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Exploring the driving factors and their mitigation potential in global energy-related CO_2 emission

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Abstract: In order to quantify the contribution of the mitigation strategies, an extended Kaya identity has been proposed in this paper for decomposing the various factors that influence the CO_2 emission. To this end, we provided a detailed decomposition of the carbon intensity and energy intensity, which enables the quantification of clean energy development and electrification. The logarithmic mean divisia index (LMDI) has been applied to the historical data to quantify the contributions of the various factors affecting the CO_2 emissions. Further, the global energy interconnection (GEI) scenario has been introduced for providing a systematic solution to meet the 2°C goal of the Paris Agreement. By combining LMDI with the scenario analysis, the mitigation potential of the various factors for CO_2 emission has been analyzed. Results from the historical data indicate that economic development and population growth contribute the most to the increase in CO_2 emissions, whereas improvement in the power generation efficiency predominantly helps in emission reduction. A numerical analysis, performed for obtaining the projected future carbon emissions, suggests that clean energy development and electrification are the top two factors that can decrease CO_2 emissions, thus showing their great potential for mitigation in the future. Moreover, the carbon capture and storage technology serves as an important supplementary mitigation method.

Keywords: CO_2 emission, Kaya identity, Clean energy development, Electrification, Global Energy Interconnection, Mitigation potential.

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1 Introduction

Energy-related emissions are the main contributors to the total greenhouse gas (GHG) emissions, with a proportion of 74% in the year 2015 [1]. From 1990 to 2015, energy-related GHG emissions have increased by over 40% to 12.6 Gt CO_2 equivalent, whereas the total GHG emissions from industrial processes, agriculture, and other fields have risen by only 2.7 Gt CO_2 equivalent. The energy sector dominates carbon emissions as well as climate change. Because energy consumption continues to rise with the population growth and economic development, effective control measures for energy-related carbon emissions is of great significance to realize the Paris Agreement goals [2]. To this end, it is essential to analyze the driving factors of carbon emissions in the energy sector and their mitigation potential, in order to formulate emission reduction pathways and strategies.

Research on the factors influencing the emissions and their mitigation potential mainly depends on using historical data, such as population, economy, carbon intensity, and energy intensity according to the Kaya identity or stochastic regression models [3–4], for analysis. Studies where projected data has been used for analysis in a specific energy end-use sector have also been conducted [5]. Their results show that population and economic development are the main driving factors of energy consumption and carbon emission growth, whereas the influence of the energy intensity and carbon intensity is not obvious [6]. This is because fossil fuels still dominate the present day energy consumption, whereas clean energy occupies a lower share. Globally, the proportion of clean energy in the total primary energy consumption was only 19% in 2017. As the share of renewable and clean electricity increases in the future, the emission reduction potential of the carbon intensity and energy intensity is expected to increase, and is thus worthy of a qualitative investigation. With the aim of reducing carbon emissions, the global energy interconnection (GEI) scenario [7] has been proposed as a systematic solution for realizing mitigation in the energy sector and the Paris Agreement goals. In this scenario, a predominantly clean energy and electricity-centric energy system has been established by constructing large-scale renewable sources for power supply and grid interconnections for power allocation. Therefore, the emissions from the energy sector are significantly reduced by promoting "clean replacement," i.e., replacing the fossil fuel energy by renewables in the primary energy, and "electricity replacement," i.e., replacing fossil fuels by electricity in the end-use sectors. Furthermore, many studies have been conducted with a consensus that emissions can be significantly reduced by promoting renewables and electricity [8–9]. In particular, Jiang et al. conducted a scenario analysis for China to accomplish rapid transition in the power generation sector [10]. However, there is a lack of quantitative analysis that can reveal the relationship between renewables, electrification, and carbon emissions.

In order to overcome the existing deficiencies, a novel approach has been proposed in this work for analyzing the energy-related carbon emission reduction potential and the contribution from different driving factors. Firstly, factors, such as gross domestic product (GDP), population, electrification, proportion of renewables, etc., influencing the energy-related carbon emissions have been determined using the Kaya identity. Secondly, the GEI energy scenario, which is based on promoting large-scale renewable bases and development of grid interconnections, has been presented by considering the emission path and technology portfolios. Thirdly, by using the GEI scenario for the case of highly developed renewables and electricity that can meet the goals of the Paris Agreement, the emission reduction potential and contribution from each component have been analyzed depending on the historical as well as optimized projection data. Hence, the emission reduction contribution from components, such as electrification and proportion of renewables, has been quantitatively analyzed, and their mitigation potential in the energy sector has been determined. The results obtained from the above-mentioned analysis indicate that the development of renewables and electricity are the dominant factors that can reduce CO_2 emissions. This creates a significant mitigation potential in the energy sector.

The remainder of the paper has been organized as follows: Section 2 presents the decomposition method for analyzing the influence of the different factors on CO_2 emissions and describes the data used. The results of the decomposition obtained by using the historical data have been discussed in detail in Section 3. The GEI 2°C energy scenario, based on which the mitigation potential of the different driving factors is analyzed, has been presented in Section 4. Section 5 concludes the study and presents a few points on policy implications.

2 Methodology and data

2.1 Decomposition method based on the Kaya identity

The Kaya identity was originally put forward by Yoichi Kaya in 1989 [11]. It combines carbon emissions with energy, population, and economic scale in order to quantify the relative contributions of the key factors, namely human population and life, in CO_2 emissions. The method of Kaya identity has many advantages, such as its simple structure and residual-free and easy-to-understand analysis. Its specific formula is given as follows:

$$C = \frac{C}{E} \cdot \frac{E}{GDP} \cdot \frac{GDP}{P} \cdot P \tag{1}$$

In (1), C, E, GDP, and P refer to the total energy-related carbon emission, total primary energy consumption, gross domestic product, and total population, respectively. Here, C/E and E/GDP indicate the carbon intensity and energy intensity, respectively. *GDP/P* refers to the *GDP* per capita and represents the effect of economic development.

In this study, we have used the revised form of the Kaya identity in order to expand the method for decomposing and analyzing the energy-related CO_2 emissions. For each year, the global energy-related CO_2 emission can be divided as follows:

$$C = (1-\varepsilon)\cdot\frac{C_0}{E_f}\cdot\frac{E_f}{E}\cdot\frac{E}{PG}\cdot\frac{PG}{F_e}\cdot\frac{F_e}{GDP}\cdot\frac{GDP}{P}\cdot P \tag{2}$$

In (2), C_0 denotes the global energy-related CO_2 emission resulting from combustion of fossil fuels. ε is the share of carbon capture and storage (CCS) in the energy sector, including power generation and bio-fuel production. E_f and E represent the fossil fuel consumption and the total primary energy consumption, respectively. *PG* refers to the energy consumption from the power sector, and F_e denotes the total electricity production. For simplicity, (2) can be written as follows:

$$C = (1-\varepsilon)\cdot s\cdot\alpha\cdot\beta\cdot\eta\cdot\omega\cdot\lambda\cdot P \tag{3}$$

In (3), $s = C_0/E_f$ denotes the equivalent emission factor of the fossil fuels, which is used for representing the impact of the fossil energy structure on the CO_2 emissions. In this study, it is assumed that the CO_2 emission factors corresponding to each fossil fuel (i.e., coal, oil, and gas) are time-invariant. $\alpha = E_f/E$ is the share of fossil fuel consumption in the total primary energy consumption and indicates the effect of clean energy development on CO_2 emissions. $\beta = E/PG$ is the ratio of the energy consumption in the power generation sector to the total primary energy consumption and exhibits the effect of electrification on CO_2 emissions. $\eta = PG/F_e$ is the ratio of the energy input to the electricity output in the power sector and reflects the impact of the power generation efficiency on CO_2 emissions. $\omega = F_e/GDP$ represents the electricity intensity and indicates the influence of the improvements in the energy efficiency and economic system on CO_2 emissions.

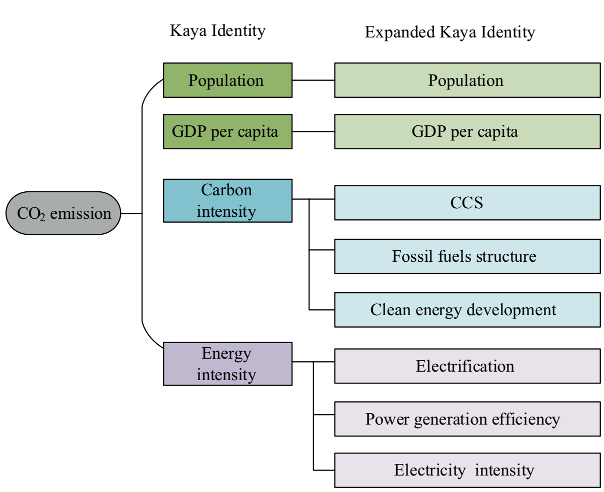

Fig. 1 Schematic of the proposed decomposition method based on the Kaya identity

Fig. 1 shows a schematic of the proposed decomposition method. Compared to the Kaya identity method (represented by (1)), the proposed method provides a more detailed decomposition of the carbon intensity and energy intensity. Accordingly, the factors that affect the carbon emission, by influencing the carbon and energy intensities, can be explicitly reflected in its equation. In turn, it would help to quantify the contribution of the factors, such as clean replacement and electricity replacement in carbon emission reduction.

2.2 Method of calculation

Based on the logarithmic mean divisia index (LMDI) method [12], the change, ΔC, in the CO_2 emissions, from the year t_2 to year t_1, can be calculated using (4). Each individual variable in (4) can be computed using (5) – (13).

$$\Delta C = C^{t_2} - C^{t_1} = \Delta C_{1-\varepsilon} + \Delta C_s + \Delta C_\alpha + \Delta C_\beta + \Delta C_\eta + \Delta C_\omega + \Delta C_\lambda + \Delta C_P \tag{4}$$

where

$$\Delta C_{1-\varepsilon} = L(C^{t_2}, C^{t_1})\ln\frac{1-\varepsilon^{t_2}}{1-\varepsilon^{t_1}} \tag{5}$$

$$\Delta C_s = L(C^{t_2}, C^{t_1})\ln\frac{s^{t_2}}{s^{t_1}} \tag{6}$$

$$\Delta C_\alpha = L(C^{t_2}, C^{t_1})\ln\frac{\alpha^{t_2}}{\alpha^{t_1}} \tag{7}$$

$$\Delta C_\beta = L(C^{t_2}, C^{t_1})\ln\frac{\beta^{t_2}}{\beta^{t_1}} \tag{8}$$

$$\Delta C_\eta = L(C^{t_2}, C^{t_1})\ln\frac{\eta^{t_2}}{\eta^{t_1}} \tag{9}$$

$$\Delta C_\omega = L(C^{t_2}, C^{t_1})\ln\frac{\omega^{t_2}}{\omega^{t_1}} \tag{10}$$

$$\Delta C_\lambda = L(C^{t_2}, C^{t_1})\ln\frac{\lambda^{t_2}}{\lambda^{t_1}} \tag{11}$$

$$\Delta C_P = L(C^{t_2}, C^{t_1})\ln\frac{P^{t_2}}{P^{t_1}} \tag{12}$$

$$L(C^{t_2}, C^{t_1}) = \begin{cases}\left(C^{t_2} - C^{t_1}\right)/\left(\ln C^{t_2} - \ln C^{t_1}\right) & if\ C^{t_2} \neq C^{t_1}\\ C^{t_1} & otherwise\end{cases} \tag{13}$$

In (4), ΔC is decomposed into eight individual factors that affect the CO_2 emission. $\Delta C_{1\text{-}\varepsilon}$ denotes the effect due to changes in CCS. ΔC_s refers to the effect due to changes in the fossil fuel structure. ΔC_α and ΔC_β indicate the effect due to changes in the clean energy development and the electrification, respectively. ΔC_η represents the effect due to changes in the power generation efficiency. ΔC_{ω} is the effect due to changes in the electricity intensity, and ΔC_{λ} and ΔC_P indicate the effect due to changes in the economic growth and population, respectively.

2.3 Data sources

In this work, we have explored the different driving factors and their mitigation potential in the global energy-related CO_2 emissions by analyzing the historical data as well as the projected data. The historical data corresponds to the period from the year 2000 to 2017. Historical energy-related CO_2 emissions [13], total primary energy consumption, fossil fuel consumption, energy consumption by the power sector, and the total electricity production data have been collected from the International Energy Agency (IEA) database [14]. Historical population data have been obtained from the United Nations database [15], and the GDP data have been acquired from the IMF database [16]. The projection data ranging from 2017 to 2050 was optimized using the MESSAGE integrated assessment model. The projected data are discussed in detail in Section 4.1.

3 Decomposition analysis of the historical CO_2 emission

Fig. 2 illustrates the contributions of the different factors that have influenced the CO_2 emissions from the year 2000 to 2017. During this period, the total CO_2 emission increased by 9,600 Mt. From the figure, it can be seen that economic development, population, and fossil fuel structure contributed to the increase in CO_2 emission, whereas clean energy development, electrification, improvement in the power generation efficiency, and electricity intensity contributed toward reducing the CO_2 emission in the same duration. Because CCS was immature and had not been utilized on a large scale during this study period, its contribution to CO_2 emission reduction was zero and has not been plotted in Fig. 2. Table 1 lists the contribution of each driving factor to the total change in CO_2 emission.

Table 1 Contribution of the different driving factors to the CO_2 emission from the year 2000 to 2017

Driving factor	Contribution (Mt CO_2)	Percentage
Economic development	11,172	116%
Population	5,729	60%
Fossil fuel structure	1,952	20%
Power generation efficiency	–5,920	–62%
Electricity intensity	–2,219	–23%
Clean energy development	–652	–7%
Electrification	–462	–5%
CCS	0	0%
Total	9,600	100%

From Fig. 2 and Table 1, it can be clearly seen that economic development contributed the most to the long-term growth of CO_2 emission, accounting for 116% of the total change. From 2000 to 2017, the world economy maintained a growing trend, especially in Asia, which constitutes emerging economies such as China and India. The World Bank statistics indicate that the global GDP increased from 61.8 trillion USD to 113.6 trillion USD, showing an annual average growth rate of 3.6%. During the same period, Asia's average GDP growth rate was approximately 5.7%, which was significantly higher than that of the rest of the world. Globally, GDP per capita increased by approximately 50% from 10.1 thousand USD to 15.1 thousand USD. Population was the second largest factor contributing to CO_2 emission from 2000 to 2017, accounting for 60% of the total change. Global population increased from 6.11 billion in 2000 to 7.52 billion in 2017, with an annual average growth of 1.2%. Compared to the economic development and population, the fossil fuel structure had a limited influence on the increase

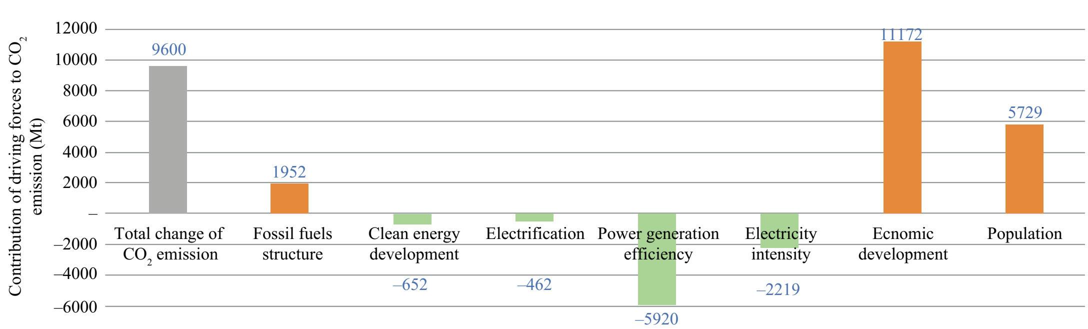

Fig. 2 Contributions of the different driving factors to CO_2 emissions from the year 2000 to 2017

in CO_2 emission and accounted for 20%. The main reason for this positive contribution was the significant increase in coal consumption as a fossil fuel energy. As shown in Fig. 3, the share of coal consumption increased from 28% in 2000 to 32% in 2017. Although the share of oil consumption decreased during the same period, it did not offset the increase in CO_2 emissions from coal because the emission factor of coal was 20% higher than that of oil.

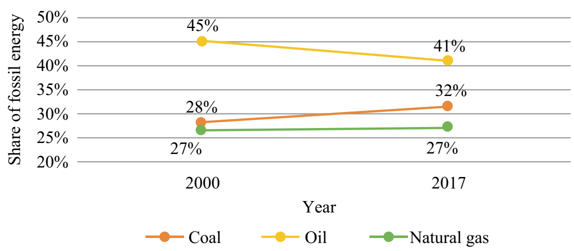

Fig. 3 Energy consumption corresponding to the use of three different fossil fuels in the years 2000 and 2017

Improvement in the efficiency of power generation contributed the most in reducing the CO_2 emission, with a decrease of 5,920 Mt (Fig. 2), thus accounting for 62% (in absolute value). Cleaner power generation structure and efficient power generation technologies could boost these emission reductions. The share of natural gas consumption among the fossil fuels by the power sector increased from 27.6% in 2000 to 32.7% in 2017. According to the IEA statistics, the generation efficiency of natural gas is 45%, much higher than that of coal (38%). Furthermore, increasingly efficient power generation technologies, such as supercritical (SC), ultra-supercritical (USC), and integrated gasification combined cycle, are being applied in thermal power plants. The global installed capacity of coal power in 2017 was 2,088 GW, in which the installed capacity of SC and USC accounted for 19% and 13%, respectively, which corresponded to an increase of 3 percentage points and 8 percentage points, respectively as compared to that in 2010 [17]. Such efficient technologies could significantly improve the energy conversion efficiency of thermal power generation by employing boiler transformation or recycling, and thus reduce the energy consumption of power generation.

As compared to the improvement in the power generation efficiency, electricity intensity had less effect on CO_2 emission reduction and accounted for 23% of the total change (in absolute value). From 2000 to 2017, electricity intensity decreased from 25 tce/million USD to 23 tce/million USD, a decline of 8%. The main reason for this decrease was the advancement of the global economy toward a higher value-added direction and the extensive application of energy-saving technologies. Due to the slow and uneven development of clean energy and electrification, these factors exhibited a limited effect on reducing the CO_2 emission and had a contribution share of 7% and 5%, respectively (in absolute value). As shown in Fig. 4, the share of clean energy in the total primary energy consumption has increased slightly from 20.4% in 2000 to 22.2% in 2017. Globally, the proportion of energy consumption by the power sector to the total energy consumption was 36.8% in 2017, which was only a 0.6 percentage point increment from 2010. Furthermore, the World Bank statistics have pointed out that there are still approximately 1 billion people without access to electricity worldwide. With the development of promising clean energy and electrification, both factors will have a great potential for emission mitigation.

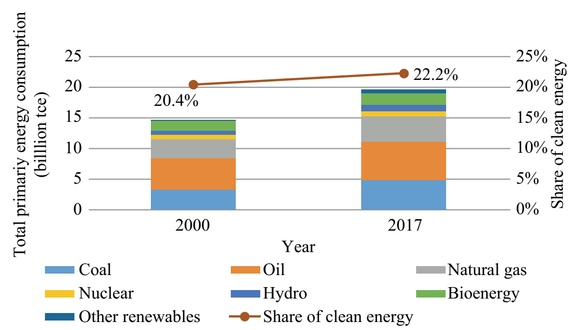

Fig. 4 Total primary energy consumption and the share of clean energy in 2000 and 2017

4 Analysis of mitigation potential in the future

4.1 GEI and GEI 2°C scenario

Accelerating the "two replacements" and promoting a green, low-carbon energy transition are reforming the entire energy system, and this will comprehensively promote the release of mitigation potential. It is worthy to note that energy interconnection is both the premise of and the foundation for this promotion. In fact, GEI provides a primary platform for the large-scale exploitation, transmission, and use of clean energy worldwide in terms of the dominance of clean energy, electricity centrality, and interconnection. In addition, it will provide an innovative solution for implementing the Paris Agreement [18].

The shared socioeconomic pathways (in particular, the middle of the road scenario SSP2) [19] have been taken as the boundary conditions for economic and social development. The world's population is estimated to grow and peak in 2070 at 9.5 billion, following which it is expected to decline. The world's economy will keep growing from 2020 to 2100. In 2100, the world's GDP is projected to reach almost 600 trillion USD. The GEI 2°C scenario has been optimized by the MESSAGE model [20–21] based on the full-century carbon budget as the overall constraints and the assumptions regarding the evolution of energy technologies and socioeconomic development. With the idea of GEI, the GEI 2°C scenario is characterized by a high electrification rate, high proportion of clean energy, large-scale development of clean energy, and a reliable system operation for providing a systematic solution to meet the 2°C goal of the Paris Agreement. Additional details of the GEI 2°C scenario can be seen in [22].

Fig. 5 illustrates the structure of the total primary energy consumption. The total global primary fossil fuel energy consumption is expected to reach its peak around 2025, following which it will decline with each year. With the accelerated implementation of clean replacement, the scale of development and utilization of clean energy will expand continuously. From 2017 to 2050, global clean energy production will increase from 4.37 billion tce to 17.68 billion tce, with an average annual increase of 4.33%.

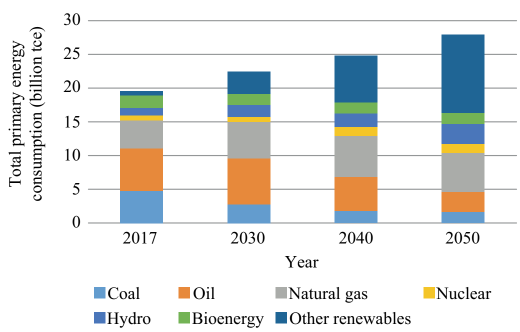

Fig. 5 Total primary energy consumption in the GEI 2°C scenario

As shown in Fig. 6, the global final energy consumption will grow steadily from 13.9 billion tce in 2017 to 15.4 billion tce in 2050 with an average annual growth rate of approximately 0.3%. With the accelerated development of electricity replacement technologies, such as electric

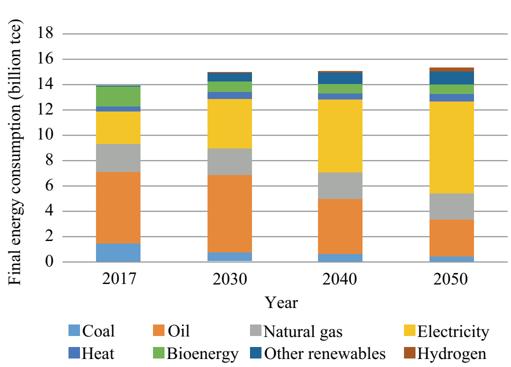

Fig. 6 Total final energy consumption in the GEI 2°C scenario

vehicles, electric heating, and electricity-produced hydrogen, the total global electricity consumption is growing with each year. By 2050, the proportion of electricity in the total final energy consumption will increase to approximately 50%.

Fig. 7 shows the CO_2 emission from the energy sector in the GEI 2°C scenario. The world's CO_2 emission will peak in 2025 with the highest emission of 32 Gt per year. Subsequently, this emission will decrease sharply from 2025 to 2070 and reach zero emission around 2065. After 2065, with the availability of the negative emission technology, the world will realize negative emission.

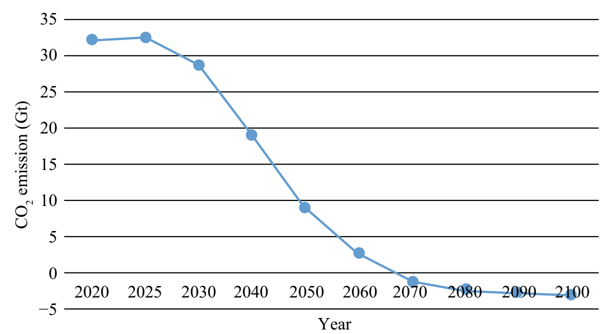

Fig. 7 CO_2 emission from the energy sector in the GEI 2°C scenario

4.2 Decomposition analysis of CO_2 emission from 2017 to 2050

Based on the CO_2 emission from the energy sector, decomposition analysis has been carried out in this study. Fig. 8 illustrates the contribution of the various driving factors to the CO_2 emission during the following three stages: Stage I (2017–2030), Stage II (2030–2040), and Stage III (2040–2050). The results indicate that from 2017 to 2050, the total change in the CO_2 emission will decrease by 23,407 Mt.

Table 2 lists the percentage of contributions of the different driving factors to the total change in the CO_2 emission in the three stages.

Results of the decomposition analysis indicate that during the three stages, economic development and population will be the main contributors to the increase in the CO_2 emission. This observation is similar to the decomposition results of the historical data from 2000 to 2017. Furthermore, electricity intensity will also play an important role in future emission increment. On the other hand, the mitigation factors will be different for the three stages. In Stage I, clean energy development, electrification, and fossil fuel structure will contribute the most to the reduction of CO_2 emission. Improvement in the power generation efficiency will also help in reducing

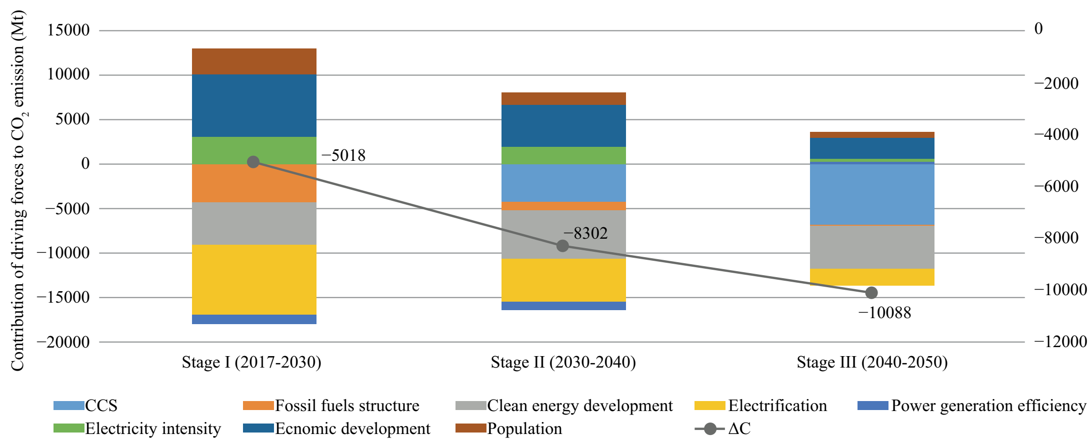

Fig. 8 Performance of the different driving factors during the three stages from 2017 to 2050

Table 2 Percentage of contribution of the different driving factors to the CO_2 emission

Driving factors	Percentage of contribution		
	Stage I	Stage II	Stage III
Economic development	157%	56%	24%
Population	43%	17%	6%
Electricity intensity	58%	24%	4%
Fossil fuel structure	–86%	–12%	–1%
Power generation efficiency	–21%	–11%	2%
Clean energy development	–96%	–65%	–48%
Electrification	–155%	–59%	–19%
CCS	0%	–50%	–68%
Total	100%	100%	100%

the emissions. In Stage II, in addition to the above-mentioned four mitigation factors, utilization of the CCS technology, whose contribution is slightly lower than that of electrification, will help in significantly promoting the reduction of CO_2 emission. In Stage III, the mitigation effect of CCS will become more prominent, exceeding the clean energy development and electrification. Fossil fuel structure will have a very limited effect on emission reduction in this stage.

(1) Stage I (2017–2030)

Economic development is the main contributor to the growth of CO_2 emission, which accounts for 157% of the total change in this stage. From 2017 to 2030, the global GDP will keep increasing at an annual rate of 2.6%. The second most influential factor is the electricity intensity, which accounts for 58% of the total change. In Stage I, electricity intensity will increase from 23 tce/million USD to 25 tce/million. This indicates that rapid electrification will lead to a huge increase in electricity consumption, which will be faster than the GDP growth. The contribution of population to the increase in CO_2 emission is expected to be slightly lower than that of the electricity intensity, which is 43%. It is estimated that the world's population will peak around 2070. Therefore, in this stage, the world's population will still be climbing.

Among all the mitigation factors, electrification will contribute the most to the reduction in CO_2 emission, accounting for 155% of the total change (in absolute value). This is primarily due to the rapid growth in the power demand brought about by industrialization, urbanization, and the development of electricity replacement technology, such as railways, electric vehicles, and clean heating. The proportion of energy consumption by the power sector is expected to increase to 47.6% in 2030, about 11 percentage points higher than that in 2017. Clean energy development will be the second largest factor influencing CO_2 emission reduction, accounting for 96% of the total change (in absolute value). The share of clean energy in the total primary energy consumption will increase from 22.2% in 2017 to 33.8% in 2030 (about 0.9 percentage points per year). Fossil fuel structure will also have a significant influence on mitigation due to the cleaner energy structure. It is expected to contribute to a reduction in the CO_2 emission by approximately 4,300 Mt in 2030 as compared to that in 2017.

(2) Stage II (2030–2040)

Economic development, population, and electricity intensity will remain the main contributors to the increase in CO_2 emission, accounting for 56%, 17%, and 24%, respectively. The results of the decomposition analysis indicate that the positive effect of these three factors on

CO_2 emission increment will be smaller than that in Stage I. Slow economic and population growth could result in the decrease of the positive contributions to CO_2 emission. Globally, the GDP per capita will increase by 30% in 2030 as compared to the corresponding value in 2017, whereas it will only increase by 22% from 2030 to 2040. The average annual growth of the world population will gradually decrease from 0.8% in Stage I to 0.6% in Stage II.

From 2030 to 2040, clean energy development and electrification will still play a dominant role in reducing CO_2 emissions. With the increased implementation of clean replacement, the increase in clean energy demand after 2030 will be quite significant. The share of clean energy consumption will increase from 33.8% in 2030 to 47.6% in 2040 (about 1.3 percentage points per year), faster than that in Stage I, leading to a total decrease of 5,432 Mt of CO_2. During this period, CCS, whose contribution is predicted to be slightly lower than that of electrification, will promote the emission reduction significantly. The main reason for this will be the rapid increase in the implementation of CCS in the process of fossil fuel combustion. In 2030, the proportion of CCS in the power sector and in the liquid fuel production process is expected to be 6% and 2% and will further increase to 20% and 7%, respectively. From 2030 to 2040, the accumulated effect of CCS will lead to a decrease of 4,129 Mt of CO_2.

(3) Stage III (2040–2050)

Economic development, population, and electricity intensity will be the top three factors that will contribute in increasing CO_2 emissions, and their contributions are expected to be smaller than those in Stages I and II. Similar to the previously described analysis, the reason for this prediction is the relatively slower economic and population growth. Globally, the GDP per capita will increase by 19% in 2050 compared to its value in 2040, slower than that during Stages I and II. The average annual growth of the world's population will continue to decrease, from 0.6% in Stage II to 0.4% in Stage III.

From 2040 to 2050, clean energy development and electrification will continue to play an important role in reducing CO_2 emissions, accounting for 48% and 19%, respectively (in absolute value). Furthermore, the mitigation effect of CCS will become more prominent, exceeding the two factors mentioned before. During this period, the accumulated effect of CCS will be a decrease of 6,860 Mt of CO_2, which accounts for 68% of the total change (in absolute value). Due to the decline in the carbon capture costs, CCS will be widely used in the power generation sector, liquid fuel production, and hydrogen production. By 2050, the contribution of CCS in the power sector will reach more than 60%, where the contribution of coal and natural gas power generation will reach 100% and 60%, respectively. By 2050, the contribution of CCS in the liquid fuel production process will exceed by 90%.

5 Conclusions and policy implication

Inspired by the Kaya identity technique, this study provides a detailed decomposition of both carbon intensity and energy intensity, based on which a new method for decomposing and analyzing energy-related CO_2 emissions has been proposed. The LMDI method has been applied for analyzing the factors such as the CCS, fossil fuel structure, clean energy development, electrification, power generation efficiency, electricity intensity, economic development, and population, which drive the changes in the CO_2 emissions.

The decomposition analysis of CO_2 emission from 2000 to 2017 indicates that economic development and population contribute the most in the growth of CO_2 emission, whereas power generation efficiency and electricity intensity contribute in reducing CO_2 emission. In contrast, clean energy development and electrification show a very limited effect on reducing CO_2 emission. With the development of promising clean energy sources and electrification, both will have great potential for emission mitigation.

The decomposition analysis of CO_2 emission from 2017 to 2050 indicates that economic development and population will remain the main contributors to the increase in CO_2 emission. Furthermore, electricity intensity will also play an important role in future emission increment. Among the main mitigation factors, clean energy development and electrification will contribute the most to reducing the CO_2 emission, exhibiting promising mitigation potential. From 2017 to 2050, their accumulated effect will be a decrease of 29,642 Mt of CO_2, showing their great mitigation potential for CO_2 emission. In addition, utilization of the CCS technology will become increasingly prominent in reducing CO_2 emission. Following clean energy development and electrification, their accumulated effect will lead to a decrease of 10,989 Mt of CO_2.

For future mitigation policies, firstly, a national long-term mitigation plan, such as a timetable for zero carbon emission, needs to be developed. Considering that each country differs in their development phase, technology advancement, and resource endowment, the timetable could be different. However, the ambitious zero carbon emission timetable will provide a clear goal for each country to make efforts toward reducing their CO_2 emission. Secondly, in the case of regions where electricity is generated mainly from fossil fuels, an increase in the share of renewable power generation, such as hydropower, wind power, solar power, etc., can be an effective way to reduce emissions. Although there are abundant clean energy resources in the world, they are unevenly distributed and far from load centers. Therefore, the construction of a GEI is essential for reducing the CO_2 emission globally, and the GEI can provide an optimal allocation of clean energy through this plan. Furthermore, the support policies for renewables, such as fiscal subsidies, guarantee to grid priority, clean energy credits in the carbon market, would help solve financial problems in the early times of low-carbon development. Thirdly, in the case of international cooperation on climate change, governments will be required to work together and share the most advanced technology to reduce the cost of renewables, since many renewable technologies are still unavailable in some undeveloped countries even if they are rich in renewable resources.

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Declaration of Competing Interest

We declare that we have no conflict of interest.

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