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Driving Forces of CO₂ Emissions in Emerging Countries: LMDI Decomposition Analysis on China and India's Residential Sector

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Driving Forces of CO₂ Emissions in Emerging Countries: LMDI Decomposition Analysis on China and India's Residential Sector

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Abstract: The main objective of this paper is to identify and analyze the key drivers behind changes of CO₂ emissions in the residential sectors of the emerging economies, China and India. This paper also aims to draw policy implications in terms of finding challenges and opportunities to reduce residential CO₂ emissions in both countries. For the analysis, we investigate to what extent changes in residential emissions are due to changes in energy emissions coefficients, energy consumption structure, energy intensity, households' income, and population size. We decompose the changes in residential CO₂ emissions in China and India into these five contributing factors from 1990 to 2011 by applying the Logarithmic Mean Divisia Index (LMDI) method. According to our results, the increase in per capita income level is the biggest contributor to the increase of residential CO₂ emissions, while the energy intensity effect had the largest effect on CO₂ emissions reduction in the residential sectors in both countries. This implies that investments for energy savings, technological improvements, and energy efficiency policies were effective in mitigating CO₂ emissions. It is also found that the change in CO₂ emission coefficients for fuels, which is the ratio of CO₂ emissions arising from consumption of fuels to the consumption level slowed down the increase of residential emissions. In addition, results demonstrate that changes in the population and energy consumption structure drove the increase in CO₂ emissions.

Keywords: CO₂ Emissions; Emerging Economy; Residential Sector; Logarithmic Mean Divisia Index (LMDI) Method.

JEL Classification Numbers: C02, C15, C43, C65, O32, O33, Q01, Q48, Q55, Q56, R11, R22

1. Introduction

Global warming has been regarded as one of the most important environmental problems of our age. The ever-increasing amount of CO₂ emissions, which are partly to blame for the greenhouse effect, is aggravating climate change. In an effort to mitigate climate change, the international society has been undertaking numerous efforts to reduce CO₂ emissions at the national level. Given their high growth potential, emerging economies significantly affect future emission levels. Indeed, among the world's emerging economies, China and India are the largest CO₂ emitters, accounting for almost one-third of the world's CO₂ emissions [1] [2]. Accordingly, in recent years, rapid economic growth accompanied by increasing CO₂ emissions has focused the world's attention on China and India in the context of emissions reduction.

The rapid economic growth experienced by China and India in recent years has led to an exponential increase in the countries' energy consumption [3]. Over the last few years, China and India have been ranked significantly high in terms of energy demand; China was ranked the largest global energy consumer in 2011, followed by the United States, Russia, and India [4] [5] [6] [7] [8]. As the energy consumption structures of both countries are heavily dependent on coal, it is highly likely that the spurt in economic growth will cause their CO₂ emissions levels to rise even further in the coming years [9]. Furthermore, more than three quarters of the world's energy-related CO₂ emissions growth is expected to come from China and India [10], while it is predicted that the share of the other industrialized countries will fall continuously.

As mentioned above, the recent impressive economic growth in these countries has intensified their demand for energy across all sectors, including the residential sector. The residential sector in China accounts for 23% of total final energy consumption, the second largest share in its economy. India's residential sector consumes 36% of its total final energy and constitutes the largest sector in this respect. More importantly, with increasing household income and rapid electrification in these countries, the residential sector is recognized as being key toward mitigating CO₂ emissions at the national level. Trends in CO₂ emissions are closely tied to economic growth and energy consumption. Therefore, understanding the factors driving increased CO₂ emissions is essential to design effective energy and environmental policies aimed at emissions reductions.

In this paper, we use the Logarithmic Mean Divisia Index (LMDI) decomposition technique to analyze how socio-economic factors contribute to changes of CO₂ emissions in the residential sector over time (from 1990 to 2011). The LMDI approach has been used previously to analyze the determinants of CO₂ emissions in the residential sector [11] [12] [13] [14] [15]. However, these studies are limited to a single country and do not conduct a comparative analysis between countries. Therefore, the main objective of this paper is to identify and understand the drivers behind CO₂ emissions from the residential sector in China and India, so as to draw implications in terms of challenges and opportunities with regard to their countries' energy policies. Furthermore, by comparing the factors affecting the trends of CO₂ emissions in these countries, we propose to shed light on the possible energy policy implications for other developing countries.

The rest of this paper is organized as follows. Section 2 introduces the LMDI methodology and datasets used for the decomposition analysis. Section 3 presents the

main results from the decomposition analysis on residential CO₂ emissions in China and India. Section 4 concludes and draws policy implications from the analysis.

2. Methods and Data

2.1. The Logarithmic Mean Divisia Index (LMDI) Method

Index decomposition analysis (IDA) has been widely applied to studies that focus on analyzing the driving factors of energy consumption and greenhouse gas (GHG) emission trends. Index decomposition starts by defining the various factors associated with the aggregate variable (e.g., industrial energy consumption and industrial energy-related carbon emissions). Using these defined factors, different methods can be formulated to quantify the impacts of changes in the factors on the aggregate variable [14] [15]. The IDA approach can be divided into two groups: methods linked to the Laspeyres index and methods linked to the Divisia index. Since 2000, the LMDI method, classified as a Divisia index approach, has been the most popular IDA approach [15] [16]. The LMDI approach has advantages in terms of practical implementation; it does not contain an unexplained residual term and is consistent in aggregation [17] [18] [19]. Furthermore, the literature notes that the LMDI method can be used to investigate changes in GHG emissions both in the theoretical and practical contexts [15] [19] [20]

This paper investigates the evolving patterns of CO₂ emissions in the residential sectors of China and India for the years 1990 to 2011 using the LMDI approach. Given their rapid rates of economic growth, these countries have been experiencing a sharp increase in energy demand. Rampant urbanization has triggered high construction activity in the world's top two populous nations. Therefore, household share of total CO₂ emissions will continue to grow as these emerging economies transfer to higher industrialization and higher income levels [21]. Given the strong prospects for continued rapid economic growth and higher future CO₂ emissions, a number of studies have explored the key factors influencing changes of CO₂ emissions in the residential sector, with a special focus on China and India [11] [12] [13] [22] [23].

In the case of China, Wang et al. [22] decomposed China's CO₂ emissions at the regional level (focusing on Tianjin city) and concluded that income and population effects are the dominant positive factors affecting the growth in CO₂ emissions for all sectors. Zhao et al. [13] concluded that price effects resulting from price deregulation in the energy sector contribute to reduction of energy consumption, and thus slowed down CO₂ emissions. Zha et al. [11] estimated and compared CO₂ emissions trends and key factors influencing these trends for the urban and rural residential sectors. They found that energy intensity and income effects, respectively, contributed the most to the decline and the increase of residential CO₂ emissions in both urban and rural areas. Xu et al. [23] also reported that an increase in per capita energy usage contributed to rising emissions in the residential sector, while the effects of the shifts in the energy mix and emission coefficients on the change in CO₂ emissions are marginal. For the Indian residential sector, Das et al. [24] identified that income level, energy consumption expenditure level, and population size are the main factors responsible for increasing CO₂ emissions at the household level. Pachauri [25] analyzed the variations in the pattern of household energy consumption using micro level survey data. The

econometric analysis showed that income level and age of the household head are important explanatory variables for variation in energy requirements across households. As one of the analysis tools, the LMDI approach has been employed in a number of practical applications pertaining to the analysis of the determinants associated with the change of CO₂ emissions in the residential sector.

2.2. Model Construction

The LMDI method can be either additive or multiplicative form [14] [15]. In our analysis, we use the additive form of the LMDI approach to analyze the driving forces contributing to changes in CO₂ emissions from the residential sectors in China and India. Annual aggregate residential CO₂ emissions can be decomposed into five factors as follows (equation (1)):

$$CO2^t = \sum_i^n CO2_i^t = \sum_i^n \frac{CO2_i^t}{ENE_i^t} \frac{ENE_i^t}{ENE^t} \frac{ENE^t}{GDP^t} \frac{GDP^t}{POP^t} POP^t \quad (1)$$

As shown in the equation (1), $CO2^t$ refers to each country's aggregate CO₂ emissions from the residential sector, and $CO2_i^t$ represents the CO₂ emissions arising from consumption of fuel type i (e.g., coal, oil, gas, and electricity). In calculating those values, both direct CO₂ emissions from residential fuel use and indirect CO₂ emissions arising from the electricity and heat consumption are considered. In addition, we define the following variables for year t : ENE_i^t , the residential energy consumption level for fuel i ; ENE^t , total energy consumption in the residential sector; GDP^t , Gross Domestic Product (GDP) level; POP^t , population size in each country. Hence, the equation (1) can be expressed as an equation (2):

$$CO2^t = \sum_i^n CO2_i^t = \sum_i^n COEFF_i^t \cdot ES_i^t \cdot EIN^t \cdot INC^t \cdot POP^t. \quad (2)$$

In the equation (2), $COEFF_i^t (= \frac{CO2_i^t}{ENE_i^t})$ term is the emission factor of each fuel in the residential sector, which is CO₂ emission coefficient effect. This effect evaluates the fuel quality [11], and this covers both direct emission coefficients and indirect emission coefficients. $ES_i^t (= \frac{ENE_i^t}{ENE^t})$ captures the energy consumption share of fuel i relative to the total final energy consumption, which is the energy substitution effect. In addition, $EIN^t (= \frac{ENE^t}{GDP^t})$ term presents energy intensity of the residential sector, which is related to investments for energy savings, technological improvements, and energy efficiency policies. $INC^t (= \frac{GDP^t}{POP^t})$, and POP^t are, respectively, per capita income, and population effect associated with the change in the residential CO₂ emissions.

Based on this structure, we can decompose the observed changes in CO₂ emissions ($\Delta CO2^t$) from the residential sector from a base year ($t-1$) to a target year (t) into five different effects as mentioned above: the change in emission factor in energy consumption ($\Delta CO2_{COEFF}$: CO₂ emission coefficient effect), the change in energy consumption structure ($\Delta CO2_{ES}$: energy substitution effect), the change in residential energy intensity ($\Delta CO2_{EIN}$: energy intensity effect), the change in the income of residents ($\Delta CO2_{INC}$: income effects), and the change in population size

($\Delta CO2_{POP}$: population effects). Hence, the changes of aggregate residential CO_2 emissions between year (t-1) and year (t) can be expressed as following equation (equation (3)).

$$\Delta CO2^t = \Delta CO2_{COEFF} + \Delta CO2_{ES} + \Delta CO2_{EIN} + \Delta CO2_{INC} + \Delta CO2_{POP} \quad (3)$$

In addition, those five contributing factors can be derived from equation (4) to equation (8). Those factors give information upon relative contributions to changes in residential CO_2 emissions. Each of those five effects is isolated by measuring changes in residential CO_2 emissions associated with the change in the corresponding variable, while fixing the other variables constant with respective values in base year (t-1) [26] [27].

$$CO2_{COEFF} = \sum_i \left[\frac{(CO2_i^t - CO2_i^{t-1})}{(\ln CO2_i^t - \ln CO2_i^{t-1})} \right] \cdot \ln \left(\frac{COEFF_i^t}{COEFF_i^{t-1}} \right) \quad (4)$$

$$\Delta CO2_{ES} = \sum_i \left[\frac{(CO2_i^t - CO2_i^{t-1})}{(\ln CO2_i^t - \ln CO2_i^{t-1})} \right] \cdot \ln \left(\frac{ES_i^t}{ES_i^{t-1}} \right) \quad (5)$$

$$\Delta CO2_{EIN} = \sum_i \left[\frac{(CO2_i^t - CO2_i^{t-1})}{(\ln CO2_i^t - \ln CO2_i^{t-1})} \right] \cdot \ln \left(\frac{EIN^t}{EIN^{t-1}} \right) \quad (6)$$

$$\Delta CO2_{INC} = \sum_i \left[\frac{(CO2_i^t - CO2_i^{t-1})}{(\ln CO2_i^t - \ln CO2_i^{t-1})} \right] \cdot \ln \left(\frac{INC^t}{INC^{t-1}} \right) \quad (7)$$

$$\Delta CO2_{POP} = \sum_i \left[\frac{(CO2_i^t - CO2_i^{t-1})}{(\ln CO2_i^t - \ln CO2_i^{t-1})} \right] \cdot \ln \left(\frac{POP^t}{POP^{t-1}} \right) \quad (8)$$

where $\Delta CO2_{COEFF}$, $\Delta CO2_{ES}$, $\Delta CO2_{EIN}$, $\Delta CO2_{INC}$, and $\Delta CO2_{POP}$ denote the changes in CO_2 emissions from the residential sector arising from the CO_2 emission coefficient effect, energy substitution effect, energy intensity effect, income effect, and population effect, respectively.

2.3. Data Collection

In order to apply above mentioned additive form of the LMDI approach, we collect the data related to the energy consumption and CO_2 emissions from the residential sectors in China and India. Data for the residential CO_2 emissions levels from 1990 to 2011 in both countries are collected from the International Energy Agency's (IEA) datasets [1] [2] [28]. The values of energy consumption in the residential sectors from 1990 to 2011 have been sourced from other IEA datasets [6] [7].

For China, we divide energy sources into eleven categories according to [6] [7], including coal (bituminous coal, patent fuel, coke oven coke, gas works gas, and coke oven gas), oil (liquefied petroleum gases (LPG), kerosene, and gas/diesel oil), natural gas, electricity and heat. In addition, seven categories of energy sources, including coal (coking coal, bituminous coal, and brown coal briquettes (BKB)), oil (liquefied petroleum gases, and kerosene), natural gas, electricity and heat are considered for India's residential energy consumption structure. Furthermore, according to the accounting methodology for CO_2 emissions proposed by the Intergovernmental Panel

on Climate Change (IPCC) [28], biofuels is not considered in assessments of CO₂ emissions from fuel combustion.

By constructing those datasets, both direct CO₂ emissions from fuel combustion and indirect emissions associated with the electricity and heat consumption have been considered to understand the residential CO₂ emissions. CO₂ emissions from electricity and heat generation have been allocated to residential sectors in proportion to the electricity and heat consumed. In case of direct emissions from fuel use, emission factor (coefficient) by fuel type is calculated by dividing CO₂ emissions arising from consumption of fuel *i* by consumption level of fuel *i* in the residential sector. Likewise, indirect emission factor is derived from dividing indirect CO₂ emissions by the amount of electricity and heat demand from the residential sector. The population and GDP levels during the study period were obtained from the statistics collected by the Organization for Economic Co-operation and Development (OECD) [29] [30].

3. Analysis Result

3.1. Residential CO₂ Emissions and Energy Consumption Structure

The CO₂ emissions from the residential sector in China, including both direct emissions and indirect emissions) increased by 136%, from 398.9 million tonnes CO₂ equivalent (MtCO₂e) in 1990 to 942.1 MtCO₂e in 2011, during the study period (2009-2011). India also shows a clear trend of a rapid increase between 1990 (79 MtCO₂e) and 2011 (278 MtCO₂e). When comparing the absolute emissions levels between the countries, China shows higher values, as it is the largest CO₂ emitter in the world. Moreover, residential CO₂ emissions in India show a steady increase from 1990 to 2011, while the numbers for China reveal a period of decline before 2000, followed by a steady rise until 2011 (Figure 1).

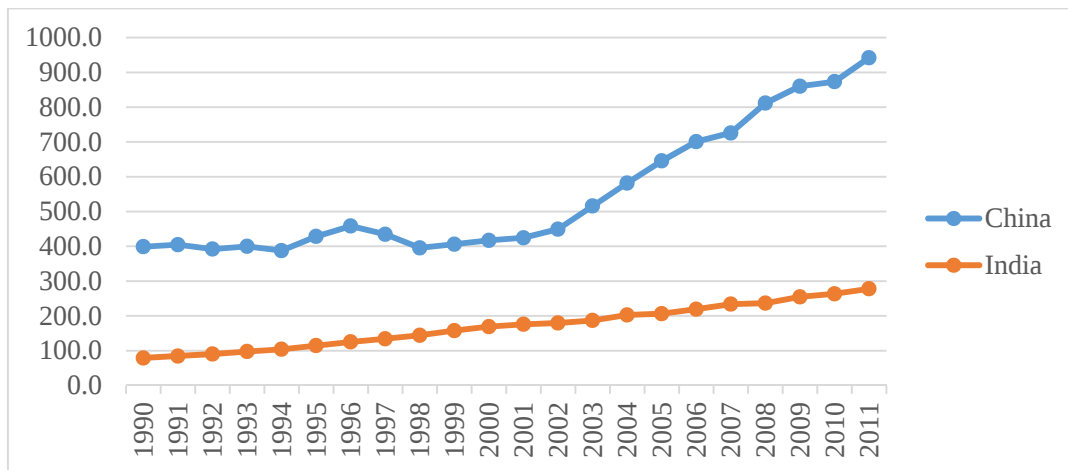


Figure 1. Residential CO₂ emissions from China and India (Unit: MtCO₂e).

The energy consumption structures associated with the CO₂ emissions in both countries reflect the structural changes related to fuel switching (Tables 1 and Table 2)

and the quantity of energy used (Figure 2). Residential energy consumption in China is more than triple that of India in terms of the aggregate level. However, both countries experienced rapid rates of energy consumption in the residential sectors from 1990 to 2011, mainly due to rapid urbanization, industrialization, and economic growth [31]. Those factors contributed to the accelerated growth of energy demand in their residential sectors.

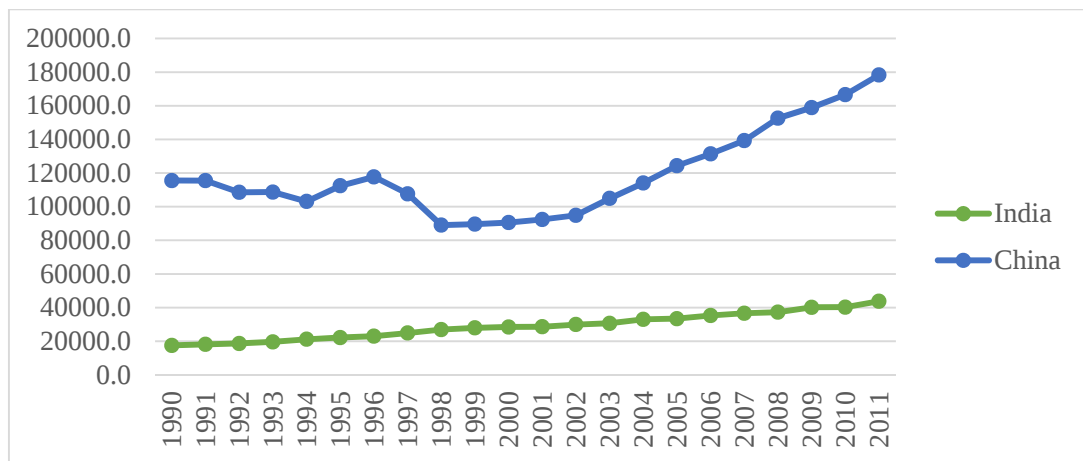


Figure 2. Trends of energy consumption level in China and India (Unit: kTOE).

The structural transitions of energy consumption by the residential sectors of both countries are reported in Tables 1 and 2. As shown in Table 1, coal and peat products account for the largest proportion of energy consumption during the whole study period. However, it is also pertinent to note that the residential sector in China has shifted from using the most carbon-intensive energy source (coal, including bituminous coal, patent fuel, etc.) to oil products, natural gas, and electricity. In the case of China, the share of coal and peat products in energy consumption by the residential sector declined from 90.3% in 1990 to 34.5% in 2011. On the other hand, the shares of oil products, natural gas, and electricity grew by 13.1%, 11.1%, and 23.6%, respectively, between 1990 and 2011.

**Table 1. Final energy consumption structure of China's residential sector
(Unit: %).**

		1990	1995	2000	2005	2010	2011
Coal/ Peat	Bituminous Coal	89.09%	73.92%	48.82%	38.42%	31.71%	29.75%
	Patent Fuel	0.00%	4.59%	5.63%	5.48%	2.43%	2.35%
	Coke Oven Coke	0.19%	0.79%	1.02%	0.49%	0.18%	0.16%
	Gas Works Gas	0.29%	0.90%	2.54%	2.08%	1.00%	1.40%
	Coke Oven Gas	0.78%	0.92%	1.90%	1.65%	1.27%	0.85%
Oil	LPG	1.65%	5.70%	11.38%	12.82%	10.49%	10.82%
	Kerosene	0.83%	0.64%	0.86%	0.23%	0.13%	0.14%
	Gas/Diesel Oil	0.00%	0.15%	2.01%	3.33%	4.72%	5.12%
Natural Gas		1.35%	1.44%	2.99%	5.34%	11.39%	12.40%
Electricity		3.97%	8.27%	16.73%	20.22%	27.02%	27.64%
Heat		1.85%	2.68%	6.13%	9.93%	9.66%	9.38%

**Table 2. Final energy consumption structure of India's residential sector
(Unit: %).**

		1990	1995	2000	2005	2010	2011
Coal/ Peat	Coking Coal	2.44%	1.17%	0.86%	0.00%	0.04%	0.04%
	Bituminous Coal	16.86%	13.89%	11.27%	10.23%	9.14%	8.53%
	BKB	2.29%	1.77%	0.91%	0.65%	0.68%	0.81%
Oil	LPG	12.21%	15.56%	21.56%	33.24%	34.70%	34.38%
	Kerosene	50.27%	46.87%	41.56%	29.90%	22.66%	19.23%
Natural Gas		0.24%	0.66%	0.97%	0.19%	0.06%	3.62%
Electricity		15.69%	20.07%	22.85%	25.79%	32.72%	33.41%

For India, it is found that the residential sector in India also experienced a structural transition in terms of the relative importance of different types of energy sources (Table 2). In 1990, the majority of India's energy demand was fulfilled by coal (21.6%) and oil products (62.5%), respectively. However, shares of coal and oil products in total final energy consumption in the residential sector declined to 9.4% and 53.6%, respectively,

in 2011. These declines were accompanied by increased shares of natural gas and electric power during this period. In summary, like Pachauri and Jiang [31], we find that both China and India are undergoing transitions with regard to residential energy consumption, which are described by their shifting away from poorly efficient solid fuels to more efficient liquid and gaseous fuels and electric power.

It is also essential to look into the electricity generation mix by fuel type for each country, as indirect emissions arising from the electricity consumption are taken into consideration when analyzing changes of residential CO₂ emissions. In China, the electricity consumption by the residential sector has grown rapidly from 53.4 TWh (approximately 4.0% of final energy consumption in the residential sector) in 1990, to 573.1 TWh (27.6% of total final energy consumption) in 2011 (Table 1). In addition, as shown in Figure 3 China's electricity sector is predominantly reliant on fossil fuels, especially via coal-fired generation [32,33]. It is found that total electricity output from coal-fired power plants with high emission coefficients has grown significantly, from 600.3 TWh in 1992 to 3,751.0 TWh in 2012. Dominance of coal-fueled power plants in China can be attributed to its large proven coal reserves [34], firmly holding the first place among coal producing countries.

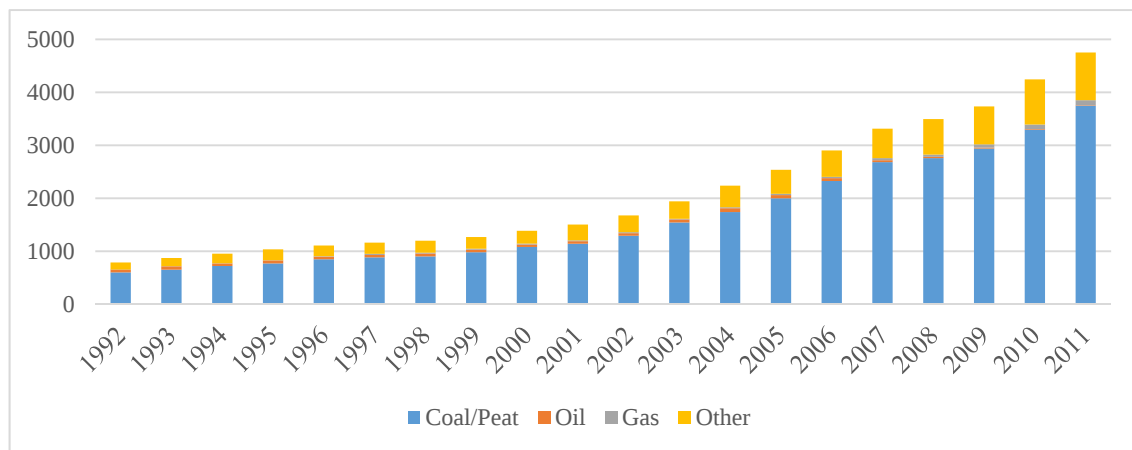


Figure 3. Generation mix by fuel type in China (Unit: TWh).

As with China, the demand for greater electricity generation has shown in India's residential sector during the study period. India's residential sector has shown rapid rates of electrification, and the share of electricity in final energy consumption has grown by 7.9% annually, increasing from 15.7% in 1990 to 33.4% in 2011 (Table 2). India's electricity sector is also heavily dependent on fossil fuels, especially coal, because it is the least expensive fossil fuel for power generation in the Indian economy (Figure 4). This can be understood by the India's domestic coal reserves (3rd largest coal reserves in the world), and relatively easy access to affordable imported coal [34]. From 1990 to 2011, increased electricity generation was accompanied by increased coal-fired generation [32] [33]. It is also found that total electricity generation output has grown from 229.3 TWh in 1992 to 714.9 TWh in 2011.

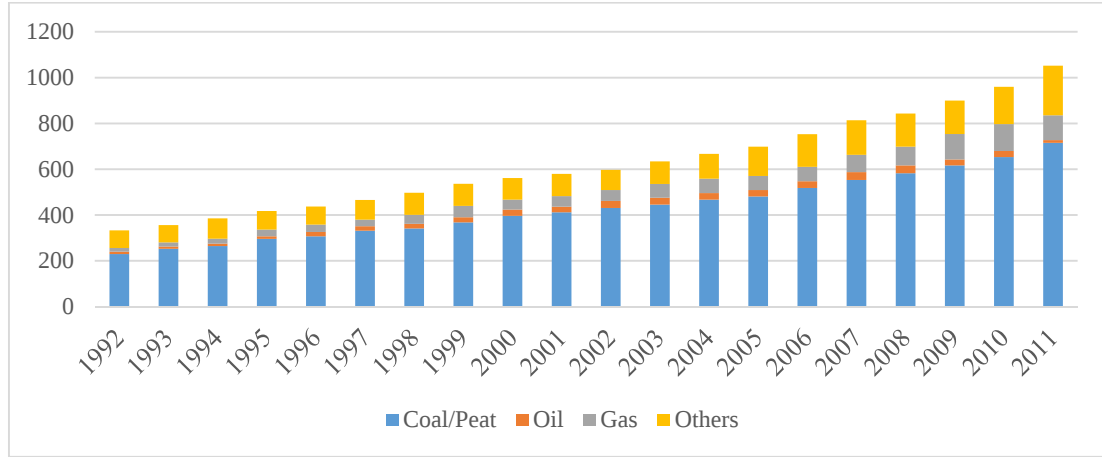


Figure 4. Generation mix by fuel type in India (Unit:TWh)

3.2. Main Results from the LMDI Methodology

This section presents the main results of the year-by-year decomposition analyses of China's and India's residential CO₂ emissions from 1990 to 2011. We use the equations and datasets mentioned in section 2 to investigate the degree of contribution of socio-economic factors to trends in CO₂ emissions. The decomposition analyses allow us to understand the impact of factors driving these trends in each country. Furthermore, we find common features in the identified contributing factors and accordingly draw political implications for major CO₂ emitting countries like China and India.

Figures 5 and 6 present the LMDI decomposition results from 1990 (the base year) to 2011 (the target year) for China and India, respectively. In the case of China (Figure 5), the emission coefficient effect ($\Delta CO2_{COEFF}$) and the energy substitution effect ($\Delta CO2_{ES}$) account for a decrease of 43.0 MtCO₂e and an increase of 234.5 MtCO₂e, respectively, in CO₂ emissions from the residential sector. Furthermore, the intensity effect ($\Delta CO2_{EIN}$) contributes to a decrease of 697.6 MtCO₂e, whereas the income effect ($\Delta CO2_{INC}$) and population factor ($\Delta CO2_{POP}$) cause increases of 965.5 MtCO₂e and 83.7 MtCO₂e, respectively.

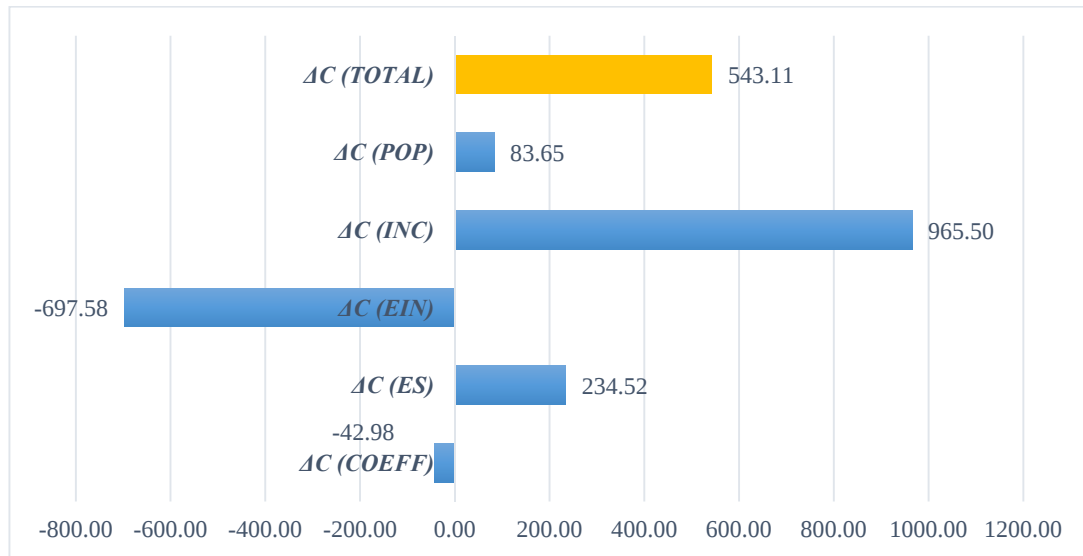


Figure 5. Results of LMDI decomposition from 1990 to 2011 in China (Unit: MtCO₂e).

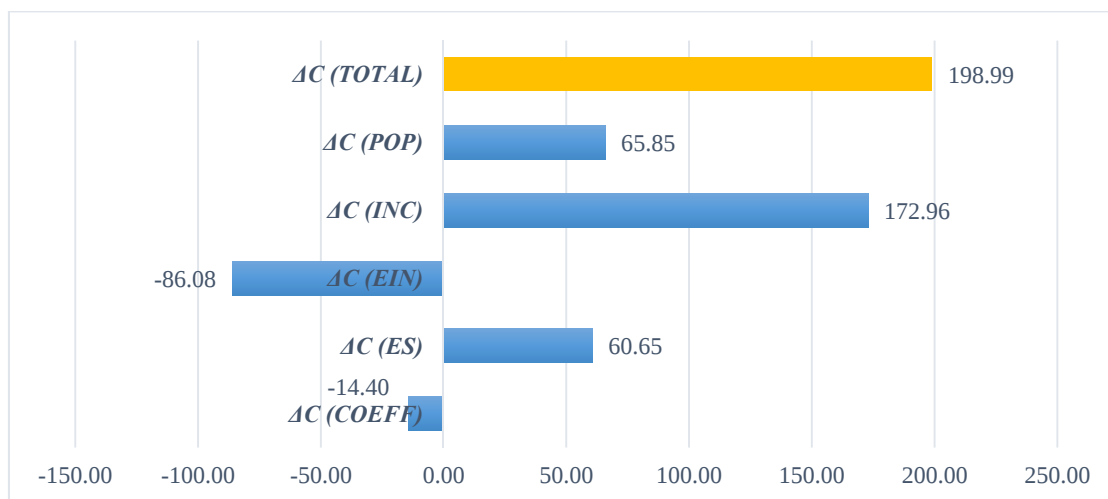


Figure 6. Results of LMDI decomposition from 1990 to 2011 in India (Unit: MtCO₂e).

When analyzing the corresponding factors for India (Figure 6), similar trends are observed from 1990 to 2011. The CO₂ emission coefficient effect is responsible for a decrease of 14.4 MtCO₂e in residential CO₂ emissions, while changes in the fuel mix pertaining to the energy consumption structure account for an increase of 60.7 MtCO₂e. In addition, the change in the population increases CO₂ emissions by 65.0 MtCO₂e. The income effect is the main contributory factor raising CO₂ emissions from India's residential sector, as it records an increase of 173.0 MtCO₂e. On the other hand, the change in energy intensity is mainly responsible for slowing down residential CO₂ emissions, causing a decrease of 86.1 MtCO₂e between 1990 and 2011.

Accordingly, it can be stated that the income effect was the major contributory factor leading to increased CO₂ emissions in both countries during the study period.

The changes in energy consumption structure, population also drove increase both countries' CO₂ emissions from their residential sectors, while CO₂ emission coefficient effect slowed down the residential CO₂ emissions. In addition, the energy intensity effect was mainly responsible for the CO₂ emissions reduction in the residential sectors of China and India from 1990 to 2011.

Besides analyzing the overall trends from the decomposition analysis, it is essential to analyze year-by-year trends of factors contributing to residential CO₂ emissions. Figures 7 and 8 highlight several characteristics of the decomposition analysis of residential CO₂ emissions since 1991. It is worthwhile to identify the forces responsible for residential CO₂ emissions and the differences between the two countries in terms of policy interventions associated with this issue. We discuss each of the five contributing factors in the following sub-sections.

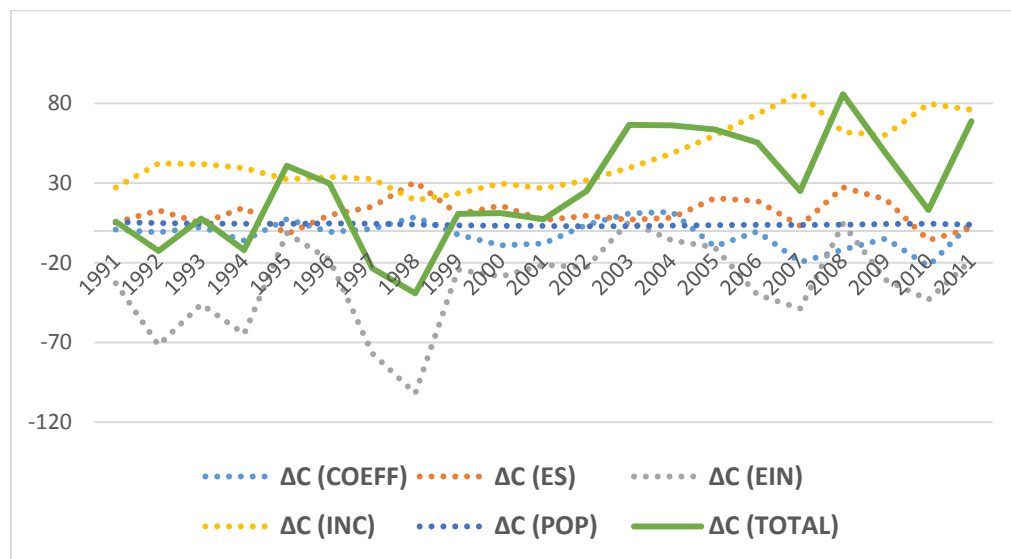


Figure 7. Year-by-year decomposition analysis for China (Unit: MtCO₂e).

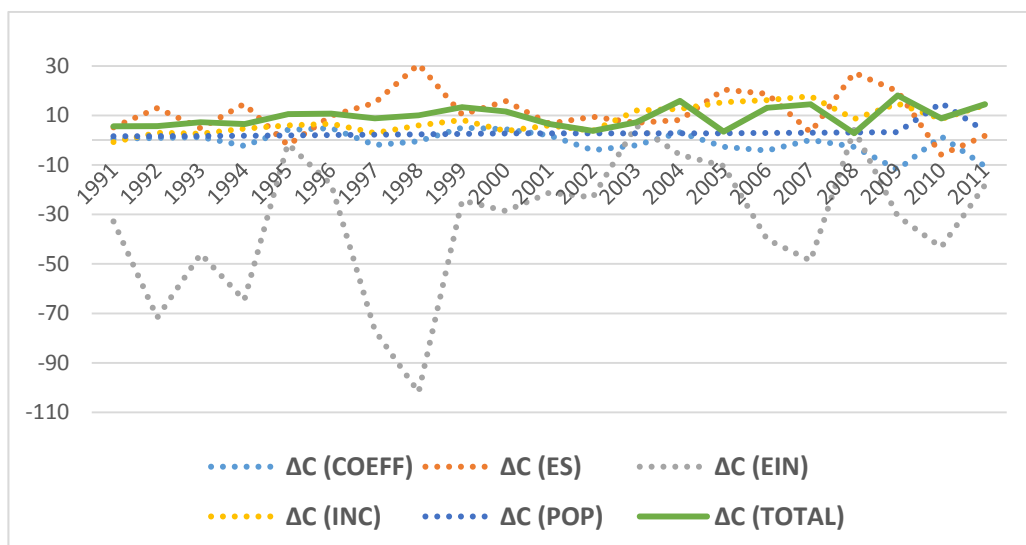


Figure 8. Year-by-year decomposition analysis for India (Unit: MtCO₂e).

3.2.1. CO₂ Emission Coefficient effect

Figure 7 shows that the CO₂ emission coefficient effect ($\Delta CO2_{COEFF}$) contributes the least toward changes in residential CO₂ emissions in China. In fact, during the entire period under study, the CO₂ emission coefficient effects on the changes of residential CO₂ emissions are negative. In addition, the results for the year-by-year trend show that the effect of this factor on residential CO₂ emissions tends to fluctuate. Given that we consider both the direct emissions from fuel combustion and the indirect emissions from the consumption of electricity and heat, the CO₂ emission coefficient effect ($\Delta CO2_{COEFF}$) is associated with direct emission factors (which is calculated by dividing direct CO₂ emissions by fuel use), and indirect emission factors (which is defined as indirect emissions from the electricity consumed per unit of electricity consumed). In this context, the impact of emission coefficients on residential CO₂ emissions is mainly determined by the fluctuation of indirect emission coefficients, while the direct emission coefficient is fuel specific, and relatively constant over the study period. The electricity emission coefficient, and the indirect emission coefficient could vary depending on fuel used to generate the electricity, and electricity generation efficiency.

In the case of China, it is evident that, barring the period from 2003 to 2005, these changes have slowed down residential CO₂ emissions since 1999. As shown in Figure 3, China's electricity sector is predominantly reliant on fossil fuels, especially via coal-fired generation, and total electricity output from coal-fired power plants with high emission coefficients has grown significantly. Therefore, it can be inferred that the CO₂ emission coefficient effect ($\Delta CO2_{COEFF}$) on reducing China's residential CO₂ emissions can be attributed to increased electricity production and transmission efficiency. This lowers the indirect emission coefficients, partly offsetting the increased electricity generation from coal-fired power plants. As shown in the Figure 9, the indirect emission coefficient for China's residential sector shows a decreasing trend with the exception of the period from 2003 to 2005, which implies a strong relationship between the CO₂ emission coefficient effect ($\Delta CO2_{COEFF}$) and the indirect emission coefficient. Furthermore, it is also found that the CO₂ intensity of coal-fired generation (CO₂ emissions per KWh from electricity generation using coal) in China has decreased from 1,102 in 1990 to 950 in 2011 [32]. Efficiency improvements in the power sector can be deciphered by retracing the relevant policy implementation during this period. The decomposition analysis also indicates that the effect of the electricity emission coefficient has been decreasing since 1999.

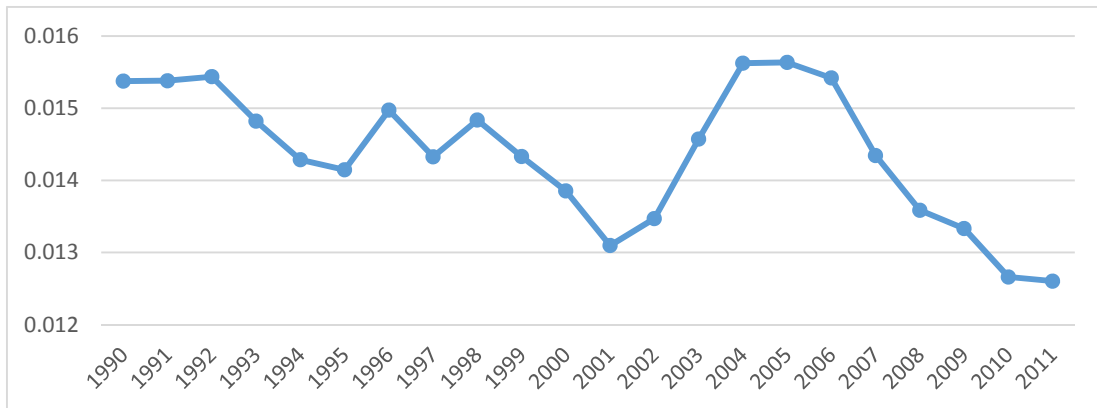


Figure 9. Trends of indirect emission coefficients in China (Unit: MtCO₂e/GWh).

A scrutiny of the regulation based policy implementation shows that China's government has made substantial efforts to increase the efficiency of the electricity production and transmission process by transforming the industry structure. In fact, the Electric Power Law legislated in 1996 aims to regulate the generation, distribution, and consumption of electricity [35]. For instance, small-scale power plants are prohibited. In 1997, the State Power Corporation was founded to resolve the power industry's structural problems, by transforming the monopoly system of the country's planned economy to a market-based economy. Furthermore, China's government dismantled the State Power Corporation on December 29, 2002 and set up 11 new companies in a move to end the corporation's monopoly of the power industry, which was expected to reduce costs and enhance efficiency [35]. Thus, the restructuring process helped improve fuel use efficiency and transmission efficiency in China's power sector. Zha et al. [36] also reported that transmission losses in China's power sector declined from 7% in 1990 to 6.5% in 2004.

Figure 8 shows that the emission coefficient factor generally drove the increase in CO₂ emissions from India's residential sector until 2004. During the periods 1990-1991, 1991-1992, 1992-1993, 1994-1995, 1995-1996, 1998-1999, 1999-2000, 2000-2001, and 2003-2004, increases of 0.57, 0.97, 1.29, 4.18, 4.88, 5.07, 4.44, 1.98, and 3.16 MtCO₂e were attributable to the CO₂ emissions coefficient factor ($\Delta CO2_{COEFF}$). Conversely, the same factor has contributed to CO₂ emissions reduction in the residential sector since 2004. During the periods 2004-2005, 2007-2008, 2008-2009, and 2010-2011, emissions reductions amounting to 2.67, 4.15, 2.68, 11.83, and 10.49 MtCO₂e could be explained by the CO₂ emissions coefficient factor. India's electricity sector is also heavily dependent on fossil fuels, especially coal, as shown in the Figure 4. From 1990 to 2011, increased electricity generation was accompanied by increased coal-fired generation with high emission coefficients. Similar to China's case, when explaining the CO₂ emissions coefficient effect ($\Delta CO2_{COEFF}$) on reducing India's residential CO₂ emissions from 2004 onwards can be attributed to gradual improvements in power generation and transmission efficiencies. As shown in the Figure 10, the indirect emission coefficient for India's residential sector shows an increasing trend from 1990 to 2002, while it shows a decreasing trend over the period from 2002 to 2011. It is also confirmed that there is strong relationship between the CO₂ emission coefficient effect ($\Delta CO2_{COEFF}$) and the indirect emission coefficient.

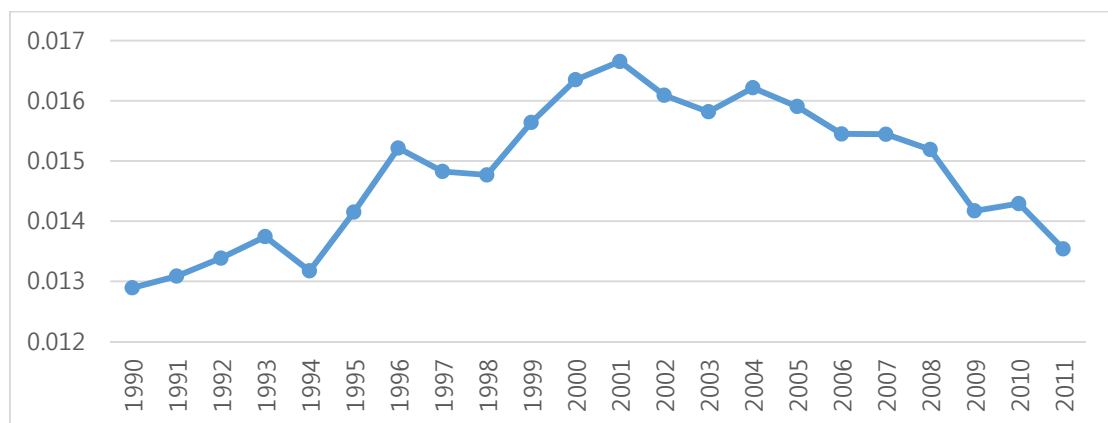


Figure 10. Trends of indirect emission coefficients in India (Unit: MTCO₂e/GWh)

Indeed, India's government implemented the Electricity Act of 2003 to create a market-based regime in the electricity sector to ensure a stable supply of electricity [37-39]. This legislation entails open access to the transmission and distribution system, introduction of competition in the power generation sector, and facilitating an electricity trading market [40]. In particular, this Act aims to improve efficiency and customer service standards by promoting competition among various players within the electricity sector [37]. Furthermore, India's short-term energy policy has been executed based on Five-Year Plans [40]. During the Ninth and Tenth Five-Year Plans (1996-2001 and 2002-2007, respectively), approximately 138 units at 29 power stations were taken up for renovation and modernization in order to improve their technological performance and efficiency [4]. Thus, its efforts to enhance efficiency in power generation have helped India realize positive technology changes related to energy conversion efficiency [41,42]

3.2.2. Energy Substitution Effect

The energy substitution effect ($\Delta CO2_{ES}$) contributed to the increase in CO₂ emissions for most of the study period for both China (234.52 MtCO₂e) and India (234.52 MtCO₂e). This energy substitution effect ($\Delta CO2_{ES}$) captures to what extent changes in residential emissions are due to changes in share of energy consumption by fuel type. Investigating the trend of the energy substitution effect requires an analysis of the energy consumption structure, as discussed in section 3.1. For China, the proportion of coal products in residential energy consumption decreases substantially from 1990 to 2011, as shown in the Table 1. On the other hand, the share of the electricity and heat, both of which have high emission coefficients, increases from 5.8% in 1990 to 37.0% in 2011. Therefore, even though there was a reduction in the direct emissions from most carbon-intensive energy sources, the indirect emissions from electricity and heat consumption increased. Accordingly, it can be inferred that the increased share of electricity with high emission coefficients which is largely based on the coal-fired generation has substituted for other fuels, which results in $\Delta CO2_{ES}$'s positive effect on CO₂ emissions.

The similar trend in energy consumption structure of the residential sector, is also detected for India (Table 2). In 1990, oil products (e.g., LPG and kerosene) accounted for the largest share of energy consumption associated with emissions from the residential sector, followed by coal products (e.g., coking coal and bituminous coal). However, in 2011, while oil products continued to dominate other fuels, emissions from electricity took the second largest proportion (33.41%). In other words, the share of coal in the energy consumption structure of India's residential sector was relatively reduced while that of electricity rose. Accordingly, it can be understood that electricity consumption which has high emission coefficients, substituted demands for other energy sources, resulting in positive effects on residential CO₂ emissions in both countries.

In 2000, India was ranked first in the world in terms of population without access to electricity (35.4%) [43]. To counter this, the Indian government launched several programs to provide households access to electricity in India. In 2000, the Prime Minister's Village Development Program was launched with a focus on providing basic services, including the rural electricity supply, to villages [44] [45]. In addition, the Rajiv Gandhi Grameen Vidyutikran Yojana (RGGVY), funded by the Rural

Electrification Corporation (REC), was launched in 2005, with the aim to electrify all villages and habitations in India. The REC designed a couple of policy programs to provide free supply of electricity to households below the poverty line and invested in fundamental infrastructure, such as electricity distribution transformers and distribution lines, to fulfill this goal [46] [47].

China's central government has also undertaken many initiatives to expand citizens' access to electricity. From 1990 to 2002, over 900 million rural residents have benefitted from these initiatives, and the country has achieved an electricity access rate of as high as 98% [48] [49]. In fact, the institutional management of rural electricity was operated by a multi-level administrative system until the late 1990s. From 1998 to 2002, China implemented and launched a series of policy instruments aimed at "reforming rural electricity management, renovating rural power grid and leveling rural and urban electricity tariffs" [49]. Moreover, the central government facilitated commercial operations in the utility market by letting the local electricity supply free from the control of local governments. Furthermore, the rural and urban electricity systems were merged to form a uniform and integrated nationwide system after 2002.

3.2.3. Energy Intensity Effect

The energy intensity effect ($\Delta CO2_{EIN}$) contributed to emissions reductions over 1990 to 2011 in both China and India. It was the main driving factor responsible for slowing down residential CO₂ emissions, as it cancelled out the positive effects arising from the other factors. This energy intensity effect ($\Delta CO2_{EIN}$) captures the effectiveness of investments for energy savings, technological improvements, and energy efficiency policies. Figure 5 shows that about 697.58 MtCO₂e of CO₂ emissions reductions are associated with the change in energy intensity of China's residential sector over the whole study period. In addition, we detected that $\Delta CO2_{EIN}$ had the largest impact in 1998, driving a decline of 101.86 MtCO₂e in CO₂ emissions. For India, about 86.08 MtCO₂e of CO₂ emissions reductions are driven by the energy intensity effect throughout the study period (Figure 6), while its impact has shown the largest in 2010, contributing to emissions reductions of 22.83 MtCO₂e. Impacts of the energy intensity effects on residential emissions reductions in both countries can be attributed to each country's efforts to improve energy efficiency by promoting technological progress and regulating standards for product energy efficiency levels. Therefore, the energy intensity effect can be interpreted as the decrease in energy consumption from energy efficiency gains, partly offsetting the increase energy consumption from economic growth [11].

China has undertaken wide-ranging efforts toward improving energy efficiency. Since the 1990s, it has been encouraging citizens to replace their old energy-inefficient home appliances [50]. In 1990, the Chinese government unveiled its first program on energy efficiency standards for appliances such as air conditioners and washing machines [51] [52] [53]. After modernizing the energy efficiency standard system in the mid 1990s, the Energy Conservation Law was formulated in 1998 to introduce mandatory minimum efficiency standards and energy efficiency labeling [51]. Accordingly, new standards and labeling requirements (such as voluntary energy efficiency labeling) were implemented in 1999, inducing appliance manufacturers to invest in technological progress [51] [54]. Furthermore, the energy efficiency labeling

system was formally established in China in 2005 in order to help consumers make more informed choices while buying appliances [11] [55].

India has also recognized the importance of energy efficiency. The government passed the Energy Conservation Act in 2001 to reduce the energy intensity of the economy [56]. In addition, the Bureau of Energy Efficiency (BEE), established in 2002 under the Ministry of Power [56,57], has initiated a number of energy efficiency initiatives in the areas of household lighting, standards, labeling of appliances, and so on. The establishment of the BEE was a turning point for articulating national initiatives for energy efficiency. In 2006, the BEE launched the Standards and Labeling Program for residential and commercial appliances/equipment, including 19 categories of products such as air conditioners, refrigerators, color TVs, washing machines, and so on. Furthermore, in 2008, India announced the National Action Plan on Climate Change, which emphasizes climate change mitigation. India's government has included the National Mission for Enhanced Energy Efficiency (NMEEE) as one of the missions under this Plan. Based on this initiative, India is making efforts to accelerate the shift to more energy efficient products and is using fiscal instruments to promote their development [58] [59].

In summary, China and India have long perceived the importance of energy efficiency and have adopted energy efficiency standards and labeling systems. However, these policies were initiated at different times, from the 1990s for China and from the 2000s for India. Therefore, we can infer that this difference in the timing of policy implementation between two countries shows up in the observed trends in their energy intensity effects.

3.2.4. Income Effect

The income effect ($\Delta CO_{2,INC}$) has the largest effect on CO_2 emissions from the residential sector for both China and India. Figure 5 shows that an increase of 965.50 MtCO₂e of emissions can be attributed to the change in the income level in China during the whole study period, while the corresponding number for India is 172.96 MtCO₂e (Figure 6). In addition, the trends for this factor show a pronounced increase from 1990 to 2011 in both countries. China and India are the world's fastest expanding large economies. From 1990 to 2011, China and India experienced rapid economic growth, as evidenced by their average GDP growth rates of 9.1% and 6.2%, respectively. The rapid growth of energy demand is a given with the continuous economic expansion evidenced in both countries. Higher household income levels and improved access to electricity encourage households to use more electric home appliances.

In fact, the electrification rates of China and India increased from 94.2% and 50.9% in 1990 to 100% and 78.7% in 2012, respectively, [60]. Bearing in mind that access to energy is essential for development and a better quality of life, the Chinese and Indian governments have launched a variety of programs to support household electrification in their countries. In the 1990s, China made great strides in enhancing rural electrification. Chinese power companies owned by the public sector enacted several

programs¹ to spur rural electrification using renewable energy such as solar and wind energy [61] [62]. In addition, in 1998 the Chinese government launched the Rural Network Development and Upgrade Program, which brought about reforms in rural electricity supply institutions, including leveling tariffs across networks, and promoting technological advances in the electricity supply system [63].

India has also executed a variety of programs to fulfill the energy and electricity demand of its rural population from the early 1990s by covering a wide range of technology and fuel options [46] [62]. For example, India's government initiated the Rural Electricity Supply Technology Mission (REST) in 2002 in order to provide decentralized electricity generation options in all villages using local renewable energy sources instead of depending on the centralized electricity supply system. This initiative includes identifying and adopting technological solutions and providing financial support to rural areas [64] [65].

Consequently, the electrification rates in both countries improved between 1990 and 2011. With better access to the electricity, the number of home appliances owned by the residential sector have increased drastically in China and India [12] [66].

3.2.5. Population Effect

The population effect ($\Delta CO2_{POP}$) contributed to increasing CO₂ emissions in China (83.65 MtCO₂e) and India (65.85 MtCO₂e) during the whole study period. From 1990 to 2011, population grew steadily, with average annual growth rate of 0.77% in China and 1.74% in India. The significant population size and its expanding growth rate drove rapid energy consumption in the residential sectors of both countries. Furthermore, the urbanization rate (which refers to the share of population living in urban areas) increased from 26% in 1990 to 51% and 31% in 2011 in China and India, respectively [67]. In fact, China and India became home to a third of the world's urban population. China has the largest urban population (758 million), followed by India (40 million). Therefore, the process of urbanization, along with the already large population size, drove the increase of CO₂ emissions in the residential sectors of both countries [68].

4. Conclusion and Discussions

Emerging economies can significantly influence future emission levels on a global scale, given their present emission levels and high growth potential. Therefore, the trends in CO₂ emissions in such countries are closely associated with their economic growth and changes in energy consumption. Among the emerging economies, China and India are the world's largest CO₂ emitting countries, together accounting for almost one-third of global CO₂ emissions. Moreover, their recent impressive economic growth has intensified their energy demand in all sectors, including the residential sector. The residential sector in China accounts for 23% of the country's total final energy consumption, comprising the second largest share in its economy. India's residential sector is responsible for 36% of the nation's total final energy consumption, comprising the largest sector in its economy. More importantly, increasing household incomes and

¹ In the 1990s, the power stations owned by the government implemented a variety of programs, such as "Serving Agriculture, Serving Peasants," "Serving Rural Economic Development," and "Project for Reducing Poverty and Simultaneously Enriching Rural and Urban Households by Electrification."

rapid electrification in these countries points to the need to focus on the residential sector as an important segment in mitigating CO₂ emissions at the national level.

Therefore, it is essential to analyze trends in residential energy consumption and CO₂ emissions and the key drivers responsible for them. After identifying these determinants, we can investigate the challenges and opportunities pertaining to the countries' existing energy policies. In this paper, we analyzed residential CO₂ emissions for China and India using LMDI decomposition analysis. Five socio-economic factors were considered as key contributing factors affecting changes of residential CO₂ emissions: CO₂ emission coefficient effect ($\Delta CO2_{COEFF}$), energy substitution effect ($\Delta CO2_{ES}$), energy intensity effect ($\Delta CO2_{EIN}$), income effect ($\Delta CO2_{INC}$), and population effect ($\Delta CO2_{POP}$). We found that during the period 1990-2011, the increase in per capita income level contributed to the most to the increase in CO₂ emissions while the energy intensity effect had the largest effect on CO₂ emissions reduction in the residential sectors in both countries. This implies that investments for energy savings, technological improvements, and energy efficiency policies were effective in mitigating CO₂ emissions. It is also found that the change in CO₂ emission coefficients for fuels, which is the ratio of CO₂ emissions arising from consumption of fuels to the consumption level slowed down the increase of residential emissions. In addition, results demonstrate that changes in the population and energy consumption structure drove the increase in CO₂ emissions.

Based on the result of our research, strategies and policies for low carbon economy in developing countries are discussed from now on.

(1) Technology policy

Technology policy is directly linked to R&D investment and R&D activities for developing generation technology. Despite prior policy implementation to enhance the energy efficiency of their respective electricity sectors (as discussed in section 3.2), the energy efficiency of thermal power generation in China and India has been consistently poor compared to that of other countries (e.g., the United States, Japan, Australia, Germany, and Italy) [69]. Thus, there is considerable potential to reduce CO₂ emissions via energy efficiency improvements in the electricity sector. The analysis shows that the electricity emission coefficient decreased recently for both countries. Therefore, both China and India need to further reduce the CO₂ emission intensity of electricity by adopting advanced technologies to enhance energy efficiency in their existing power generation systems. In addition, the introduction of wind energy, solar energy, and other renewables in electricity generation will reduce the dependence on fossil fuel power generation. Notably, rural areas would benefit from the introduction of small-scale decentralized electricity systems based on renewable energy sources. These are economical options that improve access to electricity and simultaneously reduce CO₂ emissions from the residential sector. Hence, combining renewable energies, such as the wind and solar power, with electricity efficiency improvement options can help both countries to reduce emissions and electricity supply costs.

(2) Industry policy

Active government's regulation on energy sector and policy implementation can achieve stated goal associated CO₂ emission reduction. According to the empirical research conducted by Lawrence Berkeley National Laboratory, industry policy to

mitigate CO₂ emission was effective. Specifically, Ten Key Energy Conservation Project implemented by Chinese government aimed to increase energy efficiency through adjusting and optimizing the industry structure, establishing a strict management system and implementing effective incentive mechanism in energy sector. The study reported total government investment for this project was about 735 million USD and the saving from 2006 to 2008 was estimated at around 150Mtce [70]. Additionally, industrial structure change by small plant closure and phase-out of outdated capacity accomplished energy saving of 63Mtce in final energy and 150Mtce in primary energy [70]. Hence it is strongly recommended for developing countries to replace the small, inefficient plants by modern facilities.

(3) Economic policy

Without doubt, it has been generally accepted that emerging countries such as China and India sustained high economic growth continuously by consuming much conventional energy and consequentially emitting CO₂ for long time. However, it has been empirically shown that neither carbon emissions nor energy consumption leads economic growth [71]. Therefore, the government of China and India can pursue conservative energy policy and carbon emissions reduction policy in the long run without impeding economic growth. This article also demonstrated that there has been a decoupling between GDP growth and residential energy consumption growth by finding negative effects of energy intensity on residential CO₂ emissions in both countries. Hence, it is recommended that an increasing share of renewable energy in the energy mix of a developing country is more likely to meet the growing future demand of energy while influencing economic growth. Investment of renewable energy resource is able to not only reduce environmental impact associated with fossil fuels but also contribute to regional economic development as they can be used for a densely settled population in urban without conventional energy sources, and could reduce costs associated with climate change[68].

(4) Population policy

Population policy for reduction of CO₂ emissions can be divided into direct policy and indirect policy. Direct policy is to directly regulate fertility rate and maintain size of population while indirect policy means planning and management of per capita CO₂ emission. For instance, reducing the CO₂ emission through urban planning and city management is one of the typical approaches of an indirect policy. In terms of direct policy, China implemented one child policy for last two decade as a part of family planning policy. In the perspective of CO₂ emissions, unfortunately there was no clear evidence so far that supports one child policy led to reduced energy consumption and CO₂ emissions. Rather than direct population policy such as controlling fertility rate by governmental regulation, more attention should be given to indirect policy. Increasing awareness of the urbanization will have to include the impact of cities on the environment and their contribution to global environmental solutions [72].

Additionally, the household income level, and urbanization indicate that the residential sectors of both countries must receive great attention when planning CO₂ emission mitigation effort at the national level. Government officials of both countries need to note that urban China and India are now experiencing significant increases in per capita urban incomes through rapid urbanization and development, offering vibrant new consumer markets for businesses to serve [73]. In fact, private consumption plays

a large role in India and China's economy, accounting for 60 % and 36% of GDP in 2005 respectively [74]. In this regard, policy should pay more attention to educating citizens about purchasing environmental friendly products, consuming less energy in daily life which will ultimately mitigate CO₂ emissions in both countries.

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