Long-Term Increases and Recent Slowdowns of CO₂ Emissions in Korea

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Abstract: Korea is one of the fastest-growing CO₂-emitting countries but has recently experienced a dramatic slowdown in emissions. The objective of the study is to examine the driving factors of long-term increases (1990–2015) and their slowdown (2012–2015) in emissions of Korea. This study uses an extended index decomposition analysis model that better fits Korea’s emission trends of the last 25 years by encompassing 19 energy end-use sectors (18 economic sectors and a household sector) and three energy types. The results show that emission increases in the long term (1990–2015) come from economic growth and population growth. However, improvements in energy intensity, carbon intensity, and economic structure offset large portions of CO₂ emissions. The recent slowdown (2012–2015) mainly resulted from a decline in energy intensity and carbon intensity in the economic sectors. Among the different energy types, electricity has played a significant role in decreasing emissions because industries have reduced the consumption of electricity per output and the source of electricity generation has shifted to cleaner energies. These results imply that the Korean government should support strategies that reduce energy intensity and carbon intensity in the future to reduce CO₂ emissions and maintain sustainable development.

Keywords: CO₂ emission; index decomposition analysis; energy intensity; electricity; Korea

1. Introduction

South Korea is one of the fastest-growing GHG (greenhouse gas)-emitting countries. The average annual growth rate of Korea’s GHG has been 3.8% since 1990, the highest among the Organisation for Economic Co-operation and Development (OECD) members (e.g., USA 0.3%, EU –0.6%, and OECD 0.2%) [1]. This rapid increase in CO₂ emissions has led Korea to become the fourth largest contributor to climate change among OECD countries as of 2014, an increase in ranking from eighth in 1990 [2].

However, Korea has recently experienced a dramatic slowdown in GHG growth. The annual average emission growth rate has dropped to 0.3% since 2012. Furthermore, the economy achieved negative emission growth in 2014 for the second time [3]. This was phenomenal, as its first cut in 1998 was due to the Asian financial crisis that reduced CO₂ emissions in other Asian countries including China, Japan, Indonesia, Thailand, Malaysia, and the Philippines [2]. An interesting question is how Korean society achieved this slowdown in recent years after experiencing a long-term emission increase.

This study aims to examine the driving factors of the national energy-related CO₂ emissions in Korea between 1990 and 2015. We are particularly interested in the drivers that led to the emission downturn after 2012. To find the driving forces, we use index decomposition analysis (IDA). Another popular approach in the literature is structural decomposition analysis (SDA). For our analysis, IDA is more useful, as it requires a smaller amount of data compared to SDA. IDA uses aggregated sectoral data so that it is useful to calculate with relatively long-term datasets. Unlike, SDA can capture indirect effects of final demand on CO₂ emission growth by using input–output tables. However,
the input–output tables are not usually published annually and long-term datasets are not available (see [4,5] for a detailed comparison between IDA and SDA).

It is not difficult to find IDA studies in energy or environmental fields. For example, in a case study about Turkish CO$_2$ emission growth, [6] found that the economic activity was the main driver of it. Ref. [7] found that fuel shifts are the biggest contributor to the reduction in CO$_2$ emissions from EU’s power sector after 2007. Ref. [8] demonstrated that the use of household appliances has increased Chinese residential energy consumption between 2002 and 2010. The IDA technique is also applied to group studies across 33 countries [9], G20 countries [10], the European Union [11], and the Asia-Pacific Economic Cooperation (APEC) countries [12]. Two survey papers by [13,14] covered a comprehensive and in-depth review on the IDA studies. This method is also employed for Korea’s energy consumption and CO$_2$ emissions. Ref. [15] analyzed Korea’s energy-related CO$_2$ trends with four driving factors in three terms (1990–1997, 1997–1998, and 1998–2005) for 14 sectors. They found economic growth contributed the most to CO$_2$ emission increases in Korea. Since manufacturing is one of the primary CO$_2$-emitting industries in Korea, [16,17] focused on the industrial sector’s emissions and found that the effects of structural change and energy intensity play major roles in offsetting greenhouse gas emissions in Korea. However, these studies do not address the recent slowdown that has happened since 2012.

We further adopted the IDA method to better fit the emission trends in Korea over the last 25 years. The household sector plays a significant role in Korea’s emission growth [18]. Accordingly, we introduced an extended model similar to [19,20] and considered not only economic sectors, but also the household sector, which is not typically considered in the standard IDA model [21]. Additionally, [18] reported that Korea has increased CO$_2$ emissions by consuming more electricity and gas, but fewer coal and oil products. To capture contributions of each energy sector to emission changes in the last few years, we further decompose the results into three energy types (coal and oil products, electricity, and gas). We find that electricity in particular played a significant role in recent emission reductions in Korea. This conclusion would not have been realized without this detailed disaggregation.

The rest of this paper is organized as follows: In Section 2, we explain the data and decomposition methodology in detail. Section 3 presents the results of IDA and we discuss the significance of the results. Section 4 concludes our arguments.

2. Data and Methodology

2.1. Estimation of CO$_2$ Emissions by Sector

The estimation procedure of energy-related CO$_2$ emissions follows the IPCC 1996 guidelines [22]. Sectoral energy consumption data are employed from the energy balance [23] that contains energy use by fuel type (primary energy), energy transformation, and energy end-use sectors (final energy). Primary energy is the sum of final energy and energy transformation. Our analysis is based on the sum of final energy and energy transformation to analyze CO$_2$ emissions by end-use sectors. Consequently, we examined national energy-related CO$_2$ emissions. We focus only on the use of fossil fuels in the final energy because non-fossil energies such as nuclear, hydro, renewable energy, and biomass combustion are excluded from energy-related carbon emissions according to [24] and international conventions, such as [25]. In order to estimate CO$_2$ emissions, two factors are adopted: the conversion factor and carbon emission factor. The former is to convert gross calorific values into net calorific values, while the latter one is to acquire the amount of CO$_2$ emissions according to energy consumption. Following the recommendations of [24,26], national specific emission factors [3] are used rather than IPCC data. We provide a sensitivity analysis by using the IPCC emission factors in the Supplementary Materials.

Table 1 presents the re-classified energy end-use sectors for the sectoral analysis. We match the end-use sector of the energy balance with the industry of national accounts [27]. Apart from the economic sectors, we also take into account the household sector involving the residential sector and household vehicle use. We reallocate the contribution of private car use to emission increases,
which originally belonged to land transportation, into the household sector for the following reasons: (i) the literature usually classifies energy consumption associated with private car use as household energy consumption (e.g., [28, 29]); (ii) private car use hardly makes economic profit; and (iii) a change in the fuel used in private cars is related to the lifestyle of the household. In order to separate energy consumption for household vehicle use from the land transportation sector, the Energy Consumption Survey [30] and Transportation Statistics [31] are used.

| Economic sectors | This Study | Energy Balance | National Account |
|------------------|------------|----------------|-----------------|
| 1. Agriculture and fishery | Agriculture and fisheries | Agriculture, forestry, and fishing |
| 2. Mining | Mining | Mining and quarrying |
| 3. Food and tobacco | Food and tobacco | Food, beverages, and tobacco products |
| 4. Textile and apparel | Textiles and apparel | Textile and leather products |
| 5. Wood, wood product, and publications | Wood and wood products | Wood and paper products, printing, and reproduction of recorded media |
| 6. Petroleum chemical | Petroleum chemical | Petroleum, coal products, and chemical products |
| 7. Non-metallic mineral products | Non-metallic | Non-metallic mineral products |
| 8. Iron and steel | Iron and steel | Pig iron and crude steel |
| 9. Non-ferrous metal | Non-ferrous | Nonferrous metal ingots and primary nonferrous metal products |
| 10. Fabricated metal | Fabricated metal | Fabricated metal products |
| 11. Electronic equipment, transportation equipment, and other manufactured products | Other manufacturing | Machinery, equipment, electronic, electronic equipment, precision instruments, transportation equipment, and other manufactured products |
| 12. Construction | Construction | Construction |
| 13. Commercial | Commercial | Services except for transportation, public administration, and defense |
| 14. Public | Public | Public administration and defense |
| 15. Rail transportation | Rail transportation | | Transportation ¹ |
| 16. Water transportation | Water transportation | | |
| 17. Air transportation | Air transportation | | |
| 18. Road transportation | Land transportation | | |
| Household | Household (including household vehicle use) | Residential | Household final consumption expenditures |

¹ Transportation national account was divided into four kinds of transportations in the energy balance column (#15 to #18) according to [30].

We reallocate the CO₂ emissions from energy transformation into the energy end-use sectors (the 18 economic sectors and the household sector) as in [1]. In the energy balance for Korea [23], energy transformation consists of electricity generation, district heating, gas manufacturing, and its own use and loss. Electricity and gas are the goods produced by other energies, but at the same time, they are the energies consumed by end-users. Some studies treat them as economic sectors, while others regard them as energy types like coal, oil, and natural gas [14, 32]. This study treats them as types of energies because it is important to capture electricity and gas consumption behavior given recent trends in Korea. The energy substitution of coal and oil products with electricity or gas is a remarkable trend in Korea’s recent energy use [18]. As electricity and gas are ultimately consumed by end-users, the associated carbon emissions also need to be assigned to the 19 end-use sectors.

This study examines a relatively longer term of data, over 25 years (1990–2015 inclusively) for analysis. We use the Korean energy balance database from 1990 because data prior to 1990 do not
distinguish residential sectors from commercial sectors. The last year for this analysis is 2015. National account sector classification has dramatically changed since 2015 such that matching the end-use sector of energy balance with that of national accounts in a systematic manner is impractical. Data frequency is annual. As the analysis relies on multiple datasets, uncertainty may exist, such as data quality or measurement assumptions. For example, measurement errors in national accounts are recognized in the economics literature [33–35]. The energy balance database also carries uncertainty in measuring energy demand and supply. Accordingly, the influence of uncertainty on the results and conclusions can vary with such datasets.

2.2. IDA

We extend the Kaya identity [36] to differentiate the 18 economic sectors from the household sector. The national energy-related CO\(_2\) emissions at time \(t\) consists of emissions in the economic sector \(i\) and in the household sector \(H\).

\[
\text{CO}_2 = \sum_i \text{CO}_2^i + \text{CO}_2^H = \sum_i \text{CI} \cdot \text{EI} \cdot \text{STR} \cdot \text{PGDP} \cdot \text{POP}_i + \text{CIH} \cdot \text{EIH} \cdot \text{HC} \cdot \text{POP}_H.
\]

(1)

where \(\text{CO}_2\), \(\text{Energy}\), \(\text{GDP}\), \(\text{HFCE}\), and \(\text{POP}\) are abbreviations for \(\text{CO}_2\) emissions, energy consumption, real gross domestic product, household final consumption expenditure, and population, respectively. To simplify the notation, each factor is rewritten as \(\text{CI}\) for the carbon emissions per energy use, \(\text{EI}\) for the energy consumption per GDP, \(\text{STR}\) for the economic structure, \(\text{PGDP}\) for GDP per capita, \(\text{CIH}\) for the household carbon emissions per energy use by households, \(\text{EIH}\) for the household energy consumption per household expenditure, and \(\text{HC}\) for household final consumption expenditure per capita.

We then apply the LMDI approach for its simplicity and popularity in recent IDA studies (see [5,37,38] for detail on the desirable properties of the LMDI). Changes in carbon emissions between two periods can be decomposed as follows:

\[
\Delta \text{CO}_2 = \sum_i \Delta \text{CO}_2^i \left( \frac{\Delta \ln \text{CI}^i}{\Delta \ln \text{CO}_2} + \Delta \ln \text{EI}^i + \Delta \ln \text{STR}^i + \Delta \ln \text{PGDP} + \Delta \ln \text{POP}_i \right) + \Delta \text{CO}_2^H \left( \frac{\Delta \ln \text{CIH}}{\Delta \ln \text{CO}_2} \Delta \ln \text{EIH} + \Delta \ln \text{HC} + \Delta \ln \text{POP}_H \right)
\]

(2)

where \(\text{CI} = \sum_i \left( \frac{\Delta \text{CO}_2^i}{\Delta \ln \text{CO}_2} \Delta \ln \text{CI}^i \right)\) and others are similar forms.

Economic sectors consequently have five effects (\(\text{CI}, \text{EI}, \text{STR}, \text{PGDP}\), and \(\text{POP}\)), while the household sector has four (\(\text{CIH}, \text{EIH}, \text{HC},\) and \(\text{POPH}\)). The \(\text{CI}\) effect measures not just changes in the conversion and carbon emissions factors, but also changes in fuel types (e.g., changes in the relative mix of electricity sources). The \(\text{EI}\) effect captures the energy consumption per GDP, reflecting innovation in energy efficiency technology. The effect of the shift in economic structure in terms of carbon emissions (e.g., from a high-carbon economy to a low-carbon economy or vice versa) is assessed in \(\text{STR}\). The PGDP effect captures the economic growth (GDP per capita), whereas the POP effect represents the population growth. The summation of the five factors is consequently identical to the \(\text{CO}_2\) emissions increase in the 18 economic sectors. In the case of households’ contribution, \(\text{CIH}\) and \(\text{EIH}\) account for households’ substitution among energies and changes in energy consumption per household expenditure, respectively. The HC factor captures changes in households’ expenditure per capita. Lastly, \(\text{POPH}\) measures the contribution of population growth to households’ emissions increases. Table 2 shows driving factors’ acronyms and descriptions.
Table 2. Driving factors: acronyms and descriptions.

| Sector         | Factor | Description                  |
|----------------|--------|------------------------------|
| Economic Sector| CI     | Changes in carbon intensity  |
|                | EI     | Changes in energy intensity  |
|                | STR    | Shift in economic structure  |
|                | PGDP   | Growth in GDP per capita     |
|                | POP    | Growth in population         |
| Household      | CIH    | Changes in carbon intensity of household |
|                | EIH    | Changes in energy intensity of household |
|                | HC     | Growth in households’ expenditure per capita |
|                | POPH   | Growth in population         |

3. Results and Discussion

3.1. Driving Forces of the Increase in CO₂ Emissions between 1990–2015

Korea’s CO₂ emissions have increased from 228.1 megatonnes (Mt) CO₂ in 1990 to 609.2 MtCO₂ in 2015. The right side of Table 3 displays the contributions of nine driving factors of the total emission increase for the last 25 years (381.2 MtCO₂ = 609.2 MtCO₂ − 228.1 MtCO₂) and reveals that the effect of economic growth (PGDP) is dominant. Economic growth (PGDP) accounts for 92.7% of the emissions increases, which is consistent with those of [15,16,39]. The growth in population (POP) is another significant driver of the emissions increases. The considerable contributions of PGDP and POP to the emission growth may seem obvious as the Korean economy and the population have continuously increased in the last 25 years.

Table 3. CO₂ emissions and IDA results of the 19 end-use sectors (1990–2015) (unit: MtCO₂, %).

| End-use sectors | Factor | 1990 | 2015 | CI | EI | STR | PGDP | POP | Total |
|-----------------|--------|------|------|----|----|-----|------|-----|-------|
| Economic sectors|        |      |      |    |    |     |      |     |       |
| 1. Agriculture and fisheries | 5.4 | 11.3 | 0.0 | 0.6 | -2.5 | 3.0 | 0.5 | 1.6 |
| 2. Mining | 0.7 | 1.0 | 0.0 | 0.1 | -0.3 | 0.2 | 0.0 | 0.1 |
| 3. Food and tobacco | 4.6 | 7.1 | 0.1 | -0.2 | -1.3 | 1.8 | 0.3 | 0.7 |
| 4. Textiles and apparel | 8.7 | 7.2 | 0.3 | -1.1 | -3.1 | 3.0 | 0.5 | -0.4 |
| 5. Wood, wood products, and publications | 4.7 | 6.5 | 0.1 | -0.7 | -1.5 | 2.2 | 0.3 | 0.5 |
| 6. Petroleum chemical | 17.3 | 78.1 | -3.7 | 2.4 | 2.3 | 12.9 | 2.0 | 15.9 |
| 7. Non-metallic mineral products | 15.9 | 19.5 | 0.4 | -3.7 | -3.0 | 6.2 | 1.0 | 9.9 |
| 8. Iron and steel | 35.8 | 123.3 | 0.6 | 5.6 | -5.3 | 19.1 | 3.0 | 23.0 |
| 9. Non-ferrous metal | 0.5 | 0.9 | 0.1 | 0.0 | -0.2 | 0.2 | 0.0 | 0.1 |
| 10. Fabricated metal | 7.1 | 53.1 | 0.2 | 4.9 | -0.7 | 6.6 | 1.0 | 12.1 |
| 11. Electronic equipment, transportation equipment, and other manufactured products | 4.3 | 29.5 | 0.9 | -4.1 | 4.7 | 4.4 | 0.7 | 6.6 |
| 12. Construction | 1.6 | 2.5 | 0.0 | 0.2 | -0.4 | 0.5 | 0.1 | 0.3 |
| 13. Commercial | 15.9 | 73.5 | 0.3 | 0.6 | -0.6 | 12.9 | 2.0 | 15.1 |
| 14. Public | 8.8 | 18.7 | 0.2 | -0.7 | -0.8 | 3.4 | 0.5 | 2.6 |
| 15. Rail transportation | 1.3 | 1.4 | 0.0 | -0.3 | -0.2 | 0.5 | 0.1 | 0.0 |
| 16. Water transportation | 24.5 | 45.8 | 0.0 | -1.9 | -0.6 | 3.0 | 0.5 | 1.0 |
| 17. Air transportation | 5.0 | 8.7 | 0.0 | 0.2 | 0.2 | 1.8 | 0.3 | 2.5 |
| 18. Road transportation | 2.5 | 12.0 | 0.2 | -5.1 | -2.2 | 11.0 | 1.7 | 5.6 |
| Economic sectors total | 164.6 | 500.3 | -0.2 | -3.3 | -15.4 | 92.7 | 14.3 | 88.1 |

| End-use sectors | Factor | 1990 | 2015 | CIH | EIH | - | HC | POPH | Total |
|-----------------|--------|------|------|-----|-----|---|----|------|-------|
| 19. Household sector | 63.5 | 108.9 | -1.5 | -9.2 | 18.9 | 3.7 | 11.9 |
| Sum of 19 sectors | 228.1 | 609.2 |     |     |    |   |    |      |       |
On the contrary, three effects (CI, EI, and STR) are negative. In particular, the negative STR effect (−15.4%) implies that structural change in the industries is an important factor in offsetting CO₂ emissions over an extended period. The role of carbon intensity, energy intensity, and structural change in reducing emissions in the long term is also observed in other countries, such as the United States, Japan, Canada, Australia, Mexico, China [12], Spain [40], and Ireland [41].

One of the most important sectors among the 19 end-users is the household sector. Households were the largest CO₂-emitting sector in 1990 and the second largest in 2015. Household behavior accounts for an 11.9% increase in emissions, mainly due to an increase in HC (18.9%) and POPH (3.7%). The intuitive reasoning behind the large contribution of HC and POPH is the same as before: the growth in the Korea’s economy and population. Nonetheless, the changes in energy intensity and carbon intensity greatly reduced emissions (EIH: −9.2%, CIH: −1.5%). We further break down the two negative factors, CIH and EIH, into three energy types (coal and oil products, electricity, and gas). Figure 1 shows only coal and oil products contributed to negative EIH and CIH, while both electricity and gas increased emissions. The negative EIH of coal and oil products (and the positive CIH of electricity and gas) imply that households have consumed relatively fewer coal and oil products (and more electricity and gas) compared to 1990. The net effect of this energy substitution is a large carbon reduction, which is consistent with [18]. The negative CIH of coal and oil products can be interpreted as the consequence of the energy substitution within the products: from more carbon intensive products (e.g., coal) to less intensive ones (e.g., oils). This trend also contributed to offsetting the emissions caused by economic growth in Korea.

![Figure 1. Household carbon emissions per energy use by households (CIH) and household energy consumption per household expenditure (EIH) by three energy types.](image)

The iron and steel sector, the petroleum chemical sector, the commercial sector, and the fabricated metal sector also made large contributions to emissions growth. These four sectors show a relatively large positive EI (5.6%, 2.4%, 0.6%, and 4.9%, respectively), which demonstrates these industries consumed more energy during the production process and increased CO₂ emissions. Instead, the electronic equipment, transportation equipment, and other manufactured products sector, the road transportation sector, and the non-metallic mineral products sector have large negative EI effects (−4.1%, −5.1%, and −3.7%, respectively).

The time series of Korea’s emissions and the driving factors reveals three findings (see Figure 2). First, CO₂ emissions growth peaked in 2010 (54.3 MtCO₂). The sudden surge in 2010 is attributed to PGDP (25.3 MtCO₂), HC (4.0 MtCO₂), and STR (17.4 MtCO₂), implying an influence of economic recovery during the post-global financial crisis period. This “rebound effect” that resulted in a surge of
carbon emissions occurred around the world [42]. The upturn in CO$_2$ emissions in 1999 (31.2 MtCO$_2$) right after the Asian financial crisis was also dominantly derived from the PGDP effect (28.7 MtCO$_2$) and HC (7.6 MtCO$_2$), verifying the rebound effect after the economic shock.

Second, the rapid CO$_2$ emissions growth in Korea has fallen since 2012. Except for 1998, the emission growth rate is higher than 1.4% before 2012. After 2012, however, it drops to 1.2% at most. The annual average emission growth rate for 2012–2015 is 0.3%.

Third, a reduction in emissions is observed in 2014. This was the first reduction in Korea since 1998. The first emissions cut observed in 1998 is clearly a result of the economic shock in relation to the PGDP of $-17.9$ MtCO$_2$ and HC of $-10.2$ MtCO$_2$. However, this emissions reduction in 2014 was achieved even with positive economic growth (13.9 MtCO$_2$) and a corresponding household consumption increase (1.4 MtCO$_2$). The economy lowered its carbon emissions owing to EI ($-10.8$ MtCO$_2$), EIH ($-4.2$ MtCO$_2$), CI ($-9.9$ MtCO$_2$), and CIH ($-2.0$ MtCO$_2$). These results demonstrate that the Korean economy achieved a CO$_2$ reduction in 2014 through the improvement of carbon intensity and energy intensity.

3.2. A Recent Slowdown in CO$_2$ Emissions after 2012

The recent slowdown in CO$_2$ in the Korean economy is remarkable, as seen in Table 4. While the average annual growth rate (AAGR) of emissions before the slowdown period (1990–2011) is 4.9% (17.8 MtCO$_2$ per annum), it plunges to 0.3% (1.7 MtCO$_2$ per annum) after 2012. While the economic growth of 5.7% is also downgraded to 2.7%, the consumption of energy (4.9% to 1.0%) and electricity (7.9% to 1.5%) was reduced faster than the GDP.
Calculating the contributions of the nine factors, we find a noticeable change in EI after 2012 ($-7.8 \text{ MtCO}_2$). Table 5 shows that economic sectors have increased the use of energy and consequently sped up the emissions growth until 2011 ($0.7 \text{ MtCO}_2$ per annum). However, it turns into one of the main contributors to the CO$_2$ reduction after 2012 ($-7.0 \text{ MtCO}_2$ per annum). The CI effect also shows a similar direction. The positive contribution of CI before 2012 ($0.6 \text{ MtCO}_2$ per annum) changes to a negative effect for 2012–2015 ($-3.3 \text{ MtCO}_2$ per annum). This implies that the Korean economy mitigated large amounts of carbon by increasingly relying on less carbon-intensive energy sources.

Table 5. Annual averages of the nine factors before and after 2012 (unit: MtCO$_2$).

| Sector           | Factor | 1990–2011 (A) | 2012–2015 (B) | Difference (B–A) |
|------------------|--------|---------------|---------------|-----------------|
| Economic sectors | CI     | 0.6           | -3.3          | -3.9            |
|                  | EI     | 0.7           | -7.0          | -7.8            |
|                  | STR    | -2.5          | -1.7          | 0.8             |
|                  | PGDP   | 14.7          | 11.4          | -3.3            |
|                  | POP    | 2.2           | 2.1           | -0.1            |
|                  | Total  | 15.7          | 1.5           | -14.2           |
| Household sector | CIH    | -0.1          | -0.7          | -0.5            |
|                  | EIH    | -1.4          | -1.2          | 0.2             |
|                  | HC     | 3.1           | 1.6           | -1.5            |
|                  | POPH   | 0.6           | 0.5           | -0.1            |
|                  | Total  | 2.1           | 0.2           | -1.9            |
| Total            |        | 17.8          | 1.7           | -16.2           |

To see how Korean society has changed the use of energies during the slowdown period, Table 6 further breaks down CI (and CIH) and EI (and EIH) by the three energy types (coal and oil products, electricity, and gas). We find that electricity played a significant role. Before 2012, the economy increased electricity consumption, emitting more CO$_2$ (EI: $3.4 \text{ MtCO}_2$ per annum). For 2012–2015, however, it achieved CO$_2$ reductions by using less electricity per GDP (EI: $-1.8 \text{ MtCO}_2$ per annum). In addition, the negative CI and CIH effects are mainly caused by electricity ($-3.0 \text{ MtCO}_2$ and $-0.5 \text{ MtCO}_2$ per annum), which implies that power generation has changed such that it now uses less carbon-intensive energy sources. This is distinctive when compared to the positive CI and CIH effects by electricity before the slowdown ($1.0 \text{ MtCO}_2$ and $0.2 \text{ MtCO}_2$ per annum). During the slowdown period (2012–2015), the share of renewables in electricity production has doubled (from 2% to 4%) and the share of nuclear power that does not produce direct CO$_2$ emissions has increased by 2% (from 29% to 31%), according to [23]. Meanwhile, less power was generated from natural gas (from 22% to 19%), while the share of coal-fired power has been stable (39% in both 2012 and 2015). This implies that the source of power generation has shifted to cleaner energies, thereby reducing carbon emissions.

When analyzing the long-term driving forces between 1990 and 2015, we point to the shift in energy use of households from coal and oil products to electricity and gas as a contributor to emission cuts. For the recent years from 2012 to 2015, however, households used more coal and oil products, but less electricity and gas relative to the rise in household expenditure. Table 6 reports that the EIH of coal and oil products is $0.2 \text{ MtCO}_2$, while that of electricity and gas is $-0.3 \text{ MtCO}_2$ and $-1.1 \text{ MtCO}_2$ per annum. It is also possible to see contributions of each economic sector to the slowdown. Table 7
shows that substantial emissions have recently declined through improvement in energy intensity (EI) among four industries: commercial (0.5 MtCO$_2$ → −2.0 MtCO$_2$); electronic equipment, transportation equipment, and other manufactured products (−0.3 MtCO$_2$ → −2.4 MtCO$_2$); petroleum chemical (0.7 MtCO$_2$ → −1.4 MtCO$_2$); and fabricated metal (0.9 MtCO$_2$ → −0.2 MtCO$_2$). We further analyze the difference in EI by separating energy types and find that commercial and fabricated metal have reduced the energy intensity of electricity, while electronic equipment, transportation equipment, and other manufactured products and petroleum chemical have reduced consumption of coal and oil products per outputs (Figure 3). Commercial, petroleum chemical, and fabricated metal improved the energy intensity of gas as well, leading to the observed decline in CO$_2$ during the slowdown period.

Table 6. Annual averages of CI and EI effects by three energy types before and after 2012 (unit: MtCO$_2$).

| Sector                     | 1990–2011 (A) | 2012–2015 (B) | Difference (B–A) |
|----------------------------|---------------|---------------|------------------|
| Energy types               | CI | EI | CI | EI | CI | EI |
| Coal and oil products      | −0.5 | −3.4 | 0.2 | −4.1 | 0.8 | −0.7 |
| Electricity                | 1.0 | 3.4 | −3.0 | −1.8 | −4.0 | −5.2 |
| Gas                        | 0.1 | 0.8 | −0.5 | −1.1 | −0.7 | −1.9 |
| Total                      | 0.6 | 0.7 | −3.3 | −7.0 | −3.9 | −7.8 |

Table 7. Annual averages of CI and EI effects by economic sectors before and after 2012 (unit: MtCO$_2$).

| Sector                              | 1990–2011 (A) | 2012–2015 (B) | Difference (B–A) |
|-------------------------------------|---------------|---------------|------------------|
| Economic Sectors                    | CI | EI | CI | EI | CI | EI |
| 1. Agriculture and fisheries       | 0.0 | 0.1 | −0.1 | −0.1 | −0.1 | −0.3 |
| 2. Mining                           | 0.0 | 0.0 | −0.0 | −0.1 | −0.0 | −0.1 |
| 3. Food and tobacco                 | 0.0 | −0.0 | −0.1 | 0.0 | −0.1 | 0.0 |
| 4. Textiles and apparel             | 0.1 | −0.1 | −0.1 | −0.2 | −0.2 | −0.5 |
| 5. Wood, wood products, and publications | −0.5 | 0.7 | −0.7 | −1.4 | −0.2 | −2.1 |
| 6. Petroleum chemical               | 0.1 | −0.5 | −0.1 | −1.1 | −0.2 | −0.6 |
| 7. Non-metallic mineral products    | 0.2 | 0.6 | −0.3 | 1.9 | −0.5 | 1.3 |
| 8. Iron and steel                   | 0.0 | 0.0 | −0.0 | 0.0 | −0.0 | 0.0 |
| 9. Non-ferrous metal                | 0.2 | 0.9 | −0.8 | −0.2 | −0.9 | −1.1 |
| 10. Fabricated metal                | 0.1 | −0.3 | 0.1 | −2.4 | −0.0 | −2.1 |
| 11. Electronic equipment, transportation equipment, and other manufactured products | 0.0 | 0.0 | −0.0 | 0.0 | −0.0 | 0.0 |
| 12. Construction                    | 0.3 | 0.5 | −1.0 | −2.0 | −1.3 | −2.5 |
| 13. Commercial                      | 0.1 | −0.1 | −0.2 | −0.1 | −0.3 | 0.0 |
| 14. Public                          | 0.0 | −0.1 | 0.0 | 0.2 | −0.0 | 0.3 |
| 15. Rail transportation             | −0.0 | −0.2 | 0.0 | −0.9 | 0.0 | −0.7 |
| 16. Water transportation            | 0.0 | −0.1 | 0.0 | 0.8 | 0.0 | 0.9 |
| 17. Air transportation              | 0.0 | −0.1 | 0.0 | −0.1 | −0.1 | 0.1 |
| 18. Road transportation             | 0.0 | −0.8 | 0.1 | −0.8 | 0.1 | −0.1 |
| Total                               | 0.6 | 0.7 | −3.3 | −7.0 | −3.9 | −7.8 |
3.3. Discussion

Based on the results of the IDA analysis, it is clear that the negative EI and CI effects have made CO₂ emissions reductions possible for the slowdown (2012–2015) period. Ref. [43,44] reported that a recent decline in carbon intensity and energy intensity has been observed in many countries. In particular, the negative EI effect is reported in several country-case studies, such as Ireland [41], Spain [40], Turkey [6], and a group of 33 other countries [9]. Given that a rise in CO₂ emissions is naturally linked to economic and population growth over long periods of time, it would be meaningful to make continued efforts towards lowering carbon and energy intensity for sustainable development.

The EI effect, a major contributor to the recent slowdown, is closely related to innovation in energy efficiency technology. The Korean government has implemented several policies to improve energy efficiency through technological innovation, including the First National Energy Master Plan (2008–2030) [45] and the Second National Energy Plan [46]. Additionally, the Emission Trading Scheme that started in 2015 also provides incentives to develop energy efficiency technologies at the firm level. These strategies would be effective in maintaining this recent carbon reduction in Korea.

From an energy type perspective, the role of electricity in recent years is remarkable. In the long term, increasing the consumption of electricity relative to other energies has led to emissions growth in Korea [18]. The reliance on electricity is mainly due to its cheapest price among the OECD countries [47]. The price of electricity in Korea has been a debatable aspect of striking a balance in the reduction of CO₂ emissions. Korea has kept electricity prices low to enhance firms’ competitiveness and lower citizens’ living costs. However, the rapid increases in electricity consumption itself have become a source of increasing CO₂ emissions. Furthermore, Korea suffered a serious rolling power outage in 2011. The government has recently raised electricity prices not only to reduce carbon emissions but also to manage power demand. During the slowdown period (2012–2015), the electricity price has increased by 5.0% per year, which is far higher than the growth rates in OECD countries with low electricity prices such as the US (1.2%), Canada (−1.3%), and Mexico (−4.9%) [48]. This rapid increase in electricity price could influence the observed reduction in electricity consumption in Korea, one of the most significant contributors to the recent CO₂ emissions reduction.

Another contributor to the slowdown is the CI (CIH) of electricity. This is mainly caused by a change in the source of power generation into cleaner energies. As reported in the literature (e.g., [20]), the carbon intensity reductions by the diversification of the energy mix towards cleaner sources could be a crucial factor contributing to emissions mitigation. The Korean government recently declared a GHG emissions reduction roadmap in 2016 to switch power generation from coal-fueled power to cleaner energy sources by 2030. To constantly reduce CO₂ emissions, the plan needs to be well implemented.
4. Conclusions

Korea has experienced fast increases over three decades and downturns in CO\textsubscript{2} emissions since 2012, which is an interesting fact to explore Korea’s GHG situation. To examine the driving forces behind Korea’s energy-related CO\textsubscript{2} emissions from 1990 to 2015, this study investigates drivers of the recent slowdown in CO\textsubscript{2} emissions and differences from long-term driving forces of emissions before 2012. To take a close look at Korea’s unique emissions trends and their driving factors in depth, this study adopts an extended IDA approach that considers 18 economic sectors as well as the household sector. To better fit Korea’s CO\textsubscript{2} emissions, this study reallocates the CO\textsubscript{2} emissions from energy transformation into the energy end-use sectors. We further analyze the sectors by segregating three energy types used in each sector (i.e., coal and oil products, electricity, and gas). This segregation enables us to capture a significant role of electricity in slowing down emissions. The detailed step-by-step decomposition is one of the contributions of this study to environmental economics and can be applicable to other countries in similar situations.

The IDA results demonstrate that the growth in GDP per capita lead to Korea’s long-term increases in CO\textsubscript{2} emissions between 1990 and 2015, while the change in energy intensity, carbon intensity, and economic structure have reduced CO\textsubscript{2} emissions. The recent CO\textsubscript{2} emissions slowdown (2012–2015) is mainly due to a reduction in energy intensity (EI) and carbon intensity (CI, CIH). In particular, electricity has played a significant role; Korean society reduced its consumption of electricity per GDP (or household consumption) and the source of power generation has shifted to cleaner sources during the slowdown period. As the United Nations’ (2015) Sustainable Development Goals take into account environmental issues as being a high priority around the world, the Korean government will need to focus more on climate policies that improve CI and EI to maintain the slowdown trend for long periods of time.

The limitation of this study is that the indirect effects of final demand on the emissions growth could not be calculated with IDA techniques. To compare the differences of effects by using the two methods (e.g., IDA and SDA), further research can examine how the changes in final demand affect CO\textsubscript{2} emissions in Korea directly and indirectly.

Supplementary Materials: The following are available online at http://www.mdpi.com/2071-1050/12/17/6924/s1,
Table S1. CO\textsubscript{2} emissions and IDA results of the 19 end-use sectors (1990-2015) (unit: MtCO\textsubscript{2}, %), Table S2. Annual averages of the nine factors before and after 2012 (unit: MtCO\textsubscript{2}).

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