_i^0}\right)$	$F = \frac{CO2}{TPES}$
E_mix	$\Delta C_{E\_mix} = \sum_i \frac{C_i^T - C_i^0}{\ln C_i^T - \ln C_i^T} \ln\left(\frac{M_i^T}{M_i^0}\right)$	$M = \frac{TPES_i}{TPES}$

2.2. Econometric assessment

Building upon the Kaya Identity represented by eq. (1) we defined an econometric model in order to analyze the statistical relationship between key aggregate Green Energy Economy (GEE) determinants for Korea.

$$Y_t = \beta_0 + \beta_1 X_{1t} + \beta_2 X_{2t} + \beta_3 X_{3t} + \beta_4 X_{4t} + \mu_t \quad (4)$$

where Y_t = CO_2 emissions (in million tonnes) from fuel combustion (dependent variable), t = 1… T years (=42); β_0 is a constant intercept; β_1 , β_2, β_3 and β_4 are the regression coefficients to be estimated for X_1 *(Pop)*, X_2 (*GDPpc)*, X_3 (*E_int)* and X_4 *(C_int*) respectively; and μ_t is an unobserved error in the model.

Various correlation tests and regression statistics were used for assessing the relationships and contribution of independent variables to historical CO_2 emissions in Korea. First, bivariate correlation tests evaluated the relative degree of 'closeness' (or association) between each pair of variables.

Secondly, partial correlations were calculated to measure the correlation between CO_2 emissions and each independent variable while controlling for the effect of the remaining variables. This step was necessary as more than one variable could convey the same information (i.e. problem of multicollinearity) leading to unreliable estimates and high standard errors. A more important problem is that multicollinearity can make it difficult to draw any inferences about the relative contribution of a particular driver.

Thirdly, using the multiple regression model defined in (2) a stepwise regression analysis quantified the specific contribution of the various drivers of CO_2 emissions. The analysis sequentially assessed the unique impact of each independent variable on CO_2 emissions. If a variable partially explained the behavior of Y (CO_2) it was retained, while all other variables were re-tested to identify whether they were still significant contributors. When a variable no longer contributed significantly to the model, it was removed. This iterative process ran in parallel with multicollinearity tests. The aim was to identify the regression model that explained the greatest part of the variance of CO_2 emissions (i.e. highest adjusted R^2), with p-values below 0.10 (for independent variables), lowest variation coefficients, and no indication of multicollinearity. A variation coefficient $Coef\ Var_j = (Std\ error\ estimate)_j/(Mean\ value\ CO_2)_j$ of the estimated regression model j was calculated in order to evaluate the variability of the dataset and thus the predictive capability (CO_2 variability). A 10% maximum threshold was set (i.e. Coef Var j < 10%). To investigate multicollinearity, Variance Inflation Factors (VIF) were computed to quantify how much the variance of an estimated regression coefficient was increased because of collinearity. A VIF greater than five (i.e., tolerance level below 0.20) was defined a maximum threshold value. That is, any VIF value above five was taken as a strong indication of multicollinearity.

The initial hypothesis was that GDP per capita (g) was most closely correlated with CO_2 emissions, and thus it is an important determinant for explaining the behavior of such emission levels in the country. Unless otherwise stated, all tests and parameters were estimated using a 90% confidence level (i.e. α=0.10).

3. Results and discussion

After the 2008/09 financial crisis, the development of CO_2 emissions in Korea was consistent with the CO_2 rebound effect that was estimated globally. The lowering impact of the crisis on emission levels was "short-lived owing to strong emissions growth in emerging economies, a return to emissions growth in developed economies, and an increase in the fossil-fuel intensity of the world economy." (Peters et al., 2012). Korea is no exception to this and after modest growth – not even reductions – of CO_2 emissions by 11Mt (2.3%) in 2008 and 14Mt (2.8%) in 2009, emissions soared up by a staggering 49Mt (9.5%) in 2010.

While the strong carbon-rebound and the continued growth of CO_2 emissions until 2012 are a first indication for the lack of effectiveness of the Korean green stimulus, further analysis is needed to understand the dynamics of various drivers of CO_2 emissions and whether they have been affected by policies under the Korean Green Growth Strategy. The decomposition of CO_2 emissions from energy between 2008 and 2012 is a first step to understand which factors drove the increase of emissions or mitigated an even further increase.

3.1. Disentangling key drivers for the period 2008-2012

The additive decomposition of CO_2 emissions from energy revealed that between 2008 and 2012 a large share of additional annual emissions was caused by increased *economic activity* (measured in *GDPpc*), which had an emission-enhancing effect of 56Mt (see Figure 1). Both the financial crisis and the recovery are covered by the 2008 to 2012 period, in order to avoid distortions of the results by the rebound of GDP and emissions after the crisis.

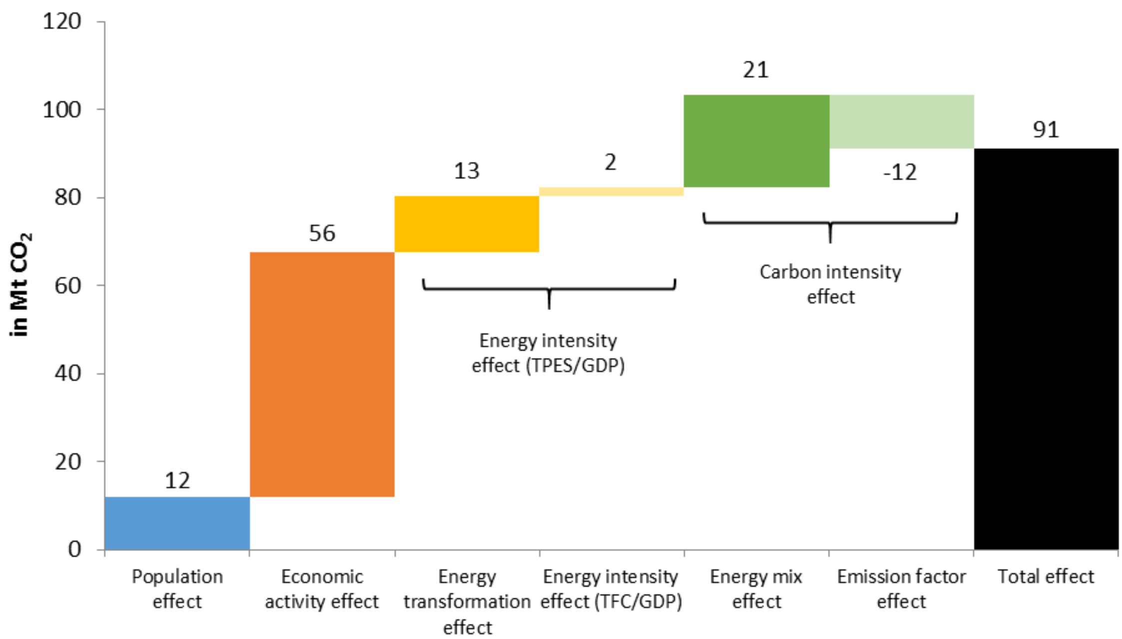

Figure 1: Results of additive LMDI decomposition of CO_2 emissions from fuel combustion in Korea for the period 2008-2012

The rise in emissions caused by the strong economic activity effect was not mitigated by other drivers. On the contrary, changes in the energy intensity and in the energy mix caused a significant *increase* in annual CO_2 emissions, of 15Mt and 21Mt respectively.[3] If the energy intensity is based on TFC of energy instead of TPES, the energy intensity effect almost completely disappears. Instead the *energy transformation effect*, which is based on changes in the ratio between TFC and TPES, drives up annual emissions by 13Mt. This indicates that additional emissions have been triggered by increased losses on the way from energy supply to final consumption, which is due to a higher combined share of coal and natural gas – fuels that are mainly used for power generation, where significant losses occur.

The only mitigating effect of 12Mt CO_2 occurred because of lowering implied *emission factors* of carbon fuels. This effect can be entirely explained by the decrease in the implied emission factor of oil[4], i.e. in 2012 less CO_2 was emitted per ton of TPES of oil than in 2008.

The short-term analysis of CO_2 emission drivers does not indicate a win-win outcome of the Korean Green Growth Strategy. Increased economic activity had the expected emission-enhancing effect, but it was not even partly offset by improvements in energy intensity or the decarbonization of its energy mix. The following section further investigates what historically were the main drivers of CO_2 emissions, and whether current developments have been the continuation of (i.e. path dependency) or departure from a long-term trend.

3.2. Unravelling CO_2 emission drivers for the period 1971-2012

The development of historic CO_2 emissions from fossil fuel combustion in Korea from 1971 to 2012 can be best explained by GDP per capita and the energy intensity of the economy. This is the main finding from econometric tests and stepwise regression (details in Appendix B), which resulted in a model where only GDP per capita and energy intensity are left as drivers (see Figure 2). This model explains 99.6% of the variability of CO_2 emissions.

The findings from stepwise regression analysis are consistent with the results from additive decomposition for the same time period (see Figure 3), where the effect from economic activity (*GDPpc*) on CO_2 emission is clearly dominating. It contributed to increased annual emissions with more than 500Mt from 1971 to 2012. The energy intensity effect (*E_int_fc*) has mitigated additional CO_2 emissions since the late 90s, whereas the energy transformation effect (*E_transf*) and the energy mix (*E*_mix) effect increased emissions over the same time period. The second mitigating effect besides energy intensity improvements can be attributed to changing implied emission factors (*C_factor*).

[3] Note that the population effect is not further discussed in this paper, as Korean population growth is slowing down and the peak of ca. 52 million is forecasted to be reached in 2030, which is only about 4% more than the current 50 million (Statistics Korea, 2014).

[4] The emission factor effect of oil was -12.4Mt, of coal 0.9Mt, of natural gas 0.4Mt and of other fuels -0.9Mt. A detailed explanation of the implied emission factor effect of oil follows under the heading "Storing carbon in oil products" in section 3.3.

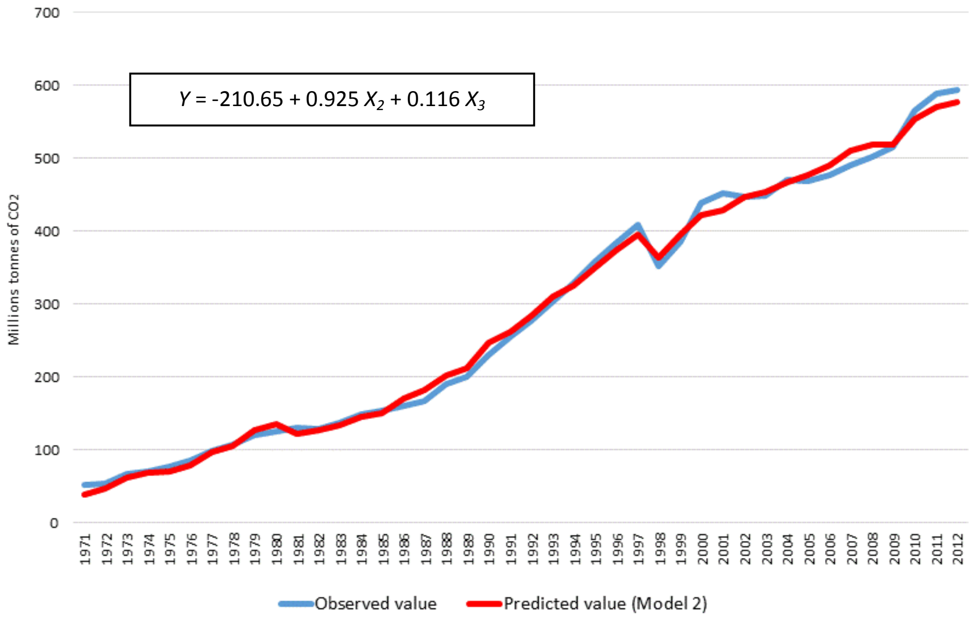

Figure 2: Observed and predicted CO_2 emissions values from fuel combustion for South Korea (1971-2012)

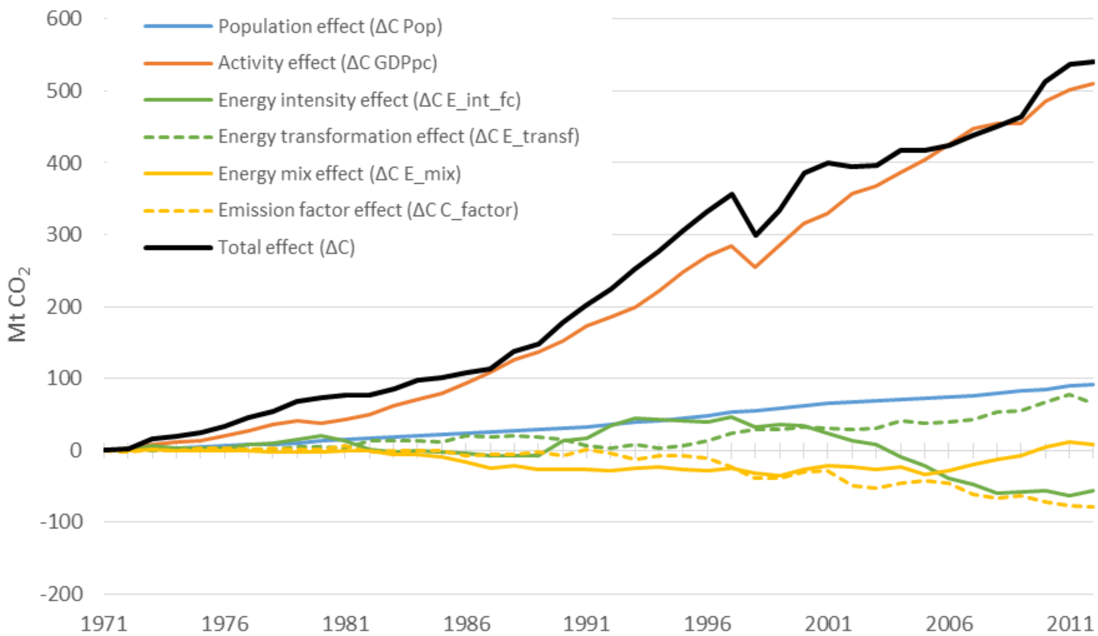

Figure 3: Results of additive LMDI decomposition analysis of CO_2 emissions (1971-2012)

3.3. Key structural developments

In the following sections, the results from additive decomposition and econometric analysis are put into the context of large structural developments that had an impact on the empirical results for the Korean energy-economy system.

The 'Miracle on the Han River'

Both in the 2008-2012 and the 1971-2012 time period GDP growth has been the main driver of CO_2 from energy. Per capita GDP consistently grew over the last four decades from USD 2,700 in 1971 to USD 8,800 in 1990 and USD 21,600 in 2012. The 'Miracle on the Han River', a term often used for the economic boom in Korea from the 60s to late 90s, is well reflected in the CO_2 emissions that can be attributed to increased economic activity (as shown in Figure 3).

The historic development of per capita GDP can be best explained by the rapid industrialization of Korea, which was driven by an active industrial policy and export promotion (J. Lee, Clacher, & Keasey, 2012), by a high educational standard (E. K. Lee, 2012), extensive innovation activity (S. Chung, 2011), and stable institutions and sound macroeconomic policies (D. Cho, 2009).

The increasing importance of international markets for Korean economic developments is reflected in the share of value added by exports in GDP, which went up from 53% in 2008 to 57% in 2012, well above the OECD average. At the same time the import-share decreased and Korea developed a large trade surplus (OECD, 2014c).

The two interruptions of economic growth, first during the Asian Crisis in 1998 and then during the Global Financial Crisis in 2008/09, are well-captured by both Model 2 of the econometric analysis and the activity effect in the additive decomposition analysis. The estimated economic rebound, and hence the rebound of the activity effect on CO_2 emissions, was much quicker in the case of the 2008/09 crisis, which had its reason in stable domestic demand, a flexible monetary policy and sound economic institutions (cf. D. Cho, 2009; Obstfeld, Cho, & Mason, 2012).

Industrialization, tertiarization and industrial restructuring

The structural change of the Korean economy between 1971 and 2012 had a large impact on energy intensity, and hence CO_2 emissions from energy. It is comprised of three major trends. First, industrialization in the 70s and 80s (continued from the 60s) increased the energy intensity of the economy and therewith CO_2 emissions (see Figure 4). Second, tertiarization, i.e. the growth of the service sector from 50% value added in GDP in 1980 to more than 60% in the mid-2000s, had a lowering impact on emissions. Tertiarization was mainly driven by growth in producer services, including communication, finance, insurance, real estate, renting of machinery and equipment, advertising and broadcasting (H.-J. Kim, 2006). Third, the structural change within industry towards less carbon intensive industries, which mitigated additional annual CO_2 emissions of 50Mt in 2009 as compared to 1999 (Jeong & Kim, 2013).

It is noteworthy that tertiarization has not continued until today. The value added in the services sector as share of GDP reached its all-time high of 61.2% in 2008. After the economic crisis the share of the services sector dropped to 59.4% in 2012, while in the same period the share of industry increased from 36.3% to 38.1% (The World Bank, 2014). This development helps to explain the increase in energy intensity from 238toe per million USD in 2008 to 244toe in 2012, which was a significant driver of CO_2 emissions.

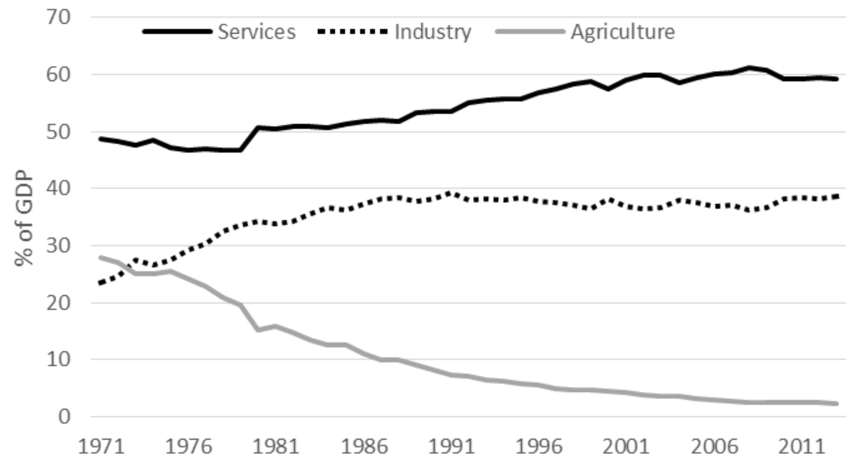

Figure 4: Value added by sector (The World Bank, 2014)

The second factor that influenced the energy intensity effect on CO_2 emissions is the efficiency in the energy system. While not at the core of this study, there are various indications for improved energy efficiency in Korea:

- the efficiency of power generation increased from 33% in 1990 to more than 40% in 2011 (Hussy, Klaasen, Koorneef, & Wigand, 2014);
- efficiency improvements in industry mitigated annual CO_2 emissions of about 50Mt through the 2000s (Jeong & Kim, 2013);
- average CO_2 emissions of cars have decreased from 182 g/km in 2005 to 141 g/km in 2011 (Ko, Myung, Park, & Kwon, 2014);
- and the TFC of energy in the building sector remained stable between 1990 and 2010 (IEA, 2012), while the number of households, in particular single-occupancy households, rose (OECD, 2014a), and the "total number of house appliances used" went up significantly for most surveyed product categories, e.g. from 1.7 million ACs in 1996 to 13.4 million in 2013 (Statistics Korea, 2014)

However, energy efficiency improvements between 2008 and 2012 where not sufficient to make up for the increase in energy intensity that resulted from the shift towards more energy-intensive economic activity. Hence, the energy intensity effect on annual CO_2 emissions did not display any mitigation in this time period (as shown inFigure 1).

From oil to nuclear, to natural gas, to coal and to renewables?

Historically, changes in the energy mix had varying impacts on CO_2 emissions in Korea. Up until the early 80s, the Korean TPES was dominated by oil for power generation and coal for heating, which had relatively stable shares (see Figure 5). In the 80s the first nuclear reactors went online and nuclear power reached its all-time highest share in electricity generation of about 50% in 1987 (S. Choi et al., 2009). This development had a mitigating effect on annual CO_2 emissions.

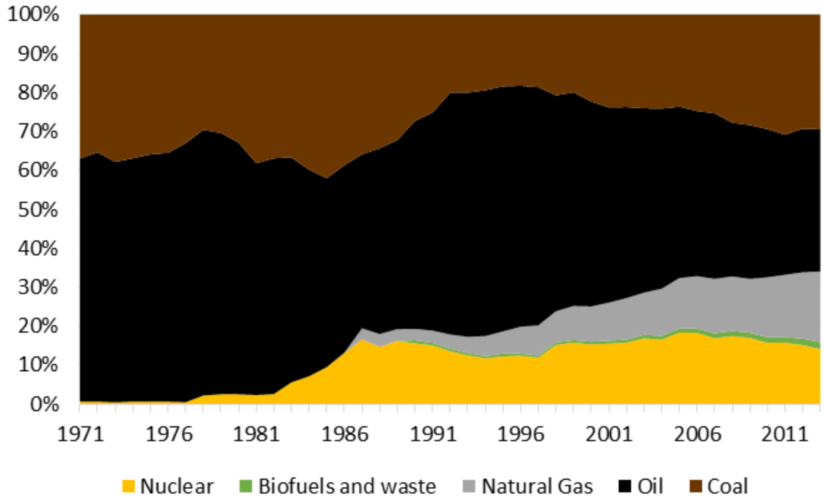

Figure 5: TPES by fuel 1971-2013

Throughout the 90s and the early 2000s several changes of the energy mix took place, but their respective impacts on CO_2 emissions largely evened out each other: the share of nuclear in TPES remained stable while natural gas was introduced into the mix and first took shares of coal and later of oil. It is important to consider that implied emission factors of different fuels also changed over time (see section below) so that for instance changes in the share of oil had a different impact on the CO_2 intensity of the energy mix in the early 80s than they would have today.

Starting around the turn of the millennium, the share of coal in TPES, by far the fuel with the highest implied emission factor, rose from about 20% to 30% in 2013. Moreover, no new nuclear reactors were added between 2005 and 2011 (World Nuclear Association, 2015), and existing nuclear power plants generated less electricity, since they underwent additional security checks in the aftermaths of the Fukushima Daiichi accident; including various incidents at domestic nuclear power plants that raised questions about their security (Duffield, 2014).

These trends were not counterbalanced by the modest increase of the share of renewable energy in TPES from 0.5% in TPES in 2005 to 1% in 2013. It is important to note that this modest increase of the *share* of renewables translates into an increase of total renewable energy by 150%, since the TPES increased by 25% over the same time period. Despite these positive dynamics, the scale of renewable energy in Korea was too small to affect the CO_2 intensity of the energy mix.

Storing carbon in oil products

Besides changes in the energy mix, carbon intensity of energy was strongly affected by changes of the implied emission factors of different fuels. In particular the per-unit CO_2 emissions from the TPES of oil, which decreased from about 3 tCO_2/toe in the early 80s to less than 2 tCO_2/toe in 2012, influenced the carbon intensity of energy. This development does not reflect changes in the carbon content of oil, but can be explained by the increasing share of the so called “non-energy use” of oil, which is treated as carbon storage[5]. Non-energy use as share of TPES of oil went up consistently from around 10% in the 70s to 38% in 2008 and 44% in 2012.

The improvement in the implied emission factor of oil largely offset the effect from a dirtier energy mix, so that the overall carbon intensity of energy remained stable between 2008 and 2012 at around 2.25 tCO_2/toe.

3.4. The impact of climate and energy policy

The following sections give an overview of the impacts of key Korean climate and energy policies on the development of CO_2 emissions and their drivers.

The green stimulus and Five Year Plan for Green Growth

Two aspects of the 2009-2012 green stimulus, which was later partly merged into the 2009-2013 Five Year Plan for Green Growth, are relevant for explaining the drivers of CO_2 emissions: the extent to which additional government spending triggered economic growth, and the extent to which this spending had the potential to lower CO_2 emissions.

Korea's share of general government expenditure in GDP is among the lowest of the OECD countries. It slightly grew from 26.6% in 2005 to 30.2% in 2011 and was particularly high in 2009 (33.1%), the year when the Korean fiscal stimulus started (OECD, 2014c). While it is impossible to determine exactly how much of the government spending on green growth programs was *additional* government expenditure that would not have occurred otherwise[6], it certainly increased spending to some extent. Furthermore, public expenditure triggered growth in the private sector that is not captured by these figures (K. Hong, 2010). Hence, government expenditure in the context of the Green Growth Strategy caused additional growth of the economic activity effect on CO_2 emissions, even though this effect of additional public spending cannot be quantified.

The envisioned outcome of avoiding additional CO_2 emissions from economic growth by investing in green areas depended heavily on the specific programs that were financed under the Green Growth Strategy. Due to the lack of evaluation of both the stimulus package and the Five Year Plan, it is impossible to determine how much of the spending was directly related to CO_2 emissions. One ex-ante evaluation of the 2009-2012 economic stimulus plan identified 23% of the green spending of USD 38 billion being targeted at the extension of the railway network, 20% at energy efficiency in buildings, 6% at low carbon vehicles, and 6% at low carbon power (Robins, Clover, & Singh, 2009; UNEP & GEI, 2009). These figures are similar to the breakdown that the Korean Government provided in its first progress

[5] It is important to treat this effect as a partly statistical phenomenon, as the category "non-energy use" in the IEA datasets does not necessarily mean that none of this fuel is combusted. If actually less and less of the oil entering the economy is combusted, there would be a clear mitigation effect. If on the other hand, more non-energy use only means, that actual CO_2 emissions vanish from the statistics, the CO_2 statistics show a too positive trend. The IEA lists the non-energy use of fuels as a source of error in their calculation of CO_2 emissions from fuel combustion: "the IEA assumes that 100% of kerosene, white spirit and petroleum coke that is reported as non-energy use in the energy balance is also stored. Country experts calculating the inventories may have more detailed information." (IEA, 2014b)

[6] Furthermore, it is not all clear from the available literature how large the overlaps between the stimulus package and the Five Year Plan were. Some large projects as high-speed rail and restoration of the four major rivers appeared in both plans, which suggests a large overlap (OECD, 2012; Presidential Commission on Green Growth, 2010; Robins, Clover, & Singh, 2009).

report under the Green Growth Strategy, the only major exception being that the combined share of "green car & clean energy" is reduced from 12% to 5% (Presidential Commission on Green Growth, 2010). It is important to note that just some of the relevant spending – assuming that it was carried out as planned – had the potential for short-term emissions reduction. This includes for example energy efficiency in buildings. On the other hand, investments into rail infrastructure take longer until a potential impact becomes visible. Another example is off-shore wind turbines, which take many years from start of construction until grid connection.

Within the Five Year Plan's overall budget of USD 98.8 billion, which included at least parts of the stimulus spending, the shares with relevance for CO_2 from energy were smaller (see Table 3).

Table 3: Spending items of the Five Year Plan for Green Growth 2009-2013 with potential relevance for CO_2 emissions from energy (OECD, 2012)

Spending item under the Five Year Plan	**in USD bn**	**share of total**
Total	*98.8*	*100.0%*
Construction of railways	11.7	11.9%
Other spending on climate change mitigation and energy independence	7.8	7.9%
Promoting renewable energy	3.4	3.4%
Nuclear energy development	1.6	1.7%
Developing green villages	0.9	0.9%
Mitigating vehicle emissions	0.5	0.5%
All potential low-carbon energy spending	**25.9**	**26.3%**

Despite uncertainties about the overlap between stimulus and Five Year Plan and the actual implementation of investment plans, a couple of observations can be made. First, the share of public spending with relevance for short-term CO_2 emissions reduction was comparatively small. Second, large infrastructure projects, as the construction of high-speed railways or the Four Major Rivers Restoration Project, made up larger shares of the total spending but lacked the potential for short-term emissions reductions. On the contrary, due to increased demand for resources such as concrete and expanded construction activity, they potentially increased CO_2 emissions. Hence, it is possible that the economic stimulus and the Five Year Plan were short-term drivers of the increase in CO_2 emissions, rather than instruments to mitigate emissions. This is well-reflected in our quantitative analysis, which found that both the energy mix and the energy intensity of the economy worsened their effect on CO_2 emissions between 2008 and 2012. The long-term effects of infrastructure spending under the Five Year Plan are difficult to anticipate in quantitative terms. Since the changes made to the Korean energy system were only marginal, it cannot be expected that the Five Year Plan will trigger large emission reductions in the future.

Moreover, Korea's current Three Year Plan for Economic Innovation (2014-2017) departs from the green growth agenda and puts still more emphasis on economic development. This is reflected in the headline targets of 70% employment, return to annual GDP growth of 4% and more, and increasing GDP per capita into USD 40,000. (Ministry of Strategy and Finance, 2014)

Support to renewables

The core support program for distributed renewable energy has been the One Million Green Homes Scheme, which provides since 2009 financial support for solar PV and solar thermal panels, as well as geothermal energy and small wind power. Furthermore, support at a larger scale was provided to offshore wind projects, tidal energy and wood or pellet fired boilers. (IEA, 2012)

Supplementary to these investment subsidies, a government funded feed-in tariff scheme ran between 2002 and 2011. In 2012 this scheme was replaced by a Renewable Portfolio Standard (RPS) under which the largest power generators have to produced or purchase a fixed share of their electricity from renewables, which started at 2% in 2012 and is going to rise to 10% in 2022. (Duffield, 2014)

The public support to renewable energy was the essential factor for the dynamic growth of renewable energy. It has, however, not been sufficient to help renewable energy gain a significant share in TPES and improve the carbon intensity of the overall energy mix, yet. Furthermore, several policies such as the RPS and subsidies to offshore wind and tidal energy take time to become effective.

Expanding nuclear power

Nuclear power generation appeared in our analysis as one of the few factors improving the carbon intensity of the power mix. The Korean nuclear power program started in the late 50s and built on cooperation with the US. Today Korea has the 6th largest nuclear power capacity in the world and plans further extension (S. Choi et al., 2009). However, it could not keep up with the growth of power demand so that the share of nuclear power generation decreased throughout the 90s and 2000s (as indicated by Figure 5).

Irrespective, whether nuclear power is regarded a safe and sustainable option, it is clear that short to mid-term decarbonization depends partly on the use of existing nuclear energy capacity. Several scenario analyses for deep decarbonization in Korea go much further and heavily build on nuclear power in the electricity mix (S. Hong, Bradshaw, & Brook, 2014; SDSN & IDDRI, 2014). However, the steep increase of nuclear capacity as foreseen in these scenarios, and to a lesser extent in government plans[7], is severely challenged by questions surrounding proliferation, safety, costs and, most importantly, the unsolved problem of storing spent nuclear fuels (Duffield, 2014).

Taxing road transport

Fuels for transportation are the energy products that are taxed highest in Korea, at a tax level close to the OECD average (OECD, 2013). While the level of transportation fuel taxes is high compared to other countries, the trend between 2008 and 2012 does not reflect progressive decarbonization policy. The excise duties remained roughly the same, while some fuel prices (before tax) increased. Thus, the share of excise tax in the fuel price decreased in the case of petrol and remained the same in the case of diesel and LPG (see Table 4).

[7] While the First Energy Basic Plan from 2008 envisioned a nuclear share of 41% in the 2030 electricity mix, the more recent Energy Master Plan (2014) decreased this share to 29% in 2035. Interestingly, in both plans the targeted share represents an installed capacity of 43GW, as the updated Energy Plan assumes a much higher future demand for electricity (Ministry of Trade, Industry and Energy, 2014). In order to realize 43GW nuclear capacity, the current capacity of 20.7GW has to be more than doubled. This becomes even more challenging as a couple of the operating power plants will retire in the period until 2035 (World Nuclear Association, 2015).

Table 4: Share of excise taxes in transportation fuel prices between 2008 and 2012 (IEA, 2014c) and change in CO_2 emissions from oil products in road transport

Tax share in fuel prices (before VAT)	**2008**	**2012**
Diesel	32,7%	32,2%
Petrol (95)	48,1%	38,5%
Petrol (92)	51,8%	41,3%
LPG	22,7%	22,1%
CO_2 emissions from oil products in road transport	*77.1Mt*	*80.4Mt*

While the 2020 targets for the transportation sector, i.e. GHG emissions reduction by 34% and a fuel efficiency representing 97g CO_2/km (Duffield, 2014), are ambitious, strong policy instruments are yet to be introduced. The approach of merely setting the regulatory limit of CO_2 emissions to 97 g/km by 2020 is “likely to fall short” to reach a continuous decrease of absolute emissions from passenger vehicles. For that a further reduction of the regulated limit and incentive schemes would be necessary (Ko et al., 2014). In 2009 a motor vehicle tax system that incentivizes the purchase of fuel efficient vehicles was announced for 2015, but later in 2014 it was postponed at least until 2020 (Yonhap News Agency, 2014b).

Considering the increasing CO_2 emissions from road transport, the lack of progressive fuel taxes and CO_2 based motor vehicle taxation illustrate well that green growth programs need supplementary pricing policies and regulation to be effective both on the short and long term.

Market prices for electricity

One of the main policy challenges in improving the energy intensity of the economy was artificially low electricity tariffs. State-owned KEPCO (Korea Electric Power Corporation), which controls more than 90% of power generation operated with annual losses from 2007 until 2012 due to an electricity tariff structure that did not cover costs. In 2013 two electricity tariff hikes were implemented which, in combination with stable fuel costs and a strong Korean currency, resulted in a profit for KEPCO again (K. Cho & Kim, 2014). Still tariffs were low in comparison to other OECD countries which led to a situation in which the power sector was responsible for a large share of the increase in TPES (Duffield, 2014). Once again, this suggests that a pricing reform to support the green growth spending was lacking, which helps to explain the short-term development of emission drivers that we observed.

Pricing carbon

As long as CO_2 emissions are free or even indirectly subsidized the energy mix cannot be decarbonized. Despite its Green Growth Strategy, Korea heavily subsidized fossil fuel exploration and production. Fossil fuel subsidies based on government tax expenditure totaled USD 4.3 billion in 2011 (Y.-G. Kim, 2013). Ironically, even the Five Year Plan for Green Growth included USD 4.6 billion for the development of foreign oil fields (OECD, 2012).

Moreover, there were no or only marginal explicit or implicit taxes on carbon in Korea between 2008 and 2012 other than the transportation taxes mentioned above (IEA, 2014c). A nation-wide carbon tax was debated for many years but was never introduced. In the context of the Green Growth Strategy, a target management scheme for CO_2 emissions was implemented – also to establish a basis in monitoring, reporting and verification of emissions and prepare for the later introduction of an emissions trading scheme (ETS). Under the target management scheme and starting in 2012, facilities with emissions higher than 25kt CO_2 had to agree with the government on CO_2 emission targets and energy conservation targets. From 2014 on also facilities with annual emissions higher than 15kt were included (GIR, 2014). The impact of the target management scheme on emissions has not been evaluated, yet.

4. Key policy challenges in short and mid-term decarbonization

From an historical perspective, our findings show that the long-term drivers of the steep increase in CO_2 emissions were not halted or even reversed under the Korean Green Growth Strategy (as summarized in Table 5). This is due to the numerous structural and political factors that have kept Korea on an emission growth trajectory: rapid economic growth, the sustained high share of energy intensive industries, the increasing dependence on coal in the power sector, the marginal share of renewable energy, the disputable safety of nuclear power and the challenge of storing spent nuclear fuel, the low retail price of electricity, as well as environmentally harmful subsidies to fossil fuel exploration, production and infrastructure.

Table 5: Overview of factors impacting energy CO2 emissions and related policy factors 2009-2013

Drivers	**Impact on CO_2 emissions***		**Driver-related policy challenges**
	1971-2012	**2008-2012**	
Economic activity (GDPpc)	↗	↗	Orienting policies towards improvements in well-being rather than GDP growth[8]
Energy transformation (TPES/TFC)	↗	↗	Introduce carbon pricing to improve the efficiency of power generation (e.g. substitution of coal by natural gas)
Energy intensity (TFC/GDP)	↘	→	Carbon pricing and market pricing of electricity to improve energy efficiency Incentives for energy efficiency in transportation and the residential sector Tax shift from labor to energy in order to incentivize the tertiarization of the economy
Emission factors (CO_2/TPES of various fuels)	↘	↘	
Energy mix (shares of various fuels in TPES)	→	↗	Effective support to renewable energies Clarification of the role of nuclear power Carbon pricing

* The arrows stand for the respective factor's impact on CO_2 emissions (→ = stable; ↗ = enhancing; ↘ = mitigating).

In order to identify which policies are necessary to effectively drive a low-carbon economy in Korea, it is useful to have a look at the development of various drivers in two different target-fulfillment scenarios (see Figure 6). In 'Scenario A' we make the conservative assumptions that TPES will grow 2.1% per year, that GDP (PPP constant USD) will grow 2.6% per year, and that the share of CO_2 emissions from fuel

[8] This distinction between the improvement of well-being and GDP growth is informed by relevant literature from ecological economics (cf. Daly, Cobb, & Cobb, 1994; Jackson, 2011), the clear distinction between income and happiness (Easterlin, 1995), and the comprehensive criticism of GDP as the key metrics for economic development (Stiglitz, Sen, & Fitoussi, 2009).

combustion in total GHG emissions will remain constant.[9] 'Scenario B' is a more stringent sustainability scenario, where annual GDP growth amounts to 1% and TPES remains stable. The assumptions about GDP and TPES in Scenario A are optimistic but within the range of government projections, while Scenario B goes far beyond projected developments.

In order to reach the 2020 CO_2 emissions target of 30% reduction against BAU the carbon intensity effect has to mitigate 179Mt CO_2 by 2020 in Scenario A and 101Mt in Scenario B. The energy intensity effect has to contribute with another 36Mt (Scenario A) and 46Mt (Scenario B) respectively.

This brief comparison illustrates that even under the extreme assumptions of 1% annual GDP growth and no increase in TPES, a quick and radical decarbonization of the energy mix is needed to meet the self-imposed climate target. Such a rapid change is unprecedented since 1971 – our initial year of historical analysis. Furthermore, the comparison between the two scenarios illustrates that significantly less decarbonization of the energy mix is needed, if the economy is growing at a lower rate and energy intensity is improving more rapidly.

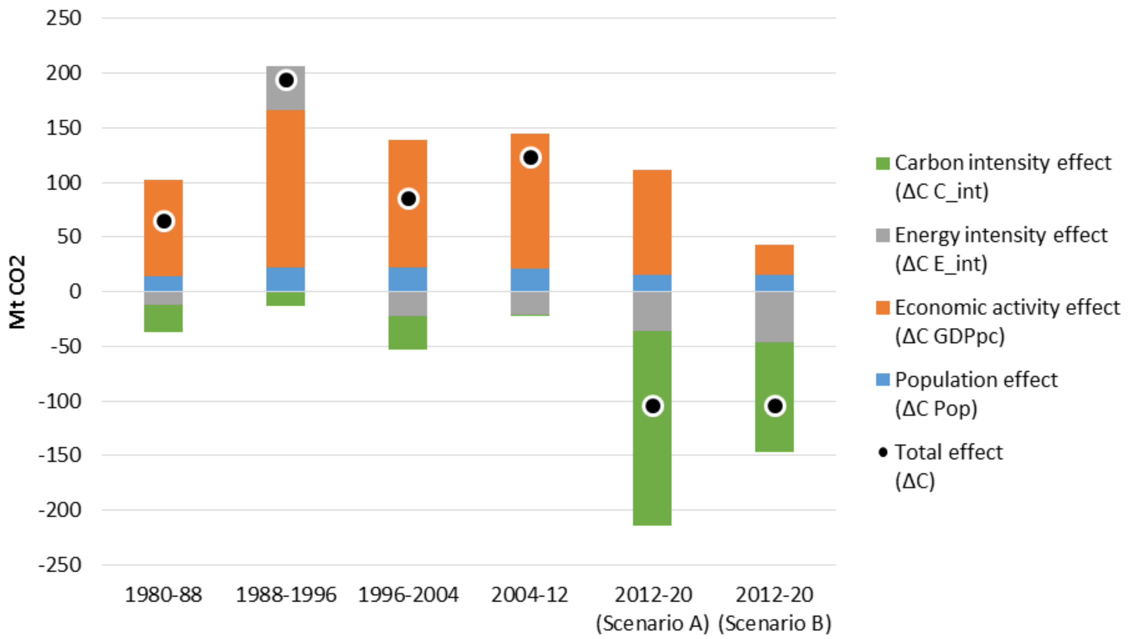

Figure 6: Additive LMDI decomposition analysis of CO2 emissions until 2020 based on emissions reduction target and energy intensity target

Despite the start of the ETS in 2015 and the modestly ambitious RPS, full implementation of current policies would only result in emissions reduction to between 630Mt and 670Mt CO_2 in 2020 (see range shown in Figure 7) – falling about 100Mt CO_2 short of the Korean pledge of 569Mt (Roelfsema et al., 2014). From a target fulfillment perspective, one example for insufficient policies is the newly introduced ETS[10]. In order to reach the emissions reduction target, the cap will have to decrease to 360Mt CO_2 by

[9] The Korea Energy Demand Outlook from 2014 calculates in its low-growth scenario with an average annual increase of GDP by 2.6% and of TPES by 2.1% between 2013 and 2018 (KEEI, 2014).

[10] The ETS started only in 2015. Its first trading period (2015-2017) is a testing phase, in which all allowances are allocated for free (grandfathering). Several last minute changes were made to the ETS, to relax its impact on

2020 (Bloomberg NEF & Ernst & Young, 2013). A steep reduction like this is virtually impossible, since for the period 2015-2017 allowances representing 1,687Mt CO_2 are allocated, on average 562Mt per year (M. Cho, 2014), which is still largely above of what is needed by 2020.

In the context of the ETS the RPS can be seen as an instrument to lower the abatement costs for the power sector. It does not affect the cap of the ETS, but compliance for the power sector becomes cheaper. The RPS's 2020 target of 11% renewable electricity is demanding and it will help to drive up the share of renewables on the long run if fully and effectively implemented. Still it will not be sufficient to achieve the decarbonization of the energy mix that is required to reach the emission reduction target of 30% against BAU.

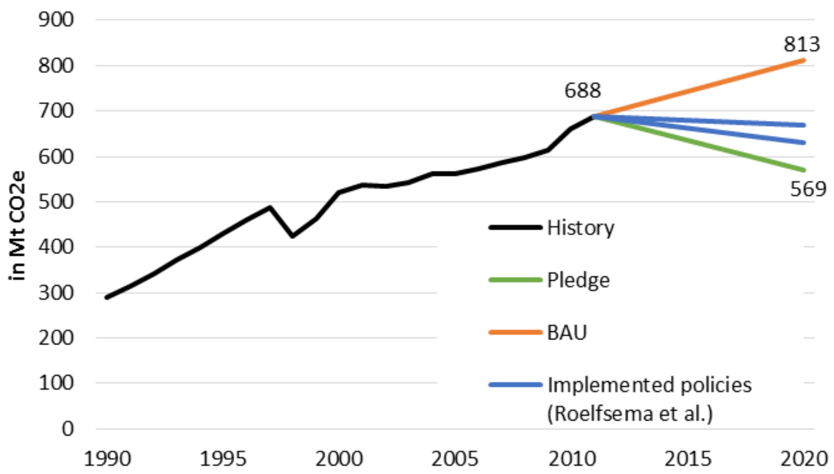

Figure 7: Different scenarios for the development of GHG emission in South Korea 2011-2020 (adapted from Roelfsema et al., 2014)

The key policy challenges that can be derived from the ex-post analysis of emission drivers and the ex-ante analysis of two target-fulfillment scenarios are listed below (in brackets we indicate in italics which drivers are addressed):

- Evaluate the existing portfolio of policy instruments, verify results, withdraw inefficient and ineffective policies and make the necessary corrections so policies are capable of achieving the impacts and outcomes that justify their existence. (*all drivers*)
- Find ways to reorient economic policies from GDP growth to improvements of well-being, job creation, and a structural change of the economy. (*economic activity*)
- Enable growth in the service sector by lowering labor costs relative to energy costs, e.g. by shifting taxes from labor to energy consumption and CO_2 emissions in a comprehensive ecological tax reform. (*energy intensity*)
- Ensure a significant and stable price on carbon to improve the efficiency and carbon intensity of power generation, e.g. by substituting coal with low carbon technologies). (*energy transformation, energy intensity and energy mix*)

industry. The cap was increased by about 3% still in September 2014 (M. Cho, 2014); and in December 2014 the Korean government decided to exempt emissions trading from taxation (Yonhap News Agency, 2014a).

- Speed up the transition towards a renewable energy system by ensuring a stable and reliable support scheme both for individuals and for large power generators. (*energy mix*)
- Address the challenges of nuclear safety, management of spent fuels and public acceptability and re-evaluate the role that nuclear power can play in the decarbonization of the economy. (*energy mix*)
- Increase electricity tariffs by introducing market pricing and taxes in order to manage demand and incentivize energy efficiency. (*energy intensity*)
- Reduce CO_2 emissions in road transport by giving incentives for the purchase of low-emission vehicles, e.g. by a revenue neutral feebate system that rewards the purchase of low-emission vehicles and progressively taxes vehicles with high CO_2 emissions. (*energy intensity*)

Successful decarbonization of the Korean economy needs to address various drivers and cannot rely on an expansion of low-carbon technology alone. The reasons for this are summarized well in the outlook that the International Energy Agency provides (IEA, 2012), stressing that the country is densely populated, heavily reliant on energy-intensive industries, and has not yet started to considerably utilize its renewable energy potential , in particular offshore wind and tidal energy (cf. G. Kim et al., 2012). Korea is therefore likely to rely on fossil fuels for a large part of its energy demand in the foreseeable future. As energy demand is likely to increase, a reduction in the share of coal and gas might in absolute terms still translate into a rise in consumption. In other words: without a rapid improvement of the energy intensity of the economy (including both energy efficiency and structural change of the economy) CO_2 emissions from energy are likely to rise for another decade and more. The prevailing concentration of large shares of GDP in few energy intensive industries does not only pose environmental risks (Duffield, 2014), but increases the vulnerability of the economy, which means that the strengthening of the service sector represents an opportunity to support a low-carbon economy (cf. W. Choi et al., 2013; D. Park & Shin, 2012).

5. Conclusions

Korea's green growth ambitions, and in particular its green stimulus spending, have been frequently referred to as good practice in the international policy arena. Our findings, however, do not fully support this reading of the impacts of the Korean Green Growth Strategy. One key macro-economic indicator of green growth, namely CO_2 emissions from energy, reveals a low performance, i.e. CO_2 emissions increased significantly. We neither observed a change in trends when decomposing CO_2 emissions into various drivers in the short-term (2008 – 2012), nor when comparing estimated short-term trends to the historical long-term drivers of CO_2 emissions. While it is impossible to attribute driver-specific changes in CO_2 emissions to general policy programs, it is clear that the National Green Growth Strategy of Korea between 2009 and 2013 has not yet been successful in reversing the long-term trend of increasing CO_2 emissions. The targeted peak of emission in 2014 has most likely not occurred, yet.

Some possible explanations for the estimated figures arise from the policy review. First, the specific allocated amount for low-carbon technologies was in fact very modest and measures devoted to short-term effects, such as energy efficiency in buildings and transportation, did not deliver as expected. Secondly, and due to the empirical nature of our study, findings are incapable to capture future long-term effects. In addition, some key policy instruments have been implemented recently: a renewable portfolio standard was introduced in 2012 and the emissions trading scheme was launched in January

2015. Thirdly, the stimulus package was not supported by complementary pricing reforms (transport and electricity) that are also needed to drive a green economy.

The results of our analysis reflect the most challenging aspect of any green or low-carbon growth policy: how to make economic growth truly compatible with low CO_2 emissions, i.e. how to make it coincide with radical improvements of the energy intensity of the economy or the carbon intensity of the energy system. A serious green growth policy program needs to phase out rather than include subsidies to fossil fuels; it further needs to attempt the greening of the existing economy by changing its structure and improving its efficiency instead of merely supporting additional ‘green growth engines’. Above all, it has to go beyond public spending and include ambitious targets and supplementary policies, such as pricing reforms, carbon-energy taxes and stringent regulatory frameworks. Whether all of the above is still compatible with economic growth rates as high as Korea enjoyed them in previous decades is not self-evident. Whereas it is clear that without policies as they are outlined above high economic growth rates do not seem compatible with the decarbonization of the economy.

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Appendix

A. Input data for LMDI decomposition analysis and econometric tests

Table 6: Input data for LMDI and econometric tests

	TPES (in Mtoe)						TFC	CO2 from fuel combustion (in Mt CO2)					Population (in million)	GDP (in bn 2005 USD)
	Oil	Coal	Natural Gas	Biofuels & waste	Non-carbon TPES	TOTAL	TOTAL	Oil	Coal	Natural gas	Other	TOTAL		
1971	11	6	0	0	0	17	14	31	21	0	0	52	33	88
1972	12	7	0	0	0	18	14	32	22	0	0	54	34	92
1973	13	8	0	0	0	22	17	40	27	0	0	67	34	103
1974	15	9	0	0	0	23	18	42	29	0	0	71	35	110
1975	16	9	0	0	0	24	19	46	31	0	0	77	35	116
1976	17	10	0	0	0	27	21	52	33	0	0	85	36	129
1977	21	10	0	0	0	32	25	62	36	0	0	98	36	142
1978	24	10	0	0	1	35	27	70	37	0	0	106	37	155
1979	27	12	0	0	1	40	30	78	42	0	0	120	38	165
1980	27	14	0	0	1	41	31	76	48	0	0	124	38	163
1981	24	15	0	0	1	40	31	75	54	0	0	129	39	173
1982	26	16	0	0	1	43	31	74	55	0	0	129	39	186
1983	27	17	0	0	3	47	33	77	60	0	0	137	40	205
1984	27	20	0	0	4	51	36	76	73	0	0	149	40	222
1985	26	22	0	0	5	54	38	73	80	0	0	153	41	237
1986	29	24	0	0	8	61	42	76	84	0	0	160	41	262
1987	29	24	2	0	11	66	45	78	84	4	0	166	42	292
1988	35	25	2	0	11	74	50	94	89	6	0	189	42	323
1989	38	25	2	0	13	79	54	109	85	6	0	200	42	344
1990	50	25	3	1	15	93	65	135	86	6	1	229	43	376
1991	56	25	3	1	15	100	72	158	87	7	2	254	43	411
1992	69	22	4	1	15	111	81	183	82	10	2	277	44	435
1993	78	25	5	1	16	124	89	199	91	12	2	304	44	462
1994	83	26	7	1	16	132	96	215	96	16	2	329	45	502
1995	91	27	8	1	18	145	105	234	102	19	4	359	45	547
1996	97	29	11	1	20	157	112	239	117	26	2	384	46	586
1997	105	32	13	1	20	171	119	248	126	31	2	408	46	613
1998	87	32	12	1	24	156	107	189	130	29	3	351	46	571
1999	95	34	15	1	27	173	118	210	136	36	3	385	47	625
2000	99	42	17	1	29	188	127	220	174	40	5	438	47	678
2001	96	45	19	1	30	191	130	217	186	44	5	452	47	705
2002	97	47	21	2	31	199	135	214	178	49	5	446	48	756
2003	96	49	22	2	34	203	138	212	181	51	6	449	48	777
2004	96	50	25	2	34	208	138	208	195	60	7	470	48	813
2005	92	50	27	2	39	210	140	204	195	64	6	469	48	845
2006	91	53	29	2	39	214	142	196	205	68	7	477	48	889
2007	94	56	31	3	38	222	147	198	211	73	8	490	49	934
2008	90	63	32	3	40	227	147	181	236	75	9	502	49	955
2009	91	65	32	3	39	229	148	182	253	72	9	516	49	959
2010	95	73	39	3	39	250	158	187	277	91	10	564	49	1019
2011	94	80	42	4	41	260	161	183	298	98	12	590	50	1057
2012	97	77	45	4	40	263	166	184	291	106	12	593	50	1078

B. Detailed results of econometric analysis

First, all independent variables showed the potential to individually explain the behavior of Korea's CO_2 emissions (see **Error! Reference source not found.**). The variable that showed the highest correlation with CO_2 was *GDPpc* (99.4%). However, the fact that independent variables appeared highly correlated indicated early signs of multicollinearity for the regression analysis.

Table 7: Bivariate correlation test (n=42; all correlations significant at 0.01 level)

	CO_2	*Pop*	*GDPpc*	*E_int*	*C_int*
CO_2	1	0.964*	0.994*	0.660*	-0.912*
Pop		1	0.956*	0.731*	-0.946*
GDPpc			1	0.588*	-0.912*
E_int				1	-0.695*
C_int					1

Estimates from partial correlation tests started to confirm the initial hypothesis: *GDPpc* is the most significantly correlated variable (98.1%) with CO_2 emissions (see **Error! Reference source not found.**). The level of correlation dropped marginally (-1.3%) compared to bivariate correlation tests. This suggested that the relationship between CO_2 and *GDPpc* was slightly mediated by *P, E_int* or *c_int*. Partialling out *P*, *GDPpc*, and *C_int* individually suggested that *E_int* was the principal mediator (86.8%).[11]

Table 8: Partial correlations tests

Controlled variables: *GDPpc, E_int, C_int*		***CO_2***
Pop	Correlation	-0.259
	p-value	0.111
Controlled variables: *E_int, C_int, Pop*		***CO_2***
GDPpc	Correlation	0.981
	p-value	0.000
Controlled variables: *GDPpc, Pop, C_int*		***CO_2***
E_int	Correlation	0.868
	p-value	0.000
Controlled variables: *GDPpc, Pop, C_int*		***CO_2***
C_int	Correlation	0.888
	p-value	0.004

Results from the stepwise regression can be summarised as follows (see **Error! Reference source not found.**). First, all variables but *Pop* were introduced in our original model (in the following 'Model 1'), which was based on eq. (4). Model 1 was significant ($F_{3, 38}$ = 4710.29; *p*-value = 0.000) and explained 99.7% of the variability of CO_2 emissions (R^2 = 0.997). The coefficient of variation for Model 1 ($Coef\_Var_{Model\text{-}1}$= Std. error estimate (+/-9.29) / mean value of CO_2 emissions (285.74 $MtCO_2$)) yielded a value of 3.25%, which suggested that large fluctuations of CO_2 emissions could be explained by the estimated model. However, estimated VIF values for Model 1 revealed strong signs of multicollinearity,

[11] In addition, partial correlation results also revealed that the relationship between $C0_2$ and *E_int* was significantly mediated by *Pop* and *C_int* in particular (correlation increased from 66-6% to 86.8%). In fact, the relationship between $C0_2$ and *Pop* was no longer significant ($p\text{-value}_{Pop}$ = 0.111).

with estimated indexes for *GDPpc* and *C_int* in particular, much higher than the defined maximum threshold value.

Table 9: Summary output from stepwise regression analysis

REGRESSION SUMMARY	R	R^2	Adjusted R^2	Std. Error		
Model 1*	0.999	0.997	0.997	9.29		
Model 2**	0.998	0.996	0.996	11.08		
ANOVA		**Sum of Squares**	**df**	**Mean Square**	**F**	***p*-value**
Model 1*	Regression	1220304.51	3	406768.17	4710.29	0.000
	Residual	3281.57	38	86.35		
Model 2**	Regression	1218797.91	2	609398.96	4963.60	0.000
	Residual	4788.16	39	122.77		
COEFFICIENTS		**β (Standardised)**	**Std. Error**	***t***	***p*-value**	**VIF**
Model 1*	β_0	-403.27	49.63	-8.12	0.000	-
	β_2 *(GDPpc)*	1.000	0.00	48.35	0.000	6.05
	β_3 *(E_int)*	0.140	93.80	11.83	0.000	1.98
	β4 (C_int)	0.097	11536.00	4.17	0.000	7.66
Model 2**	β_0	-210.65	21.88	-9.62	0.000	-
	β_2 *(GDPpc)*	0.925	0.00	74.69	0.000	1.52
	β_3 *(E_int)*	0.116	98.27	9.39	0.000	1.52

* Predictors: (Constant), *GDPpc*, *E_int*, *C_int*
**Predictors: (Constant), *GDPpc*, *E_int*,

As a consequence, a second simulation round took place. This resulted in 'Model 2' containing only *GDPpc* and *e_int* as significant drivers for South Korea's CO_2 emissions. Model 2 was significant ($F_{2, 39}$ = 4963.6; *p*-value = 0.000) and the estimated adjusted R^2 was still very high: 99.6% of the variability of CO_2 emissions is explained collectively by *GDPpc* and *E_int*. This level of determination was only marginally reduced compared to Model 1 (see Table 6). Although the standard error was slightly higher (+/- 11.08 $MtCO_2$) compared to Model 1, the estimated $Coef\_Var_{Model\text{-}2}$ was equal to 3.87%, which suggested that Model 2 would also be useful in predicting CO_2 emission interval values (i.e. ratio is lower than 10% threshold). VIF measures revealed no signs of multicollinearity, with estimated values for the independent variables equal to 1.52, a value lower than the defined 5 maximum threshold value. Finally, estimated coefficients (standardised) confirmed that *GDPpc* had the strongest impact on CO_2 emission levels.

C. Further details of the LMDI decomposition analysis

The two figures presented below provide a closer look at the drivers energy intensity and carbon intensity of energy in the LMDI decomposition analysis. In most decomposition analyses energy intensity is based on TPES (cf. IEA, 2014b). Figure 8 shows that basing energy intensity on final consumption, and hence extracting the energy transformation effect, results in a more differentiated picture of the effect of energy intensity on CO_2 emissions. In this case energy intensity based on final consumption had a more consistent mitigation effect on CO_2 emissions since the late 90s than energy intensity based on TPES.

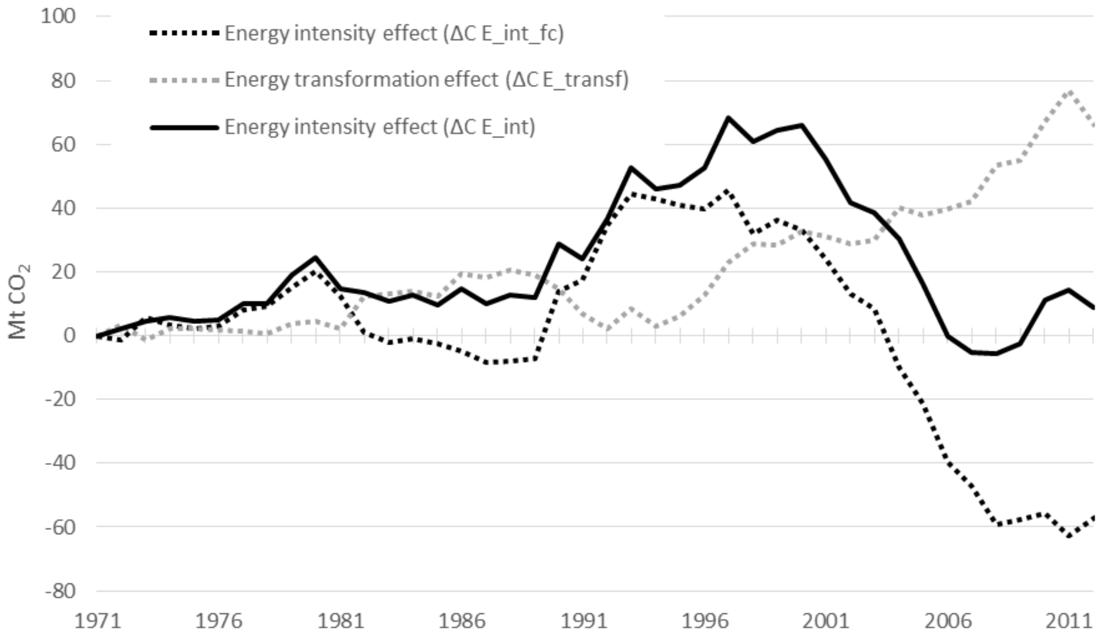

Figure 8: Results of additive LMDI decomposition analysis of CO_2 emissions – energy intensity and energy transformation effect

Similarly, splitting the carbon intensity of energy effect into an energy mix and emission factor effect reveals new trends. Both the mitigating effect of lowering emission factors since the early 90s and the increase of emission due to changes in the energy mix after 2005 were "hidden" in the carbon intensity of energy effect.

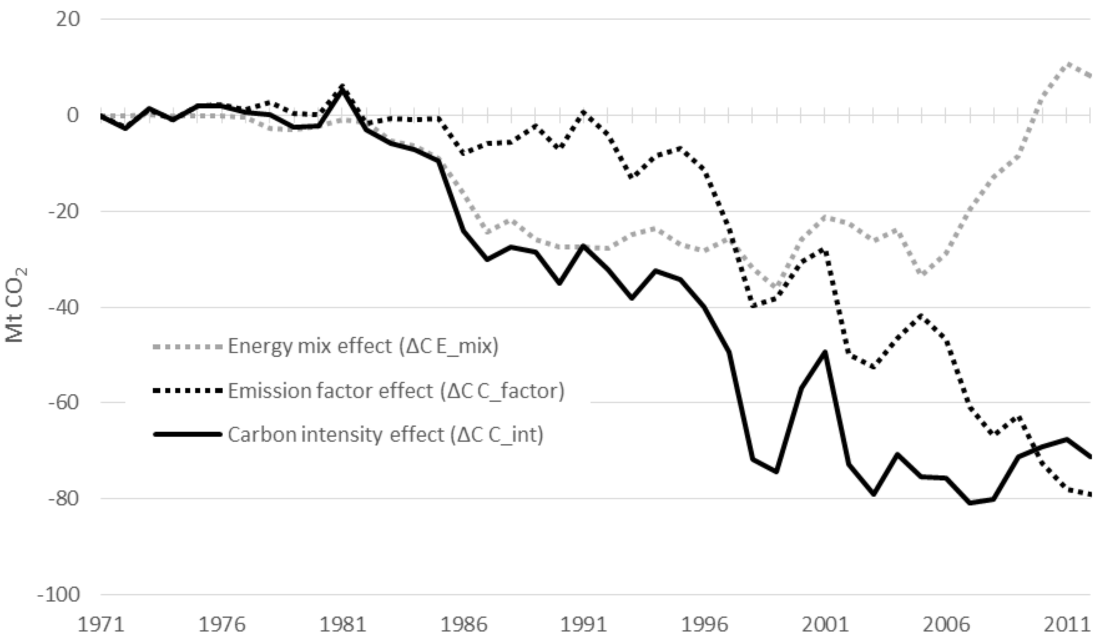

Figure 9: Results of additive LMDI decomposition analysis of CO_2 emissions – carbon intensity, energy mix and emission factor effect