Direct and indirect carbon emissions of Korean households from 1995 to 2010: An input-output analysis-

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Abstract

As carbon emission abatement can be realized through changes in the composition of goods and services consumed, there is a need to assess indirect and total household carbon emissions. The Korean household sector was responsible for more than 55% of Korea's total energy related carbon emissions in the 1995 to 2010 period. More than 66% of household carbon emissions were indirect. Thus, not only direct but also indirect household carbon emissions should be the target of carbon emission abatement. Electricity consumption became in 2009 the main source of household carbon emissions in Korea. Households consume more and more electricity intensive goods and services, a sign of increasing living standards. Decrease in carbon intensities of products and switching towards less carbon intensive products consumed by Korean households contributed greatly to reduce the increase in the total household carbon emissions. This study differentiates prices of oil products and electricity between households and industries, as to allow more accurate estimation.

Keywords: Household carbon emissions; Indirect carbon emissions; Carbon input-output analysis

1. Introduction

The Korean economy has been very carbon intensive. Korea emitted 238.6 Mt (million metric tons) CO_2 in 1990, 440.99 Mt CO_2 in 2000 and 579.67 Mt CO_2 in 2010, according to the International Energy Agency statistics (IEA, 2012a). Although the annual average growth rate of carbon emissions slowed down from 6.3% in the 1990s to 2.8% in the 2000s, it is very alarming. Korea was ranked 7th in the world for its CO_2 emissions by energy consumption in 2010. Only China, the USA, Russia, India, Japan and Germany emitted carbon more than Korea. The Korean per capita carbon emission was 11.52 t CO_2 in 2010. Among the OECD countries only Luxembourg (20.98 t CO_2)[1], the USA (17.31 t CO_2), Australia (17 t CO_2), Canada (15.73 t CO_2), and Finland (11.73 t CO_2) emitted carbon more than Korea. The first step for the abatement of carbon emissions is to assess such emissions by economic activities like consumption, investments

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[1] Countries like Luxembourg, Belgium, the Netherlands and Korea are very energy and carbon intensive due to their large share of iron & steel and petrochemical industries in the economy.

and exports and by industrial sectors. Korean households (private consumption in the national accounts) spend a lion's share of GDP for consumption. The household consumption expenditure amounted to 617.1 trillion Korean Won (TWon) or USD 533 billion, corresponding to 59.1% of GDP in 2010. Often the discussion focuses on direct carbon emissions by energy consumption in the form of electricity, fuel oil, gasoline, town gas and district heat by households. Many households are not paying much attention to abatement of carbon emissions by energy consumption as a relatively small portion of their income is spent for direct energy use. In 2010 the Korean households spent only 6.1% of their incomes to pay energy utility bills and to buy gasoline, diesel and Liquefied Petroleum Gas (LPG) for their cars according to the 2010 input-output tables of the Bank of Korea (BOK, 2012).

However, the households cause substantial carbon emissions embodied in the goods and services they consume. The so-called indirect carbon emissions depend on carbon intensities of products consumed and on the mix of products consumed, hence on the household consumption behavior/ pattern. Abatement of carbon emissions can be realized, if consumption can be directed towards less carbon intensive products. The first step for such abatement is the quantification of total (direct and indirect) household carbon emissions. This study aims to quantify direct and indirect household carbon emissions in Korea from 1995 to 2010 by using 168 sector classification input-output tables.

This study discusses first the way in which the household carbon emissions can be calculated. (Monetary) input-output tables are transformed in two steps from monetary to energy input-output tables and then from energy to carbon input-output tables. Next, income development, energy consumption and carbon emissions in Korea from 1995 to 2010 are briefly described. Then the paper presents the results concerning direct and total carbon intensities, direct, indirect and total household carbon emissions as well as causes of the increase in carbon emissions over the studied period. At the end some limitations of this study are discussed and some conclusions are drawn.

2. Quantification of the household carbon emissions

Well established are the two basic methods to quantify indirect energy requirement or indirect carbon emissions, e.g., process chain analysis and input-output analysis, and hybrid combinations of the two methods. The process chain analysis or life-cycle assessment calculates indirect energy requirement or indirect carbon emissions by adding up energy inputs or carbon inputs (contents) in all stages of the production process of a product or a service. This method enables to assess indirect energy requirement or carbon emission in a very detailed manner. However it is very work intensive and requires a detailed database (IFIAS, 1978; Boustead and Hancock, 1979; Schaefer, 1982; SETAC, 1993) and it is typically used for assessing individual products or services.

The input-output analysis computes with the help of the Leontief inverse intermediate or cumulative energy inputs or cumulative carbon inputs (contents) of a sector/ branch. This analysis can be applied easily to all sectors regardless length and complexity of their production processes.

However, as the number of the sectors in a national input-output table is limited, for instance, to 403 in the case of Korea, product specific energy requirements cannot be considered (Wright, 1974; Bullard and Herendeen, 1975; Denton, 1975; Pick and Becker, 1975; Miller and Blair, 1985; Peet et al., 1985; Peet, 1993; Ospelt et al., 1996; Lenzen, 1998; Pachauri, 2002; Pachauri and Spreng, 2002; Vringer et al., 2006; Park and Heo, 2007).

The hybrid method seeks to use advantages of both methods. In other words, the process chain analysis is used to calculate energy requirement or carbon emission of energy intensive or carbon intensive products and the input-output analysis is applied to calculate that of other products. Suh et al. (2004) classifies hybrid approaches in three groups, e.g., tiered hybrid analysis, input-output based analysis and integrated hybrid analysis. To calculate the total energy requirement of Dutch households, Vringer and Blok (1995a, 1995b, 2000) used the so-called tiered hybrid energy analysis. They determined the energy intensities of about 350 basic consumption categories using the expenditure of 2767 representative households from the Netherlands Household Expenditure Survey of 1990. Although they analyzed changes in consumption patterns of Dutch households in the period from 1948 to 1996, information on energy intensities of only one year (1990) was used (available). This method is also work intensive and requires detailed data (van Engelenberg et al., 1994; Vringer and Blok, 1995a, 1995b, 2000; Vringer et al., 2006).

Cruz (2002) stresses the importance of the indirect production demand for fuels in the CO_2 emissions. 61.3% of the CO_2 emissions are attributable to indirect use of fossil fuels in Portugal in 1992. Limmeechokchai and Suksuntornsiri (2005) and Kofoworola and Gheewala (2008) assess *electricity*, *cement* and *ocean transport* as most carbon intensive sectors in terms of kg CO_2 per Baht for 1995 and 2000 for Thailand by applying an input-output framework. For China, Wang and Shi (2009) estimate the share of consumption-induced CO_2 emissions in total emissions at 45% and as the share of indirect emissions in total emissions at 76% in 2004. Bin et al. (2010) applies the total consumer impacts assessment methodology to assess energy use and related carbon emissions from U.S. household consumption from 1997 to 2007. The U.S. study assesses direct household consumption impacts of 2580 Mt CO_2 against indirect impacts of 2546 Mt CO_2 in 2007. However, indirect impacts grew much faster than direct impacts, with annual growth rates of 3.2% against 2.3% for carbon emissions for the 1997 to 2007 period.

Chung et al. (2009) try to assess the direct and total carbon emissions by energy consumption in Korea by using a different hybrid method which uses monetary and physical units in the input-output structure. Energy sectors are expressed in physical units, while non-energy sectors are expressed in monetary units. Their findings are 509 Mt CO_2 for direct emissions and 1371 Mt CO_2 for total emissions for the year 2000. Their direct emissions consist of 311 Mt CO_2 for *energy group* and 116 Mt CO_2 *for non-energy group* and 82 Mt CO_2 for *final demand group*. These total emissions of 509 Mt CO_2 (direct emissions in their terminology) for the year 2000 seem to be overestimated when compared with 441 Mt CO_2 of the IEA statistics as shown in Table 4. This study applies input-output analysis and uses relatively disaggregated input-output tables for Korea from 1995 to 2010. It converts first monetary input-output tables into energy input-output tables and then into carbon input-output tables. Used are 168 sector classification input-output tables for Korea for the years 1995, 2000, 2005, 2009 and 2010 published by the Bank of Korea (BOK, 2008, 2012), both in current and constant prices. The 168 sectors consist of 161 non-energy sectors and 7 energy sectors which are naphtha, oil products (gasoline, diesel, kerosene, LPG, aviation fuel and fuel oil), other oil products (white spirit & SBP, lubricants, bitumen, solvent, paraffin waxes, petroleum coke etc.), coal products, electricity, town gas, and steam & district heat. Input-output tables in constant deflated prices provided by the Bank of Korea are used to calculate energy intensities as to make the values for different years comparable. There are 168 sector classification input-output tables for the years 1995, 2000, 2005 and 2009 in 2005 constant prices. For comparison, 168 sector classification input-output tables for the years 1995, 2000, 2005, 2009 and 2010 in current prices are also used.

Table 1: Final and primary energy consumption in 2010 (PJ)

	Energy balance for 2010		
	Total final energy consumption (TFC)	Total primary energy supply (TPES)	Transformation efficiency
Naphtha	1371.7	1539.1	89.1%
Oil products	1916.4	2150.2	89.1%
Other oil products	139.5	156.5	89.1%
Coal products	399.6	523.1	76.4%
Town gas	852.5	905.6	94.1%
Electricity	1617.9	4832.2	33.5%
Steam & district heat	181.3	237.9	76.2%
Renewables	112.7	122.8	91.8%
Total	6591.6	10467.4	63.0%
Source: IEA (2012b)			
Note: The differences between TPES and TFC include conversion loss, own use & distribution loss.			

2.1 Energy input-output tables[2]

Energy consumption data for the entire period are taken from the Energy Balances of OECD Countries of the International Energy Agency (IEA, 2012a). However, these data are not detailed enough to construct 7 (energy sectors) × 168 energy input-output tables which are needed to calculate 168 direct energy intensities. The IEA energy statistics gives information on energy consumption of only following sectors: *agriculture/forestry*; *fishing*; 13 manufacturing sectors; 6 *transportation* sectors; *residential*; *commercial and public services* and *non-energy use*.

Moreover, energy consumption data are given in final energy terms (total final consumption, TFC) in the IEA energy statistics. This study converts these data in primary energy terms (total

[2] The approach used to develop energy input-output tables is based on Park and Heo (2007).

primary energy supply, TPES, Table 1) as not to favor those sectors especially with a higher share of electricity in the total energy consumption in calculating energy intensities. Sectors with a higher share of electricity require larger amount of primary energy equivalents than those with a lower share if energy intensities are calculated in final energy equivalents. The IEA energy consumption data in million tons of oil equivalent (Mtoe) are converted to Peta Joule (PJ) by multiplying with 41.868, thus 1 Mtoe is equal to 41.868 PJ.

Furthermore, this study excludes renewable sources of energy amounting to 116.9 PJ or about 1.1% of the TPES in 2010, as it is difficult to allocate its requirement to individual sectors.

The monetary input-output system can be formulated in Eqs. (1) - (2).

$$\sum_{i=j=1}^{168} a_{1j}`X_i + Y_1 - IM_1 = X_1 \qquad (1)$$

$$\sum_{i=1}^{7} a_{i1}`X_i + \sum_{i=8}^{168} a_{i1}`X_i + V_1 = X_1 \qquad (2)$$

$$\text{with} \sum_{i=j=1}^{168} a_{ij}` < 1$$

where X_1 is the gross domestic output (production)[3] or the total input of sector 1. The gross domestic output X_1 of sector 1 consists of the total intermediate demand $\sum_{i=j=1}^{168} a_{1j}`X_i$ and the total final demand $Y_1$ minus imports $IM_1$ as shown in Eq. (1). The total intermediate demand of sector 1, e.g. naphtha, $\sum_{i=j=1}^{168} a_{1j}`X_i$ are the products of sector 1 to be used for the production of goods of sectors 1 to 168 and $\sum_{i=1}^{168} a_{i1}`X_i$ are the total intermediate inputs from sectors 1 to 168 for the production of goods of sector 1. *Y* is the total final demand which includes consumption (private and government), investments, exports and stock changes. *IM* is the imports and *V* is the value added inputs. The first summation of Eq. (2) means the inputs of 7 energy sources (carriers). The second summation of Eq. (2) means the inputs of 161 non-energy sectors.

In the first step, this study transforms (monetary) input-output tables into energy input-output tables with the help of average (uniform) energy prices. Such energy prices are calculated as ratios of energy use (inputs by fuel) *Ei* to the gross domestic output *Xi* or the total demand (*Tdi*) minus imports (*IMi*) by fuel, expressed in kJ/Won, same as energy intensities as shown in Eq. (3). The reciprocal numbers of the energy intensities are more commonly used prices expressed in Won/kJ. Thus, higher kJ/Won values or higher energy intensities mean lower energy prices and vice versa (Energy prices in kJ/Won for the 1995 to 2009 period are given in Table 3).

$$P_i = \frac{E_i}{X_i} \text{ or } \frac{E_i}{Td_i - IM_i} \quad (kJ/Won) \qquad (3)$$

[3] The Gross domestic output is equal to the total demand (the total intermediate demand and total final demand) minus imports in the terminology of input-output tables or national accounts.

where *Ei* is energy use or energy consumption. First, we apply the uniform fuel prices to convert monetary into energy input-output tables. P_1, the average price of energy sector 1, e.g., price of naphtha, is used to quantify 168 intermediate inputs of naphtha to produce goods of 168 sectors in Eq. (4).

$$\sum_{i=j=1}^{168} a_{1j}` X_i \; * P_1 = \sum_{j=1}^{168} E_{1j} \quad (4)$$

Once intermediate energy inputs (energy input-output tables) are computed as in Eq. (4), it is easy to estimate direct energy intensities (by fuel) of individual sectors. Direct energy intensities of sector 1 are calculated as ratios of direct energy expenditure converted in energy terms to the total input (intermediate inputs and value added inputs) of sector 1, also expressed in kJ/Won in Eq. (5).

$$\sum_{i=1}^{7} I_{i1}`(direct) = \frac{\sum_{i=1}^{7} E_{i1}}{X_1} \; (kJ/Won) \quad (5)$$

where $I_1(direct)$ is the direct energy intensity of sector 1 (the sum of 7 direct intensities). Total or cumulative energy intensities (e.g., energy sector 1, naphtha intensities) of 168 sectors can be then computed by multiplying direct energy (naphtha) intensities with the Leontief inverse $\sum(I - A)^{-1}$ of the corresponding input-output table as expressed in Eq. (6).

$$\sum_{j=1}^{168} I_{1j}`(direct) \; * \sum_{i=j=1}^{168} (I - A)^{-1} = \sum_{j=1}^{168} I_{1j}`(total) \quad (6)$$

The indirect energy intensities are the differences between total (Eq. (6)) and direct energy intensities (Eq. (5)). Sectoral total or cumulative energy requirement can be computed by multiplying total energy intensity with sectoral household (private consumption) expenditure. Indirect household energy requirement is then the sum of sectoral cumulative energy requirements. Direct use of oil products, other oil products, coal products, electricity, town gas, and steam & district heat in primary energy terms by households is considered as direct household energy requirement. Total household energy requirement is the sum of direct and indirect household energy requirement.

Uniform (average) prices for fuels to all 168 sectors (total intermediate demand) and total final demand (consumption, investments and exports) minus imports are not without problem. Industries (168 sectors) will pay much lower prices than households (private consumption expenditure) for the same fuel. The price differential exists within the intermediate demand for fuels. For more discussions see Lenzen (1998).

In the second step, fuel prices are differentiated between industries (the total intermediate demand, investments, stock change, exports and imports) and consumption (households and public consumption). From 7 fuels under consideration only oil products and electricity prices are differentiated. Naphtha, the feedstock for the petrochemical industry is used only in the industry. Coal products are used mostly for power generation and iron & steel and cement production in the industry. In 2010 the Korean households consumed coal in the form of briquettes in the amount of 35.8 PJ. In comparison the industrial coal consumption was 885.5 PJ in the same year. Coal briquettes are heavily subsidized in Korea as these are considered fuels for very low income households. Thus, one can consider that there is hardly any coal price differential between industries and households. Other oil products are also used mostly in industries.

The Korean natural gas market has been regulated. There have been cross subsidies from the industry and the commercial sector to households in the gas market. The costs of storage of liquefied natural gas (LNG) in summer months, caused by household low gas demand in summer months and high gas demand in winter months, are shared evenly between industries and households. In general Korean households do not pay more for natural gas than industries. The heat market has been also regulated. Korean households pay for district heat less than the commercial and public sectors. The tariffs for district heat of the Korea District Heat Corporation, which supplies more than 50% of district heat in Korea, were Won 79.28/Mcal (1 Mcal = 4.1868 MJ) for households, Won 102.83/Mcal for the commercial sector and Won 89.90/Mcal for the public sector as of 1 June 2012. The share of the commercial and public sectors in the district heat market is small. The industry does not use district heat of 120 ℃ heat but steam which is different from district heat. The tariffs for steam are for low steam (200 ℃) Won 77.90/Mcal, for middle steam (285 ℃) Won 88.55/Mcal and high steam (380 ℃) Won 99.08/Mcal.[4] This study assumes no substantial difference in the heat price between households and industries.

Table 2: Electricity tariffs in Won per kWh

	Industry (Ind)	Residential (Res)	Industry	Residential	Ind to Res ratio applied
1995	46.14	86.47	100.0	187.4	1 to 1.8
2000	58.30	94.72	100.0	162.5	1 to 1.6
2005	60.25	91.07	100.0	151.2	1 to 1.5
2009	73.69	98.07	100.0	133.1	1 to 1.3
2010	76.63	103.38	100.0	134.9	1 to 1.3

Source: Korea Electric Power Corporation.

In the electricity market there is only one supplier, the state-owned Korea Electric Power Corporation (KEPCO). The electricity tariffs apply to the whole country without any exception to individual companies. Table 2 shows that Korean households paid 30% to 80% more than industries. This study assumes the industry to residential tariff ratios for individual years as given in Table 2.

Households consume highly taxed fuels such as gasoline and diesel and LPG for transport and fuel oil for heating while the industry uses less taxed petroleum products such as fuel oil and diesel as well as LPG for the production of synthetic gas. At the same time, households pay more than the industry for the same fuel. This study assumes that households pay on average 30% more than the industry.

[4] Information is provided from a large petrochemical company which sells also steam to other companies in a large petrochemical complex in Korea.

Table 3: Fuel prices cum energy intensities applied in kJ per Won

	1995	2000	2005	2009
Naphtha	123.2	105.7	125.3	143.5
Oil products (uniform price)	51.8	38.4	38.2	33.8
for industries	55.3	41.1	40.3	35.7
for households	42.7	31.6	31.0	27.5
Other oil products	34.1	46.0	34.9	24.8
Coal	141.9	181.7	150.9	186.9
Electricity (uniform price)	132.8	145.0	136.4	139.0
for industries	145.3	157.2	146.2	146.9
for households	80.7	98.3	97.4	113.0
Gas	45.8	55.7	52.9	54.8
Heat	45.1	101.4	117.2	141.3

According to Table 3, the average prices of oil products and other oil products increased from 51.8 kJ/Won and 33.8 kJ/Won in 1995 to 34.1 kJ/Won and 24.8 kJ/Won in 2009, respectively. These were expensive fuels in Korea. There were little changes in prices of fuels like naphtha and electricity. It is important to note that prices of electricity are lower than primary fuels like oil products and natural gas. The electricity prices are low partly because of a large share of nuclear power generation and partly because of a low electricity price policy in Korea.

2. 2 Carbon input-output tables

Energy input-output tables developed by using differentiated prices of oil products and electricity serve as the basis to construct carbon input-output tables. Energy consumption in energy terms by 7 fuels needs to be converted in carbon or t CO_2 terms. As fuels like coal products, oil products, other oil products consist of several products with different carbon emission factors (CEF), consumption weighted average carbon emission factors are calculated for each fuel and year in the study. In the case oil products the default CEF are 17.2 t C/TJ for LPG, 18.9 t C/TJ for motor gasoline, 19.5 t C/TJ for aviation gasoline, 18.9 t C/TJ for gasoline type jet fuel, 19.5 t C/TJ for kerosene type jet fuel, 19.6 t C/TJ for other kerosene, 20.2 t C/TJ for diesel and 21.1 t C/TJ for fuel oil. The consumption weighted CEF for oil products were 19.84 t C/TJ for 1995, 19.65 t C/TJ for 2000, 19.59 t C/TJ for 2005, 21.10 t C/TJ for 2009 and 19.45 t C/TJ for 2010 as shown in Table 4. The same method is applied for coal products.

Table 4: Carbon emission factors and CO_2 emissions (1995-2010)

	Unit	1995	2000	2005	2009	2010
Carbon emissions factors						
Naphtha	t C/TJ	4.00	4.00	4.00	4.00	4.00
Oil products	t C/TJ	19.84	19.65	19.59	21.10	19.45
Other oil products	t C/TJ	0.22	2.83	3.68	3.34	3.65
Coal products	t C/TJ	23.61	22.86	22.07	23.70	24.21
Town gas	t C/TJ	15.30	15.30	15.30	15.30	15.30
Steam & district heat	t C/TJ	15.30	15.30	15.30	15.30	15.30
CO_2 emissions						
Naphtha	Mt CO_2	9.869	14.722	17.750	21.425	22.573
Oil products	Mt CO_2	200.346	184.657	162.980	151.690	147.391
Other oil products	Mt CO_2	0.055	1.292	1.972	1.938	2.097
Coal products	Mt CO_2	36.131	43.675	29.488	37.568	46.433
Town gas	Mt CO_2	10.055	27.955	39.155	44.559	50.802
Steam & district heat	Mt CO_2	2.337	10.161	13.562	13.402	13.348
Electricity	Mt CO_2	97.790	129.121	178.542	237.243	264.785
TOTAL	Mt CO_2	356.583	411.584	443.449	507.825	547.430
IEA Sectoral Approach 1)	Mt CO_2	358.650	437.690	469.120	515.460	563.080
IEA Reference Approach 1)	Mt CO_2	355.280	440.990	464.630	518.150	579.670

Source: IEA, CO_2 Emissions from Fuel Combustion (IEA, 2012a).

Note: 1) CO_2 emissions according to the IPCC Sectoral Approach estimated by IEA.

Naphtha is the main feedstock for the petrochemical industry. The IPCC default CEF of naphtha is 20 t C/TJ and its default storage factor is 75%. This study uses a storage factor of 80%. Park (2005) estimated a storage factor of naphtha 88% for the years 1999 and 2000 for Korea. For instance, the Netherlands used a storage factor of 82%. Thus, the CEF of naphtha is 4 t C/TJ (20 t C/TJ times 0.2). The CEF of town gas or natural gas is 15.3 t C/TJ. This study used the same CEF for steam & district heat. In their study on heat supply system using natural gas in the residential sector Park and Kim (2008) and Park (2011) found out that there is no difference in the energy efficiency between district heating and individual gas heating using condensing boilers for the years 2005 and 2006.

Other oil products include non-energy use which converts only a part of its carbon content into carbon dioxide (CO_2) emissions. This study uses a similar estimation method as for oil products with an exception that it considers storage factors of individual fuels. Bitumen is included in the estimation, but its storage factor is 1 or 100%. The weighted average CEF of other oil products is 3.65 t C/TJ for the year 2010 (Table 5) and those for other years are listed in Table 4.

The consumption weighted average CEF for 6 fuels for the 1995 to 2010 period are given in Table 4. The CO_2 emissions by fuel are calculated by multiplying CEF in t C/TJ with 44/12 and fuel consumption in PJ of each fuel and year as shown in Table 4.[5] This study uses IEA data on

[5] The atomic weights of carbon and oxygen are 12 and 16, respectively. CO_2's weight is 44. Thus, the conversion factor carbon to CO_2 becomes 44/12.

CO_2 emissions per kWh and electricity output to calculate CO_2 emissions of the electric power sector in Korea by multiplying CO_2 emissions per kWh with the electricity output as in Table 6.

Table 5: Estimation of average carbon emission factors for other oil products for 2010

		White spirit & SBP	Lubricants	Paraffin waxes	Petroleum coke	Other products	Bitumen	Total
Non-energy use (A)	PJ	23.01	28.10	0.68	0.20	27.96	53.89	133.84
Carbon emission factor (CEF)	t C/TJ	20.0	20.0	20.0	27.5	20.0	22.0	
1 - Storage factor		0.2	0.5	0.2	0.25	0.2	0.0	
Effective CEF (B)	t C/TJ	4.0	10.0	4.0	6.875	4.0	0.0	
(A) * (B)	1000 t C	92.02	280.99	2.72	1.39	111.84	0.0	488.97
Average CEF (488.97/133.84)	t C/TJ							**3.65**
Sources: IEA, CO_2 Emissions from Fuel Combustion; and Energy Balances of OECD Countries, both 2012 edition.								
Park, Fossil fuel use and CO_2 emissions in Korea, Resources, Conservation & Recycling 45 (2005).								

Table 6: Estimation of CO_2 emissions in the Korean power generation (1995-2010)

	Unit	1995	2000	2005	2009	2010
CO_2 emissions per kWh	g CO_2/kWh	0.5399	0.4475	0.4603	0.5253	0.5331
Electricity output	GWh	181,139	288,526	387,874	451,676	496,718
Emissions	Mt CO_2	97.790	129.121	178.542	237.243	264.785
Source: IEA, CO_2 Emissions from Fuel Combustion (2012a).						

Table 4 compares CO_2 emissions for the 1995 to 2010 period between this study and the IEA estimate using both IPCC Sectoral Approach, basically a bottom-up method, and IPCC Reference Approach, a top-down method. This study applied IPCC Reference Approach or Tier I. The difference between two estimates is within 1%, except 2.9% for 2010. Once CO_2 emissions by fuel are estimated, carbon intensities in g CO_2/Won can be calculated in analogous to Eq. (3) for the energy prices.

$$CPi = \frac{CE_i}{X_i} \quad (g\ CO_2/Won) \tag{7}$$

where *CPi* is carbon price, *CEi* is carbon emission and *Xi* is gross domestic output (production) in monetary terms. CP_1, the carbon price of energy sector 1, e.g., carbon price of naphtha, is used to quantify 168 intermediate carbon contents (inputs) of naphtha in the goods produced in 168 sectors.

$$\sum_{j=1}^{168} a_{1j}`X_1 \;*\; CP_1 = \sum_{j=1}^{168} CE_{1j} \tag{8}$$

Once intermediate carbon inputs (carbon input-output tables) are computed as in Eq. (8), it is easy to estimate direct carbon intensities of individual sectors. Direct carbon intensities are calculated as ratios of direct energy expenditure converted in carbon terms to total inputs (intermediate inputs and value added inputs), also expressed in g CO_2/Won in Eq. (9).

$$\sum_{i=1}^{7} CI_{i1}`(direct) \;=\; \frac{\sum_{i=1}^{7} CE_{i1}}{X_1} \quad (g\ CO_2/Won) \tag{9}$$

where $CI_1(direct)$ is the direct carbon intensity of sector 1.

Total or cumulative carbon intensities can be then computed by multiplying them with the Leontief inverse $\sum(I-A)^{-1}$ of the corresponding input-output table as expressed in Eq. (10).

$$\sum_{j=1}^{168} CI_{1j`}(direct) \;*\; \sum_{i=j=1}^{168} (I-A)^{-1} = \sum_{j=1}^{168} CI_{1j`}(total) \qquad (10)$$

The indirect carbon intensities are the differences between total (Eq. (10)) and direct carbon intensities (Eq. (9)). Sectoral total or cumulative carbon emissions can be computed by multiplying total carbon intensity with sectoral household expenditure. Indirect (or embodied) household carbon emissions are then the sum of sectoral cumulative carbon emissions. Carbon emitted by directly using oil products, other oil products, coal products, electricity, town gas and district heat by households is considered as direct household carbon emissions. Total household carbon emissions are the sum of direct and indirect carbon emissions.

3. Income development, energy requirement and carbon emissions in Korea

Before presenting the findings of this study a brief description on income development, energy requirement and carbon emissions in Korea from 1995 to 2010 is given. The annual average income (GDP) growth was 5.2% in the second half of 1990s as shown in Table 7. It slowed down in the 2000s. The increase in household consumption expenditure decreased from 6.7% per year in the second half of the 1990s to 4.6% per year in the 2000s. The annual growth rate of total household primary energy consumption increased from 1.9% in the first period to 2.1% in the second period. The increase in direct household primary energy consumption decreased substantially from 4.4% in the 1995 to 2000 period to 0.6% in the 2000s. Thus, the income (consumption expenditure) elasticity of energy demand decreased substantially from 0.66 (6.7/4.4) in the first period to 0.13 (4.6/0.6) in the second period. The relatively high income elasticity in the second half of the 1990s was due to heavy investments in iron & steel and petrochemical industries since the late 1980s, which was one of the causes of the Asian economic crisis in Korea. Large investments were made in energy intensive industries such as petrochemical, iron & steel, and cement industries. For instance, the production capacity of ethylene, a major basic chemical, increased from 0.505 Mt (million tons) in 1988 to 5.150 Mt in 2000. Indeed, Korea's industry is very energy intensive. Korea's iron & steel industry ranks fifth and Korea's petrochemical industry measured in ethylene production ranks sixth in the world. The high per capita TPES in Korea is partly due to a large share of heavy industry in the economy.

For a per capita income of USD 19,720 economy the per capita primary energy requirement of 214.2 GJ in 2010 was very high. In comparison, the per capita primary energy requirement for France, Germany and Japan were 169.3 GJ. 167.6 GJ and 163.3 GJ, respectively according to the IEA Statistics. And the per capita income for France, Germany and Japan were USD 42,190, USD 43,280 and USD 42,050, respectively according to the World Bank. The shares of the household consumption in GDP were with between 52.3% (1995) to 54.5% (2000) smaller than most OECD countries.

Table 7: Income development, energy consumption & carbon emissions in Korea (1995-2010)

	1995	2000	2010	Annual growth rates in %	
				1995-2000	2000-2010
GDP in TWon at 2005 constant prices	539.7	695.0	1,043.8	5.2	4.2
Household consumption in TWon at 2005 prices	283.8	392.3	617.0	6.7	4.6
(Household consumption ratio to GDP in %)	(52.6)	(56.4)	(59.1)		
Per capita GNI at current USD	11,735	11,292	20,562	-0.8	6.2
Exchange rate Won/USD	770.94	1,131.12	1,156.30		
Population in million	45.093	47.008	48.875	0.8	0.4
Total primary energy supply (TPES, in PJ)	6,060.6	7,877.9	10,467.4	5.4	2.9
(Per capita TPES in GJ)	(134.4)	(167.6)	(214.2)	4.5	2.5
Total household primary energy use (PJ)	4,166.6	4,567.7	5,602.0	1.9	2.1
(Per capita total household energy in GJ)	(95.4)	(97.2)	(114.6)	0.4	1.7
Direct household primary energy use (PJ)	1,126.8	1,399.7	1,481.9	4.4	0.6
(Per capita direct household energy in GJ)	(25.0)	(29.8)	(30.3)	3.6	0.2
Total emissions (RA by IEA) in Mt CO_2	355.3	441.0	579.7	4.4	2.8
Total emissions (SA by IEA) in Mt CO_2	358.7	437.7	563.1	4.1	2.6
(Per capita emission in t CO_2)	(7.95)	(9.31)	(11.52)	3.2	2.2
Sources: BOK, IEA and own calculation.					
Notes: G = Giga, T = Tera or trillion, P = Peta, RA = Reference Approach, SA = Sectoral Approach.					

Table 8: Energy consumption patterns in international comparison for the year 2010

		Korea	Japan	France	Germany	USA
Consumption (TFC)	by sector					
Household	%	12.6	15.3	27.1	27.4	17.9
Industry	%	28.4	27.7	18.0	24.3	18.7
Transportation	%	19.0	23.7	27.2	23.4	38.9
Commercial	%	13.0	19.8	14.4	14.2	13.7
Non-energy use	%	24.4	12.3	7.4	10.4	9.0
Consumption	per capita					
Total	GJ/capita	214.2	163.3	169.3	167.6	299.2
Households	GJ/capita	17.01	16.33	28.44	31.76	36.22
	GJ/capita(adjusted)	23.78	29.27	41.97	41.13	61.40
Industry	GJ/capita	38.34	29.59	18.93	28.24	37.80
	GJ/capita(adjusted)	63.55	43.74	28.71	43.12	53.11
Iron & steel	GJ/capita	8.94	7.15	2.32	4.17	2.75
Non-energy use	GJ/capita	32.86	13.11	7.75	12.11	18.18
Consumption	of electricity					
Total	kWh/capita	9,851	8,399	7,756	7,217	13,361
Household	kWh/capita	1,254	2,396	2,505	1,734	4,662
Industry	kWh/capita	4,667	2,619	1,811	2,756	2,836
Note: adjusted in primary energy terms (generation efficiency of 40% assumed).						
TPES: Total primary energy supply; TFC: Total final consumption; toe: tons of oil equivalent.						
Source: IEA, Energy Balances of OECD (2012 Edition), OECD, database.						

Table 8 shows that the share of household consumption in total final consumption is lowest among OECD countries in comparison, while its share of the industry together with non-energy use (mostly petrochemical industry) is highest among these countries in 2010. Per capita household electricity consumption was with 1254 kWh the lowest, while per capita industry electricity consumption was with 4337 kWh the highest in 2010. The carbon emissions grew a little slower than the total primary energy supply but depended in general on its growth rates.

Table 9 shows that the per capita emission of 11.52 t CO2 in 2010 was very high in comparison to most OECD countries. Korea emitted more carbon per capita or per GDP production than most OECD countries in 2010. Only the Netherlands recorded almost the same per capita CO_2 emissions as Korea. However, Korea's carbon emissions per GDP production were much higher than other OECD countries in comparison.

Table 9: Carbon emissions in international comparison (2010)

	CO_2/Population	CO_2/GDP	CO_2/GDP PPP
	t CO_2 per capita	kg CO_2 per US$$_{2005}$	kg CO_2 per US$$_{2005}$
Korea	11.52	0.55	0.43
France	5.52	0.16	0.19
Germany	9.32	0.26	0.28
Japan	8.97	0.25	0.29
Netherlands	11.26	0.27	0.30
United Kingdom	7.78	0.21	0.24
Source: IEA, CO_2 Emissions from Fuel Combustion (IEA, 2012a).			

4. Results

4.1 Carbon intensities

Table 10 lists direct carbon intensities of the 15 most intensive non-energy sectors as of 2005 like *pig iron & ferroalloys*, *petrochemical basic products*, *cement* and *air transportation* sectors, expressed in g CO_2 (carbon dioxide) per Won in 2005 constant prices. The average direct carbon intensity decreased from 1995 to 2009. However, the carbon intensities of several sectors like *coal basic chemical products*, *pig iron and ferroalloys*, *warehouse and storage*, *paper*, *fiber yarn* and *water supply* increased from 2000 to 2009 or from 2005 to 2009. The carbon intensity of *agriculture, forestry and fishing related service* increased substantially from 0.25 g CO_2 per Won in 1995 to 0.84 g CO_2 per Won in 2009. This sector has been using more and more electricity. Indeed, electricity is heavily subsidized for the agriculture in Korea. As a consequence greenhouses to cultivate vegetables and fruits have changed as heating fuel from fuel oil or coal briquettes to electricity. With the increasing income and living standard required are more cooling and refrigeration of meat and vegetables in warehouses and storage facilities in Korea.

Table 10: Direct carbon intensity of most intensive non-energy sectors in Korea (1995-2009)

	1995		2000		2005		2009	
	g CO_2/Won$_{2005}$		g CO_2/Won$_{2005}$		g CO_2/Won$_{2005}$		g CO2/Won$_{2005}$	
	Intensity	Direct share	Intensity	Direct share	Intensity	Direct share	Intensity	Direct share
Coal chemical products	3.55	73.2	5.51	76.0	4.92	91.2		
Pig iron and ferroalloys	4.76	85.4	4.69	88.8	2.37	77.1	4.11	80.5
Petrochemical basic products	1.61	81.4	1.25	78.4	1.44	78.3	1.14	58.3
Cement	0.97	57.3	1.00	60.6	0.86	60.3	0.74	50.8
Warehousing and storage	0.62	67.8	0.48	69.0	0.76	77.4	1.02	78.1
Air transport	1.50	85.7	0.83	79.8	0.75	78.5	0.60	70.0
Fiber bleaching and dyeing	0.87	52.4	0.83	49.7	0.74	57.3	0.82	56.9
Inorganic basic chemical products	1.14	51.6	0.97	51.7	0.74	53.3	0.64	48.0
Agriculture, forestry and fishing related services	0.25	63.5	0.25	62.0	0.68	74.2	0.84	71.3
Paper	0.47	36.4	0.48	39.8	0.66	47.5	0.64	45.1
Road transport	1.22	85.6	0.75	82.1	0.64	79.6	0.61	75.1
Rail transport	0.92	81.7	0.73	76.3	0.61	74.5	0.61	72.1
Clay products	0.97	62.1	0.91	60.8	0.60	59.8	0.69	58.9
Fiber yarn	0.36	27.2	0.31	27.1	0.58	43.9	0.69	44.9
Water supply	0.55	56.1	0.51	57.9	0.56	60.9	0.61	62.0
Average direct carbon intensity (168 sectors)	0.323		0.282		0.237		0.224	

Notes: Direct shares mean shares of direct carbon intensities in the total carbon intensities.
The exchange rate was 1024.13 Won per USD 1 or 97.6 Cents per 1000 Won in 2005.

The calculated deterioration of carbon efficiency is also due to the deterioration of energy efficiency measured in economic indicators (energy requirement for the production in monetary value like kJ/Won) rather than in physical indicators (energy requirement for the production in physical terms like MJ per ton of pig iron or paper). However, energy efficiencies of these sectors should not have deteriorated, when analyzed by using physical energy indicators rather than economic energy indicators. A study on energy indicators of energy intensive Korean industries for the period from 1990 to 1997 by using physical energy indicators shows an energy efficiency improvement in iron & steel, petrochemical, paper & pulp and cement industries (Park, 2002).[6]

Table 11: Average total, direct & indirect carbon intensities in Korea (1995-2010)

	1995	2000	2005	2009	2010	Annual growth %	
	g CO_2/Won	g CO_2/Won	g CO_2/Won	g CO_2/Won	g CO_2/Won	1995-2000	2000-2009
In current prices (total)	1.413	1.025	0.681	0.629	0.544	-6.22	-5.28
" " (direct)	0.499	0.358	0.237	0.179	0.161	-6.43	-7.41
" " (indirect)	0.914	0.667	0.444	0.450	0.383	-6.11	-4.28
In 2005 constant prices (total)	1.008	0.867	0.681	0.770		-2.97	-1.31
" " (direct)	0.323	0.282	0.237	0.224		-2.68	-2.53
" " (indirect)	0.685	0.585	0.444	0.546		-3.11	-0.76

Notes: Total carbon intensity means direct and indirect carbon intensity.
The exchange rate was 1024.13 Won per USD 1 or 97.6 Cents per 1000 Won in 2005.

[6] An increase in the energy intensity does not necessarily mean energy efficiency deterioration. This is especially so, because monetary (economic) energy intensities are used in this study. The energy intensities, the fractions, will not only depend on the energy inputs, numerators of the energy intensities but also on the production values, denominators of the energy intensities. Generally the market situation, demand and supply constellation determines prices of products regardless the energy use for their production. If the price of a product falls due to decreasing demand and/ or increasing supply, its energy intensity (measured in kJ/Won) will increase. And the price is an important determinant of the value added of a product.

Most direct carbon intensive non-energy sectors are characterized by relatively high shares of direct carbon intensities in the total carbon intensities. However, the majority of sectors studied have a very high share of indirect carbon intensity in the total carbon intensity. More than 70% (from 114 out of 161 for 2000 to 120 out of 161 for 1995) of non-energy sectors had such a share higher than 60%. Average indirect carbon intensities of non-energy sectors were about twice as high as direct ones except for the year 2005 as shown in Table 11. This highlights the importance of indirect and total carbon intensities, for instance, for carbon emission abatement policies. Furthermore, Table 11 indicates a rather big decline in the indirect and total energy intensity in the 1995 to 2000 period.

Total carbon intensities in 2005 constant deflated prices for the period from 1995 to 2009 in Table 12 reveal again that iron & steel and chemical products (sectors) are most carbon intensive. It is interesting to observe that the ranks of the 3 most intensive non-energy sectors did not change much in the period considered. One exception is the *coal basic chemical products* sector the production of which decreased drastically since 2005. The average total carbon intensity decreased from 1995 to 2005 but increased from 2005 to 2009 as was the case for the average direct carbon intensity.

Table 12: Total (direct and indirect) carbon intensities of most intensive non-energy sectors in Korea

	1995		2000		2005		2009	
	g CO_2/Won$_{2005}$		g CO_2/Won$_{2005}$		g CO_2/Won$_{2005}$		g CO_2/Won$_{2005}$	
	Intensity	Rank	Intensity	Rank	Intensity	Rank	Intensity	Rank
Coal chemical products	4.85	2	7.25	1	5.39	1		
Pig iron and ferroalloys	5.57	1	5.28	2	3.07	2	5.10	1
Steel ingots and semi-finished products	4.31	3	4.20	3	2.44	3	3.73	2
Petrochemical basic products	1.98	13	1.59	15	1.84	4	3.21	3
Iron and steel foundries and forgings	2.87	5	3.08	5	1.78	5	2.74	4
Hot rolled steel products	2.99	4	2.94	6	1.78	6	2.19	6
Synthetic rubber	1.92	15	1.61	14	1.67	7	1.96	7
Other industrial organic basic chemical products	2.55	7	1.69	10	1.63	8	1.66	8
Cold rolled steel sheet, strip, and bars	2.36	9	2.38	7	1.48	9	1.62	9
Cement	1.70	21	1.65	12	1.42	10	1.55	11
Inorganic basic chemical products	2.22	11	1.88	8	1.39	11	1.53	13
Paper	1.30	41	1.20	29	1.38	12	1.53	14
Chemical fibers	2.32	10	1.44	21	1.37	13	1.45	16
Synthetic resins	1.95	14	1.49	18	1.37	14	1.41	18
Fiber yarn	1.33	38	1.13	32	1.31	15	1.33	21
Average carbon intensity (168 sectors)	1.008		0.867		0.681		0.770	

Note: The exchange rate was 1024.13 Won per USD 1 or 97.6 Cents per 1000 Won in 2005.

As the carbon emissions depend not only on the carbon intensity (carbon efficiency) but also on the amount of household consumption of goods and services, it is necessary to have a look at the household consumption expenditure (categories). Table 13 shows shares of the 20 largest sectoral household consumption expenditure categories. These shares amounted to 66.9% of the total household consumption expenditure in 1995, more than 70% in the years 2000, 2005 and 2009.

The main expenditure for non-energy sectors had relatively low total carbon intensities except *road transport and motor vehicle and motor vehicle equipment*. *Real estate* (housing rental), *postal service and telecommunication, financial services* and *insurance* recorded increases in the share in the total household consumption expenditure, a sign of increasing living standards. However, this share decreased in the case of *wholesale & retail trade* and *medical and health*.

Table 13: Largest consumption expenditure categories of Korean households (1995-2009)

	1995			2000			2005			2009		
	Expenditure Share (%)	Intensity g CO_2/Won	Rank	Expenditure Share (%)	Intensity g CO_2/Won	Rank	Expenditure Share (%)	Intensity g CO_2/Won	Rank	Expenditure Share (%)	Intensity g CO_2/Won	Rank
Real estate	8.29	0.336	2	13.88	0.214	1	13.21	0.246	1	12.80	0.292	1
Wholesale and retail trade	10.26	0.466	1	7.52	0.306	2	8.14	0.360	2	8.03	0.379	2
Eating and drinking places	6.35	0.645	4	7.21	0.450	4	7.53	0.397	3	7.61	0.451	4
Education	6.93	0.173	3	6.20	0.187	5	7.39	0.260	4	7.77	0.336	3
Medical and health services	5.84	0.319	5	7.43	0.283	3	4.73	0.283	5	4.90	0.309	5
Postal service and telecommunication	1.12	0.370	23	3.03	0.238	9	4.22	0.286	6	3.20	0.276	8
Insurance	3.53	0.254	8	2.92	0.206	10	3.47	0.212	7	4.13	0.253	6
Amusement and sports activities	1.63	0.522	15	1.98	0.311	13	3.41	0.290	8	3.19	0.293	9
Financial services	1.85	0.186	14	3.19	0.122	8	2.98	0.109	9	3.89	0.124	7
Road transport	5.15	1.423	7	3.41	0.915	7	2.75	0.806	10	2.44	0.808	12
Motor vehicles and motor vehicle equipment	1.94	0.989	13	1.77	0.848	14	2.36	0.571	11	2.41	0.616	13
Textile wearing apparels and accessories	1.62	0.791	16	1.15	0.673	21	2.26	0.525	12	2.56	0.430	11
Personal services	2.09	0.401	11	2.10	0.392	12	1.97	0.389	13	2.01	0.436	14
Vegetables and fruits	2.97	0.346	9	2.14	0.316	11	1.70	0.401	14	1.61	0.441	15
Repair services	1.18	0.679	20	1.55	0.577	17	1.65	0.484	15	1.57	0.561	16
Social organizations	0.85	0.434	27	1.05	0.391	23	1.29	0.321	16	1.24	0.346	21
Tobacco products	2.18	0.072	10	1.52	0.070	18	1.28	0.082	17	1.32	0.107	19
Bakery and confectionery products, noodles	1.50	0.556	17	1.24	0.487	20	1.17	0.423	18	1.03	0.455	24
Communications and broadcasting equipment	0.23	0.985	61	0.80	0.675	27	1.15	0.422	19	1.56	0.396	17
Meat and processed meat products	1.37	0.753	18	1.77	0.494	15	1.11	0.407	20	1.07	0.408	23
20 largest expenditure categories	66.88	0.535		71.86	0.408		73.77	0.364		74.34	0.386	
Other expenditure categories (148 sectors)	33.12	1.072		28.14	0.929		26.23	0.724		25.66	0.822	
Average total carbon intensity (168 sectors)		1.008			0.867			0.681			0.770	

Note: The exchange rate was 1024.13 Won per USD 1 or 97.6 Cents per 1000 Won in 2005; Prices are constant 2005 prices.

4.2 Direct carbon emissions of households

The direct carbon emissions of Korean households accounted for 16.6% (2005) to 19.6% (2000) of the total energy related carbon emissions. Direct household carbon emissions grew at an annual average rate of 4.1% in the second half of the1990s and slowed down to 1.7% in the 2000s as shown in Table 13. The per capita direct household carbon emission increased from 1.462 t CO_2 in 1995 to 1.932 t CO_2 in 2009. The consumption of oil products was mainly responsible for the direct household carbon emissions in 1995. Oil products were main household fuels in the 1990s. As oil products were replaced by natural gas as heating fuel and as more and more electricity is used in households for heating, cooling and operation of electrical appliances, electricity consumption became the main source of direct household carbon emissions in Korea. The oil products share in the direct household carbon emissions decreased from 72% in 1995 to 30.6% in 2009, while the electricity share increased from 17.5% to 47.7% in the same period. The share of the town gas and steam & district heat sector increased, too. The coal share decreased until 2000 as coal briquette consumption for heating and cooking was replaced by town gas and district heat with growing income. It increased in the 2000s as heavily subsidized coal briquettes became heating and cooking fuel for very low-income households.

Table 14: Direct carbon emissions of Korean households by fuel (1995-2010)

	1995	2000	2005	2009	Annual growth rate in %	
	Mt CO_2	Mt CO_2	Mt CO_2	Mt CO_2	1995-2000	2000-2009
Oil products	47.470	42.907	28.793	28.823	-2.0	-4.3
	(72.0)	(53.1)	(39.0)	(30.6)		
Other oil products	0.011	0.005	0.003	0.000	-16.3	-29.7
	(0.02)	(0.01)	(0.00)	(0.00)		
Coal	2.024	0.760	0.872	1.315	-17.8	6.3
	(3.1)	(0.9)	(1.2)	(1.4)		
Electricity	11.547	18.214	25.679	44.964	9.5	10.6
	(17.5)	(22.5)	(34.8)	(47.7)		
Town gas	3.874	15.878	14.920	14.034	32.6	-1.4
	(5.9)	(19.7)	(20.2)	(14.9)		
Steam & heat	1.000	3.014	3.536	5.041	24.7	5.9
	(1.5)	(3.7)	(4.8)	(5.4)		
Total direct	65.925	80.777	73.803	94.177	4.1	1.7
	(100.0)	(100.0)	(100.0)	(100.0)		
Estimation of CO_2 emissions without price differentiation between households and industry						
Oil products	57.615	52.144	35.547	35.449		
Electricity	18.990	26.869	35.934	55.309		
Total direct	83.514	98.669	91.098	111.150		
Per capita direct carbon emissions (t CO_2)						
	1.462	1.718	1.533	1.932	3.3	1.3
Shares of direct household carbon emissions in the country' total in %						
	18.5	19.6	16.6	18.5		
Notes: Figures in brackets are shares in the direct household carbon emissions in %.						
Oil products are gasoline, diesel, kerosene, fuel oil, aviation fuel, fuel oil, LPG etc.						
Other products are lubricants, solvent, paraffin waxes etc.						

Table 14 shows the estimation of direct household carbon emissions with price differentiation between households and industries. As discussed before, uniform prices for households and the industry applied to convert monetary into energy input-output table result in an increase of household energy consumption and concomitantly higher household carbon emissions. It is common that the industry pays fuels less than households. With the price differentiation between households and industries the carbon emissions due to oil products and electricity consumption decreased from 35.4 Mt CO_2 to 28.8 Mt CO_2 and from 55.3 Mt CO_2 to 45.0 Mt CO_2, respectively in 2009. The energy related direct household carbon emissions decreased by 15.3% from 111.2 Mt CO_2 to 94.2 Mt CO_2 in 2009. It is important to differentiate fuel prices between households and industries.

4.3 Indirect household carbon emissions

More than 66% of the total carbon emissions of households were indirect in the 1995 to 2009 period as shown in Table 15. Indirect carbon emissions of households were high as goods and services consumed were produced energy intensively, hence carbon intensively, by industries due to relatively low priced fuel oil, coal and electricity. There is hardly any tax on coal and electricity is sold below production costs. Taxes on fuel oil are very low compared to oil products used by households such as gasoline, diesel and LPG.

Direct carbon emissions of Korean households were low because relatively high prices for gasoline (high gasoline taxes) and electricity (high progressive tariffs only for households as can be seen in Table 16) discouraged household energy use, hence carbon emissions. Moreover, Table 8 shows that the per capita primary energy consumption of Korean households (direct household energy consumption less fuel consumption for private cars, as used in the conventional energy statistics) was the lowest among countries in comparison, while their per capita energy consumption of the whole economy was much higher than that of Japan, France and Germany in 2010.

Table 15: Indirect carbon emissions of Korean households by fuel (1995-2009)

	1995	2000	2005	2009	Annual growth rate in %	
	Mt CO_2	Mt CO_2	Mt CO_2	Mt CO_2	1995-2000	2000-2009
Naphtha	8.665	7.164	9.299	14.187	-3.7	7.9
	(5.4)	(4.7)	(5.4)	(6.9)		
Oil products	91.576	61.227	54.146	50.834	-7.7	-2.0
	(57.3)	(39.8)	(31.6)	(24.6)		
Other oil products	0.027	0.664	0.663	0.518	89.3	-2.7
	(0.02)	(0.43)	(0.39)	(0.25)		
Coal	11.527	17.225	10.942	19.515	8.4	1.4
	(7.2)	(11.2)	(6.4)	(9.4)		
Electricity	43.568	56.219	77.450	98.712	5.2	6.5
	(27.2)	(36.5)	(45.1)	(47.8)		
Town gas	3.768	7.423	13.964	17.983	14.5	10.3
	(2.4)	(4.8)	(8.1)	(8.7)		
Steam & heat	0.813	4.095	5.149	4.776	38.2	1.7
	(0.8)	(4.1)	(5.1)	(4.8)		
Total indirect	159.944	154.017	171.613	206.525	-0.8	3.3
	(100.0)	(100.0)	(100.0)	(100.0)		
Estimation of CO_2 emissions without price differentiation between households and industry						
Oil products	87.548	56.142	52.078	48.844		
Electricity	39.808	51.832	72.254	93.402		
Total indirect	150.106	145.640	167.278	198.471		
Per capita indirect household carbon emission (t CO_2)						
	3.547	3.276	3.565	4.237	-1.6	2.9
Shares of indirect carbon emissions in the households' total in %						
	71.3	66.2	70.6	69.5		
Shares of indirect household carbon emissions in the country' total in %						
	44.9	37.4	38.7	40.7		
Notes: Figures in brackets are shares in the indirect household carbon emissions in %.						
Oil products are gasoline, diesel, kerosene, fuel oil, aviation fuel, fuel oil, LPG etc.						
Other products are lubricants, solvent, paraffin waxes etc.						

Another reason for the high share of indirect household carbon emissions could be found in a relatively high share of iron & steel and petrochemical industries in Korea as shown in Table 8. Per capita energy consumptions of iron & steel and petrochemical industries were with 0.214 toe (8.96 GJ) and 0.785 toe (32.87 GJ) , respectively highest among OECD countries in comparison.

Indirect carbon emissions of households did not change in the second half of the 1990s. This is because higher carbon emissions by consuming electricity, town gas and steam & district heat were compensated by an abatement of carbon emissions due to decreasing fuel product consumption. Indirect household carbon emissions grew by 3.3% in the 2000s. Again higher electricity consumption was mainly responsible for indirect household carbon emissions in 2009.

It is interesting to note that the price differentiation in the development of energy and carbon input-output tables, hence readjusting uniform prices to more realistic price differentiation between households and industries, resulted in higher indirect household carbon emissions as shown in Table 15. The indirect household carbon emissions after price differentiation grew by 4% from 198.5 Mt CO_2 to 206.5 Mt CO_2 in 2009. The direct household carbon emissions decreased while the indirect household carbon emissions increased. Industries consume more energy in the price differentiation than in the uniform pricing in the development of energy input-output tables, hence more indirect household carbon emissions.

Table 16: Monthly electricity tariffs in Korea as of August 2010

Basic tariffs per month [a)] (Won/month & household)		**Working tariffs [b)] (Won per kWh)**			
				Using upto	**Cumulative**
Up to 100 kWh	380	Up to 100 kWh	56.20	100 kWh	56.20
101 - 200 kWh	840	101 - 200 kWh	116.10	200 kWh	86.15
201 - 300 kWh	1,460	201 - 300 kWh	171.60	300 kWh	114.63
301 - 400 kWh	3,490	301 - 400 kWh	253.60	400 kWh	149.38
401 - 500 kWh	6,540	401 - 500 kWh	373.70	500 kWh	194.24
More than 500 kWh	11,990	More than 500 kWh	656.20	600 kWh	271.23
				700 kWh	326.23
				800 kWh	367.48
				900 kWh	399.56
				1000 kWh	425.22

Source: Korea Electric Power Corporation (KEPCO)

Notes : [a] Basic tariffs are charged per month and household to cover fixed costs of KEPCO.

[b] Working tariffs are highly progressive with the electricity consumed in a month.

Average exchange rate in 2010: Won 1156.26/USD.

As mentioned before, the importance of indirect household carbon emissions is reported in other studies. The share of indirect household carbon emissions in household total were 76% for China in 2004 (Wang and Shi, 2009), 61.3% for Portugal in 1992 (Cruz, 2002) and 49.7% for the USA in 2007 (Bin et al., 2010).

4.4 Total carbon emissions of households

Total (direct and indirect) household carbon emissions increased from 225.9 Mt CO_2 in 1995 to 300.7 Mt CO_2 in 2009. The growth rate was higher in the 2000s as shown in Table 17. As households were responsible for about between 55.3% in 2005 and 63.3% in 1995 of the energy related carbon emissions in Korea, they should be the main policy target for carbon emission abatement. The rest of the carbon emissions was emitted by the government (7.2%), the public (5.3%) and private (20.7%) investments (26%), the net exports (10.6%) being the difference between exports and imports and stock exchange (0.9%) in 2005. Households did not realize how much they emitted carbon directly and indirectly as their direct energy purchase accounted only to from 5.1% in 2009 to 7.4% in 2000 of their consumption expenditures.

Table 17: Total carbon emissions of Korean households by fuel (1995-2009)

	1995	2000	2005	2009	Annual growth rate in %	
	Mt CO_2	Mt CO_2	Mt CO_2	Mt CO_2	1995-2000	2000-2009
Naphtha	8.665	7.164	9.299	14.187	-3.7	7.9
	(3.8)	(3.1)	(3.8)	(4.7)		
Oil products	139.046	104.134	82.939	79.657	-5.6	-2.9
	(61.6)	(44.4)	(33.8)	(26.5)		
Other oil products	0.038	0.668	0.666	0.518	77.1	-2.8
	(0.02)	(0.28)	(0.27)	(0.17)		
Coal	13.552	17.985	11.814	20.829	5.8	1.6
	(6.0)	(7.7)	(4.8)	(6.9)		
Electricity	55.115	74.433	103.128	143.677	6.2	7.6
	(24.4)	(31.7)	(42.0)	(47.8)		
Town gas	7.641	23.300	28.884	32.018	25.0	3.6
	(3.4)	(9.9)	(11.8)	(10.6)		
Steam & heat	1.813	7.109	8.684	9.816	31.4	3.7
	(0.8)	(3.0)	(3.5)	(3.3)		
Total households	225.869	234.794	245.415	300.703	0.8	2.8
	(100.0)	(100.0)	(100.0)	(100.0)		
Estimation of CO_2 emissions without price differentiation between households and industry						
Oil products	143.114	109.381	86.968	83.542		
Electricity	58.798	78.700	108.188	148.710		
Total households	233.620	244.309	258.376	309.621		
Per capita total household carbon emission (t CO_2)						
	5.009	4.995	5.098	6.169	-0.1	2.4
Shares of direct energy purchase in the household expenditure in %						
	7.3	7.4	5.2	5.1		
Shares of total household carbon emissions in the country' total in %						
	63.3	57.0	55.3	59.2		
Notes: Figures in brackets are shares in the total household carbon emissions in %.						
Oil products are gasoline, diesel, kerosene, fuel oil, aviation fuel, fuel oil, LPG etc.						
Other products are lubricants, solvent, paraffin waxes etc.						

Total household carbon emissions in spite of using low carbon intensive electricity grew fast in the 1995 to 2009 period due to low electricity tariffs especially for industries. The emissions related to oil products consumption decreased substantially as relatively expensive oil products were replaced by electricity, town gas and steam & district heat. Carbon emissions by coal grew also because the shares of coal using iron & steel and cement industries increased. This was also the case for naphtha, the basic feedstock for the petrochemical industry.

Table 18: Carbon emission patterns of Korean households (1995-2009)

	1995	2000	2005	2009	2010
	Mt CO_2	Mt CO_2	Mt CO_2	Mt CO_2	Mt CO_2
Indirect emissions					
Food & beverage	31.78	30.32	31.62	37.23	36.15
	(14.0)	(12.7)	(12.7)	(12.1)	(12.0)
Clothing & footwear	8.79	6.37	10.57	11.58	11.92
	(3.9)	(2.7)	(4.2)	(3.8)	(4.0)
Household	15.49	16.25	15.15	17.72	19.28
	(6.8)	(6.8)	(6.1)	(5.7)	(6.4)
Living	9.47	12.62	16.66	22.00	20.92
	(4.2)	(5.3)	(6.7)	(7.1)	(6.9)
Transport & communication	29.79	23.34	26.52	29.10	26.00
	(13.1)	(9.8)	(10.7)	(9.4)	(8.6)
Education	3.54	4.49	8.87	14.02	13.83
	(1.6)	(1.9)	(3.6)	(4.5)	(4.6)
Hygiene & medicare	10.27	11.06	10.04	13.89	13.94
	(4.5)	(4.6)	(4.0)	(4.5)	(4.6)
Leisure	6.82	7.58	11.93	11.69	12.52
	(3.0)	(3.2)	(4.8)	(3.8)	(4.2)
Banking & insurance	3.41	3.81	4.93	8.35	7.57
	(1.5)	(1.6)	(2.0)	(2.7)	(2.5)
Other consumption	24.35	21.40	24.51	31.08	32.49
	(28.7)	(33.8)	(29.4)	(30.5)	(28.4)
Total of indirect CO_2	159.94	154.02	171.61	206.53	218.75
	(71.3)	(66.2)	(70.6)	(69.5)	(71.6)
Direct emissions					
Coal	2.02	0.76	0.87	1.31	0.84
	(0.9)	(0.3)	(0.3)	(0.4)	(0.3)
Petroleum	47.48	42.91	28.80	28.82	24.69
	(20.7)	(18.0)	(11.5)	(9.3)	(8.1)
Electricity	11.55	18.21	25.68	44.96	43.04
	(5.0)	(7.6)	(10.2)	(14.6)	(14.1)
Town gas & heat	4.87	18.89	18.46	19.08	18.17
	(2.1)	(7.9)	(7.4)	(6.2)	(5.9)
Total of direct CO_2	65.93	80.78	73.80	94.18	85.66
	(28.7)	(33.8)	(29.4)	(30.5)	(28.4)
Note: Figures in brackets are shares in the total carbon emissions in %					

Table 17 shows that the estimation of total carbon emissions without price differentiation between households and industries is bigger than those with price differentiation. For the year 2009 households emitted carbon in the amount of 300.7 Mt CO_2 against 309.6 Mt CO_2 without price differentiation. In 2009 electricity consumption became the largest energy source for household carbon emissions, as households consumed much more electricity (4230.4 PJ) than petroleum products (2003.8 PJ) indirectly.[7]

Table 18 reveals changes in household carbon emission patterns in Korea from 1985 to 2009. Consumption groups like *living*, *education*, *leisure* and *banking & insurance* experienced an increase in their share of the household carbon emissions. Consumption groups like *food & beverage, clothing & footwear, hygiene & medicare, transport & communication* and *household* recorded a decrease in the share in the household carbon emissions. In terms of direct household carbon emissions, electricity, town gas and steam & district heat play a more important role than other fuels. All these changes are related to the increasing living standards and rapid economic growth in Korea.

Table 19 indicates that Korean households were dominant in energy related direct and total carbon emissions of the country. Investments were also important in the total carbon emissions. Carbon embodied exports have been larger than such imports since 2000. This is because Korea has had trade surpluses since 2000. Korean exports were more carbon intensive than imports in 2000 and 2005, while the opposite was the case in 1995. An energy resource poor country like Korea should import more carbon intensive goods and services and export less carbon intensive goods and services, rather than vice versa.

Table 19: Direct and total CO_2 emissions by economic activity in Korea (Mt CO_2)

	Unit	1995	2000	2005	2009
Households	Mt CO_2	65.925	80.777	73.803	94.177
Net exports		-17.833	12.919	13.929	6.606
Stock change		1.157	3.699	0.473	-21.501
Direct CO_2 emissions	Mt CO_2	49.250	97.395	88.205	79.282
Households	Mt CO_2	225.869	234.794	245.415	300.703
Government consumption		24.169	22.095	31.733	44.859
Investments		145.859	122.433	115.205	154.565
Net exports		-45.506	30.496	46.898	68.065
Stock change		6.192	1.766	4.198	-60.366
Total CO_2 emissions	Mt CO_2	356.583	411.583	443.449	507.825
Carbon intensity of exports	g CO_2/Won	2.445	2.242	1.420	1.202
Carbon intensity of imports		2.813	1.593	1.047	1.205

4.5 Changes in household carbon emissions

Although the evolution in average direct, indirect and total carbon intensities shown in Table 9 indicates a decrease in carbon intensities (carbon efficiency improvement) during the studied period, it is not clear what caused the changes in total household carbon emissions. These changes

[7] 34.1% of electricity was produced in 2009 by nuclear, 44.6% by coal, 15.1% by LNG, 3.2% by heavy oil and diesel, 1.3% by hydro and 2.6% by renewable energy and others.

(increases in household carbon emissions) are related to four factors: (1) change in the household expenditure (activity effect); (2) change in the structure of household consumption (structure effect); (3) change in the energy intensity (efficiency effect) and (4) change in the carbon intensity (carbon efficiency) with the help of a simple decomposition analysis.

The analysis used to decompose the effects of changes in activity, structure, energy efficiency and carbon efficiency on changes in carbon emissions (C) is

$$\Sigma C = \Sigma P * \frac{PPI}{\Sigma P} * \frac{\Sigma E}{PPI} * \frac{\Sigma C}{\Sigma E} \qquad (11)$$

where ΣP refers to household expenditure, *PPI* (Physical production index) means here the sum of expenditure categories weighted with energy intensities of expenditure categories of a reference year, $PPI/\Sigma P$ is structure effect, ΣE / PPI represents energy efficiency effect on production and $\sum C/\sum E$ represent carbon efficiency effect on energy. Increasing PPI of $PPI/\Sigma P$ results in higher fraction and thus more energy intensive production structure. Whereas increasing PPI in ΣE / PPI results in higher energy efficiency.

The third term and the fourth term of Eq. (11) are multiplied as to get carbon efficiency effect on production as $\sum C/\sum PPI$. This is necessary as the term $\sum C/\sum E$ is a constant and not a variable. As mentioned before, this study uses the default carbon emission factors (CEF) of IPCC which do not change over time and Korea has not revised CEF periodically to accommodate changing CEF of fuels over time. Eq. (11) becomes Eq. (12) as

$$\Sigma C = \Sigma P * \frac{PPI}{\sum P} * \frac{\sum C}{PPI} \qquad (12)$$

By decomposing the differential of Eq. (12):

$$\Delta C = \Delta C\ (Activity) + \Delta C\ (Structure) + \Delta C\ (Efficiency) + residuals \qquad (13)$$

A simple average parametric Divisia method 2 (AVE-PDM2, an additive carbon emissions technique) is used as to minimize the residuals (Ang, 1995).

- Activity effect:

$$\Delta C\ (Activity) = (P_1 - P_0) * \left(\frac{PPI_1}{P_1} + \frac{PPI_0}{P_0}\right) * \left(\frac{C_1}{PPI_1} + \frac{C_0}{PPI_0}\right) / 4 \qquad (14)$$

[8]

- Production structure effect:

$$\Delta C\ (Structure) = (P_1 + P_0) * \left(\frac{PPI_1}{P_1} - \frac{PPI_0}{P_0}\right) * \left(\frac{C_1}{PPI_1} + \frac{C_0}{PPI_0}\right) / 4 \qquad (15)$$

- Carbon efficiency effect:

$$\Delta C\ (Efficiency) = (P_1 + P_0) * \left(\frac{PPI_1}{P_1} + \frac{PPI_0}{P_0}\right) * \left(\frac{C_1}{PPI_1} - \frac{C_0}{PPI_0}\right) / 4 \qquad (16)$$

[8] The right side of Eqs. (14)-(16) is divided by 4 as to have the averages of the last two factors. For more discussion on the decomposition analysis see Farla et al., 1997a,b.

Results of decomposition of changes in household carbon emissions in periods from 1995 to 2005 are presented in Table 20. The increase in consumption expenditure (activity) was principally responsible for the rise of household carbon emissions. The large positive activity effect was partly due to growing household expenditure. The household expenditures increased at an annual growth rate of 6.7% from 283.8 TWon (Trillion Won) in 1995 to 392.3 TWon in 2000 and at an annual rate of 3.5% from 392.3 TWon in 2000 to 465.6 TWon in 2005.

Table 20: Decomposition of changes in total household carbon emissions (Mt CO_2)

	Δ Carbon	Activity	Structure	Efficiency	Residuals
1995-2000	8.925	75.705	-9.923	-57.051	0.194
	(100.0)	(848.2)	(-111.2)	(-639.2)	(2.2)
2000-2005	10.622	37.533	-6.328	-20.604	0.021
	(100.0)	(353.4)	(-59.6)	(-194.0)	(0.2)
1995-2005	19.547	115.927	-16.817	-80.211	0.647
	(100.0)	(593.1)	(-86.0)	(-410.4)	(3.3)

Notes: Figures in brackets are shares in the change in the household carbon emissions in %.
A minus sign means a decrease in carbon emissions.
A plus sign means an increase in carbon emissions.

Switching to consumption of less carbon intensive goods and services (minus sign of the structure variable) contributed to reduce the increase in total household carbon emissions from 1995 to 2005. The carbon efficiency (minus sign of the efficiency variable) contributed greatly to reduce the increase in total household carbon emissions also in the 1995 to 2005 period. There are positive structure and efficiency effects in the studied period.

5. Discussion and conclusions

5.1 Discussion

A key issue in the quantification of direct and indirect household carbon emissions for the input-output analysis is to construct energy and carbon input-output tables. As detailed sectoral energy consumption and carbon emission data are missing, monetary input-output tables are first converted into energy terms with the help of uniform (average) fuel prices. However, this kind of construction of energy input-output tables results in an overestimation of direct household energy requirement and concomitantly an underestimation of indirect household energy requirement. This study has tried to differentiate prices of oil products and electricity between households and industries. Better energy price information is crucial to construct energy input-output tables.

Second, this study converts energy into carbon input-output tables by using default carbon emission factors and storage factors of the IPCC. These factors are used because country specific data are not available in Korea. Such factors depend on the types of fuels used in a country and vary over time. Especially, non-energy statistics are not readily available and often not accurate. Therefore, better information on country specific and time (year) specific carbon emission and storage factors are required.

Despite a relatively disaggregated sector classification to 161 non-energy sectors and 7 energy sectors, sectors like *vegetables and fruits*, *meats*, *diary products* and *wholesale and retail* used in this study are too aggregated, as to make sectoral energy and carbon intensities for different years comparable. This is because large differences in energy and carbon intensities of products can exist in the same sector and because the composition of products consumed in a sector does not remain unchanged. Moreover, not only inter-sector structural changes but also intra-sector structural changes are occurring.

5.2 Conclusions and recommendations

In the first step, this study converts energy consumption data given in final energy terms (TFC) into primary energy terms (TPES). Sectors with a higher share of electricity in the energy consumption tend to have lower energy intensity than those with a lower share if energy intensities are calculated in final energy terms. Moreover, this study has used differentiated prices of oil products and electricity between households and industries. Uniform (average) prices used to convert monetary to energy input-output tables would cause an overestimation of direct household energy requirement and concomitantly an underestimation of indirect household energy requirement. In the second step, energy input-output tables are converted into carbon input-output tables with the help of carbon emission factors and carbon storage factors by fuel and year.

This study shows that average direct and total carbon intensities declined rather substantially in the 1995 to 2010 period in Korea. This means that the Korean industry moved to a higher value added consumption structure as the value added of the Korean consumption grew faster than the energy input (use) for the production, hence carbon emissions. Carbon intensive sectors belong mostly to heavy and chemical industries. Unlike to other countries like Thailand the electricity sector is not the most carbon intensive, as the share of nuclear energy in the electricity generation was high with 31.3% in 2010 and 43.1% in 1999 in Korea. The total carbon intensity of electricity was 1.14 g CO_2/Won against 3.07 gCO_2/Won for pig iron and ferroalloys and 1.42 gCO_2/Won for cement in 2005 (Table 12). In 2009, electricity consumption became the main source of household carbon emissions in Korea. Households consume more and more electricity intensive goods and services, a sign of increasing living standards. This occurred despite relatively low carbon intensity of electricity in Korea.

The Korean household sector was responsible for between 55.3% in 2005 and 63.3% in 1995 of the energy related carbon emissions in the 1995 to 2010 period. And more than 66% of household carbon emissions were indirect. Thus, the household sector is the main economic sector (driver) in carbon emissions and not only direct but also indirect household carbon emissions should be the policy target of carbon emission abatement. Decrease in carbon intensities of products and switching towards less carbon intensive products in the studied period contributed greatly to reduce the increase in the total household carbon emissions.

The share of direct household carbon emissions in the total household carbon emissions is low probably because higher fuel prices for gasoline and electricity discouraged direct household energy use, hence low carbon emissions, while lower fuel prices for the industry lead to an energy intensive industrial structure and with it to higher share of indirect use. It exemplifies that higher energy prices are a strong measure for energy conservation and carbon emission abatement. Another reason for the high share of indirect carbon emissions could be found in a relatively high share of heavy industry in the economy as well as in the total final energy consumption (TFC).

Information on energy and carbon intensities of more disaggregated sectors/ products will encourage household energy conservation and carbon emission abatement. Many consumers do not pay adequate attention to energy conservation and carbon emission abatement as they do not have such information (Hassett and Metcalf, 1993; Ü rge-Vorsatz et al., 2006).

Korea’s carbon emissions per GDP production were much higher than other OECD countries in comparison as shown in Table 9. Korea should make more effort to reduce carbon emissions. In this regard, indirect and total household carbon emissions should be the main target for carbon emission abatement.

More research should be done on indirect household carbon emissions. A future Korean study should apply a hybrid method to assess indirect household energy requirement and carbon emissions more accurately. Intensities of energy and carbon intensive products and expenditure strong products need to be assessed by the process chain analysis as to reduce errors occurred by using uniform (average) prices within the individual sector in constructing energy and carbon input-output tables and as to make energy and carbon intensities of different years more comparable.

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