Identifying the Driving Factors of Carbon Emission Changes in Malaysia's Electricity Sector

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***Abstract*—The electricity sector plays a crucial role in Malaysia's economic development, while also serving as a major contributor to national carbon emissions. Using the Logarithmic Mean Divisia Index (LMDI), we analyze the factors influencing carbon emissions changes within Malaysia's electricity sector from 2001 to 2019. Our analysis reveals that the fuel structure effect emerged as the primary driver of emission increases, accounting for 30.5%, whereas improvements in coal consumption efficiency and generation structure contributed only 3.5% and 7.8% to emissions, respectively. Transmission and distribution losses, combined with socioeconomic factors such as Gross Domestic Product (GDP) per capita and population growth, further contributed to increases in emissions. Despite advancements in energy efficiency and the deployment of renewable energy, these measures have not sufficiently offset the sector's dependence on carbon-intensive energy sources. These findings highlight the urgent need for targeted policy interventions, including the accelerated integration of renewable energy, modernization of power grid infrastructure, and the promotion of innovation in low-carbon technologies. Such actions are imperative to align Malaysia's transition toward a low-carbon economy with the dual imperatives of economic growth and environmental sustainability.**

***Keywords*—driving factors, carbon emission, electricity sector, LMDI**

I. Introduction

The impacts of global climate change are becoming more visible, and the control of CO_2 emissions is increasingly recognized as a shared global consensus [1]. Countries must first identify the driving forces behind domestic CO_2 emissions growth, but these driving factors are largely determined by the country's stage of development. Different stages of economic development and varying energy systems result in distinct CO_2 emissions drivers [2]. Hence, scientific analysis of national CO_2 emission drivers is critical for domestic policy formulation and the design of effective international cooperation strategies for emission reduction.

Malaysia's electricity sector is a major component of its economy and one of the greatest challenges in achieving carbon neutrality [3]. Between 2002 and 2019, the total power generation in Malaysia doubled from 74.2 TWh to 175.2 TWh, and CO_2 emissions from electricity generation increased significantly from 44.9 Mt to 108.9 Mt (see Section IV). Electricity production in Malaysia is heavily reliant on fossil fuels, especially coal and natural gas [4], which has led to rising power-related carbon emissions with economic growth. This trend poses a serious threat to environmental integrity and sustainability.

The National Energy Policy 2022–2040 and the Climate Change Action Plan have been adopted by the government of Malaysia to support low-carbon development. They aim to encourage the transition of the electricity sector to renewable energy, improve energy efficiency, and achieve net zero emissions by 2050. Establishing emission targets is only the first step. Effective emission reduction policies require a comprehensive understanding of the mechanisms driving carbon emissions in the electricity sector, identifying the major factors driving emission fluctuations, and a quantitative assessment of evaluating each factor contributing to increases or decreases in emissions [5].

II. Literature Review

Accurately identifying the core driving factors of carbon emissions in the power sector is a fundamental prerequisite for formulating effective mitigation policies and promoting a low-carbon transition. To identify the drivers of carbon emissions in the power sector, we need to study how changes in electricity production influence emission levels. Most studies show that the power sector output growth is mainly driven by economic expansion, energy intensity, fuel mix, and population growth [6, 7].

Economic growth is a key driver of energy consumption and carbon emissions. Carbon emissions typically rise during the early stages of economic growth, but decline as economies mature and adopt cleaner technologies [8]. However, in developing economies like Malaysia, energy systems still rely heavily on fossil fuels, which constrains efforts to decouple economic growth from carbon emissions [9]. According to data from the Malaysian Energy Commission, Malaysia's gross domestic product grew at an average annual rate of 4% from 2002 to 2019, accompanied by a doubling of electricity production.

Energy intensity is an important indicator of energy efficiency and is directly correlated to carbon emissions. Numerous Studies have demonstrated a strong positive correlation between energy intensity and carbon emissions. Elevated energy intensity levels are associated with increased carbon emissions [10]. Improvements in energy efficiency can reduce carbon emissions by lowering energy consumption while maintaining the same level of energy services. In countries at varying income levels, Qiang *et al.* found a negative relationship between income level and carbon emissions [11].

Population growth and rapid urbanization are known to increase carbon emissions in the power sector [12]. These factors have led to increased electricity demand across households, public infrastructure, and industries, thereby resulting in higher energy consumption. Electricity consumption is the primary form of secondary energy and is positively correlated with population size [13]. Growth in

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electricity consumption directly drives increased power generation, which in turn contributes to higher greenhouse gas emissions [14]. Population growth also triggers lifestyle changes, such as increased use of energy-intensive devices like air conditioners, electric vehicles, and appliances that improve living standards and carbon emissions [15].

Recent research has focused on Malaysia's carbon emissions. The increase in CO_2 emissions is closely related to economic growth [16], while improvements in energy efficiency in the manufacturing and power sectors have been identified as key mitigation strategies [17]. Ali *et al.* (2022) found that urban areas in Malaysia exhibit a higher household carbon footprint than rural areas, suggesting that urbanization and urban expansion significantly influence household energy consumption behavior [18]. Khazaei and Tareq (2021) found that emissions from Malaysia's transportation sector are primarily attributed to road transport, particularly the use of private cars and commercial vehicles [19].

Carbon emissions in Malaysia's electricity sector have been insufficiently explored from a systems perspective, including energy, economic, and social dimensions. Until recently, it was challenging to assess the key factors influencing carbon emissions in this sector due to data limitations and methodological constraints. This study analyzes carbon emissions in Malaysia's electricity sector from 2002 to 2019, with a focus on electricity generation, transmission, distribution, and end-use consumption. We further conduct a quantitative analysis of the drivers of carbon emissions.

III. Methodology and Data Sources

A. Calculation of Carbon Emissions in the Electricity Sector

The majority of carbon emissions in Malaysia's electricity sector originate from thermal power plants fueled by coal, oil, and natural gas, whereas hydropower and other renewable energy sources make a minimal contribution. Thermal power generation dominates Malaysia's electricity production, comprising around 90% of the total output [20]. Accordingly, this research specifically focuses on assessing carbon emissions from thermal power facilities. The estimation follows the guidelines of the Intergovernmental Panel on Climate Change (IPCC) guidelines and is calculated using Eq. (1) [21, 22].

$$C = \sum_i M_i \times EF_i = \sum_i M_i \times SC_i \times O_i \times k \quad (1)$$

In this equation, C refers to the total CO_2 Emissions in the Electricity Sector, where $i = 1, 2, 3, 4$ represent coal, natural gas, oil, and diesel, respectively. M_i represents the standardized quantity of the i-th fossil fuel utilized. EF_i represents the emission factor of the i-th fossil fuel. SC_i represents the carbon content per unit of calorific value of the i-th fossil fuel, while O_i denotes its oxidation rate. The constant k is defined as the ratio of the molecular weight of CO_2 to that of carbon. Table 1 presents the values of potential carbon content, oxidation rates, and CO_2 emission factors for each fuel type.

Table 1. Fuel parameters and emission factors

Type	Coal	Diesel Oil	Fuel Oil	Gas
Average lower heating value (kJ/kg or kJ/m^3)	20908	42652	41816	38931
Unit value of carbon content (tC/TJ)	26.4	20.2	21.1	15.3
Carbon oxidation rate (%)	93	98	98	99
Emission factor ($kgCO_2$/kg or $kgCO_2/m^3$)	1.8801	3.0959	3.1705	2.1622

B. LMDI Factor Decomposition Method

Factor decomposition methods are generally classified into Structural Decomposition Analysis (SDA) and Index Decomposition Analysis (IDA) [23]. Due to its methodological strengths—such as complete decomposition, elimination of residuals, and avoidance of division by zero—the LMDI method is employed in this study, which adopts the Logarithmic Mean Divisia Index (LMDI) approach to analyze the driving forces of carbon emissions in the electricity sector [24].

Following the frameworks established by the work of Xu *et al.* and Liu *et al.*, carbon emissions in the electricity sector are decomposed into several driving factors, with the definitions of the corresponding variables summarized in Table 2 [25, 26].

Table 2. Definition of variable

Variable	Definition
C	Total CO_2 emissions in the electricity Sector
C_i	CO_2 emissions of the i-th fossil fuel in the electricity sector
Q_i	The amount of the i-th fossil fuel consumed in the electricity sector
Q	The total amount of fossil fuel consumed in the electricity sector
FQ	The amount of electricity generated from fossil fuels
G	The total amount of electricity generation
L	The amount of transmission and distribution losses
N	The net electricity export amount
D	The total electricity consumption
D_j	The electricity consumption of the i-th sector
P	The total population
Y	The total output
Y_j	The output of the i-th sector
EF_i	$EF_i = C_i/Q_i$, the emission factor of the i-th fossil fuel.
EFS_i	$EFS_i = Q_i/Q$, the proportion of the i-th of fossil fuel consumption in the total fossil fuel consumption
CR	$CR = Q/FG$, the coal consumption rate in the electricity generation
ES	$ES = FG/G$, the proportion of electricity generation from fossil fuels in the total electricity generation
EI_j	$EI_j = D_j/Y_j$, the electricity consumption intensity in the j-th industrial sector.
S_j	$S_j = Y_j/Y$, the proportion of the output in the J-th industrial sector in the total output
AR	$AR = Y/P$, Per capita GDP
EIR	$EIR = D_5/Y$, residential electricity consumption intensity

$$C = \sum_i^4 C_i = \sum_i^4 \frac{C_i}{Q_i} \cdot \frac{Q_i}{Q} \cdot \frac{Q}{FQ} \cdot \frac{FQ}{G} \cdot G$$
$$= \sum_i^4 EF_i \cdot EFS_i \cdot CR \cdot ES \cdot G \quad (2)$$

Here, in Eq. (2), Q refers to the total amount of fossil fuel consumed in the electricity sector, electricity generation from fossil fuels (FQ) represents the amount of electricity generation from fossil fuels, and other parameters can be found in Table 2. Electricity flows from production to end-use consumption through a series of stages, including generation, transmission, and distribution. Accordingly, the relationship among electricity generation (G), transmission and distribution (L), net export (N), and consumption (D) can be formally established as follows, in Eq. (3):

$$G = L + N + D \tag{3}$$

End-use electricity consumption (D) comprises the industrial and residential sectors. The associated carbon emissions can be further decomposed as follows, in Eq. (4):

$$D = \sum_{j}^{5} D_j = \sum_{j}^{4} \frac{D_j}{Y_j} \cdot \frac{Y_j}{Y} \cdot \frac{Y}{P} \cdot P + \frac{D_5}{Y} \cdot \frac{Y}{P} \cdot P = \sum_{j}^{4} EI_j \cdot S_j \cdot AR \cdot P + EIR \cdot AR \cdot P \tag{4}$$

Here, Y and P represent the total output and population, and j = 1, 2, 3, 4, 5 represent the commercial, industry, transport, agriculture, and residential five sectors. The change in end-use electricity consumption demand during the period *[t, t+T]* can be decomposed using the additive decomposition method as follows.

$$\Delta D = \Delta D_{EI} + \Delta D_S + \Delta D_{AR} + \Delta D_P + \Delta D_{EIR} \tag{5}$$

Based on the derivation of Eq. (5), the final decomposition formula for carbon emissions in the electricity sector is obtained. ΔD_{EI}, ΔD_S, ΔD_{AR}, ΔD_P, and ΔD_{EIR} represent changes in electricity consumption driven by variations in industrial electricity intensity, industrial structure, per capita factors, total population, and residential electricity intensity, respectively.

$$\Delta C = \Delta C_{EF} + \Delta C_{EFS} + \Delta C_{CR} + \Delta C_{ES} + \Delta C_L + \Delta C_N + \Delta C_{EI} + \Delta C_S + \Delta C_{AR} + \Delta C_P + \Delta C_{EIR} \tag{6}$$

The expressions for the individual carbon emission effect factors are presented in Eq. (6). ΔC_{EF} represents the carbon emission coefficient effect, ΔC_{EFS}, ΔC_{ES}, and ΔC_{CR} represent the fuel structure effect, coal consumption rate effect, and electricity production structure effect, respectively. ΔC_L and ΔC_N represent transmission and distribution losses effect, ΔC_{EI}, ΔC_S, ΔC_{AR}, ΔC_P, and ΔC_{EIR} represent the industrial energy intensity effect, industrial structure effect, GDP per-capita effect, population effect, and residential electricity consumption intensity effect, respectively.

$$\Delta C_k = \sum_{i}^{4} \frac{C_{i,t+T} - C_{i,t}}{lnC_{i,t+T} - lnC_{i,t}} ln\,(k_{i,t+T}/k_{i,t}) \tag{7}$$

Here, in Eq. (7), k = 1, 2, 3, 4 represent the emission factor of the fuel (EF), the fuel structure (EFS), the coal consumption rate in electricity generation (CR), the electricity production structure (ES), and the electricity generation amount (G). In this study, t and T represent the starting time and the time interval of the analysis, respectively.

$$\Delta C_k = \Delta C_G \frac{k_{t+T} - k_t}{G_{t+T} - G_{t+T}} \tag{8}$$

Here, in Eq. (8), ΔC_G represents the electricity generation effect. k=6, 7 represent the transmission and distribution losses (L) and the net electricity export (N).

$$\Delta C_k = \Delta C_G \frac{\sum_{j=1}^{4}(D_{j,t+T} - D_{j,t})}{G_{t+T} - G_{t+T}} \cdot \sum_{j=1}^{4} \frac{D_{j,t+T} - D_{j,t}}{lnD_{i,t+T} - lnD_{i,t}} \ln\,(k_{i,t+T}/k_{i,t}) \tag{9}$$

Here, in Eq. (9), k=8, 9 represent the electricity consumption intensity of the industrial sector (EI) and the industrial structure (S).

$$\Delta C_k = \Delta C_G \frac{\sum_{j=1}^{5}(D_{j,t+T} - D_{j,t})}{G_{t+T} - G_{t+T}} \cdot \sum_{j=1}^{5} \frac{D_{j,t+T} - D_{j,t}}{lnD_{i,t+T} - lnD_{i,t}} \ln\,(k_{t+T}/k_t) \tag{10}$$

Here, in Eq. (10), k = 10, 11, represent per capita GDP (AR) and the total Population (P).

$$\Delta C_{EIR} = \Delta C_G \frac{D_{5,t+T} - D_{5,t}}{G_{t+T} - G_{t+T}} \cdot \frac{D_{5,t+T} - D_{5,t}}{lnD_{5,t+T} - lnD_{5,t}} \cdot \ln\,(EIR_{t+T}/EIR_t) \tag{11}$$

Here, in Eq. (11), ΔC_{EIR} represents the residential electricity consumption intensity effect.

C. Data Sources

The data utilized in this paper were sourced from several official statistics and authoritative sources pertaining to Malaysia's electricity sector. Electricity production and consumption data were obtained from the Malaysia Energy Statistics Handbook published by the Energy Commission. Energy balance tables and records for the period 2002–2019 were also collected from the same source. Carbon emissions coefficients were computed according to guidelines published by the Intergovernmental Panel on Climate Change (IPCC). To ensure computational accuracy, fossil fuel consumption data were compared with the Compendium of Environment Statistics published by Statistics Malaysia, while socioeconomic indicators such as GDP, GDP per capita, and population growth were sourced from the World Bank and Statistics Malaysia. The combination of these multidimensional data provided a consistent basis for decomposition analysis.

IV. Results and Discussion

A. Carbon Emissions in the Electricity Sector

To ensure the consistency between sectoral electricity consumption and output statistics, the analysis period is restricted to 2001–2019. Fuel-specific energy consumption data for electricity production were sourced from Energy Balance Tables provided in the Malaysia Energy Statistics Handbook. Fig. 1 shows the carbon emission series together with electricity production and consumption trends from 2001 to 2019.

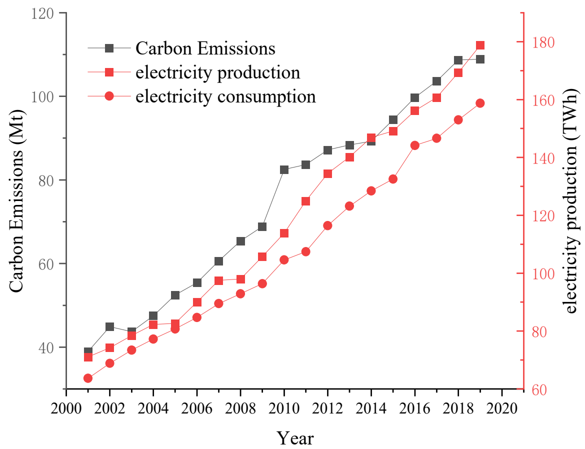

Fig. 1. The trends of carbon emissions, electricity generation, and consumption in the Malaysian electricity sector from 2001 to 2019.

The carbon emission trend in Malaysia's electricity sector is closely related to the growth of electricity production and consumption. Although the upward trend remained consistent, carbon emissions in Malaysia's electricity sector began to diverge from this pattern after 2003. Based on the observed changes in these trends, the carbon emission trajectory of Malaysia's electricity sector can be divided into seven periods: 2001–2003, 2003–2009, 2009–2010, 2010–2014, 2014–2018, and 2018–2020. The periods 2001–2002 and 2009–2010 are characterized by rapid emission growth, 2003–2009 and 2014–2018 by moderate growth, 2002–2003, 2010–2014, and 2018–2019 by relatively stable emission levels.

B. *Analysis of the Driving Factors of Typical Periods*

Carbon emissions from electricity generation are calculated on the assumption that complete combustion of fossil fuels and that the carbon emission coefficients for each fuel type remain constant [27]. Therefore, the contribution of the Carbon Emission Coefficient (CEF) is assumed to be zero, and the remaining ten driving factors are calculated using the formula above.

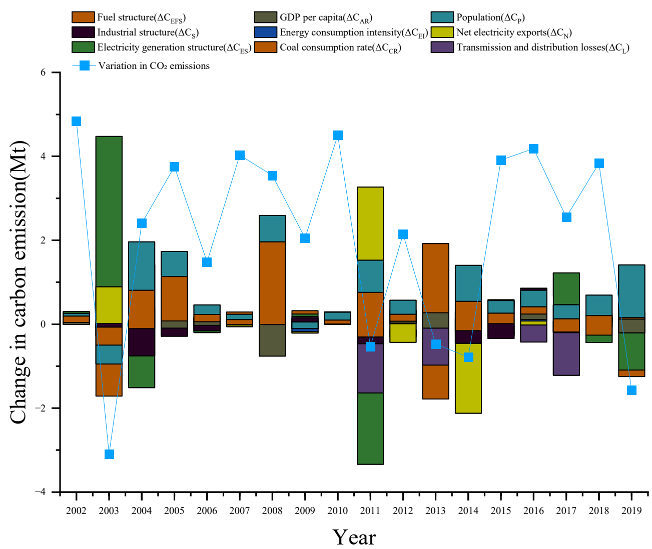

Fig. 2. Decomposition results of CO_2 emissions based on the LMDI method.

Considering both the magnitude of changes in CO_2 emissions and their relation to driving factors, emission dynamics in 2002–2003, 2009–2011, and 2018–2019 differ significantly from those in other periods. Therefore, we focus our decomposition analysis on these specific periods, as illustrated in Fig. 2. The data are summarized in Tables 3–4.

Malaysia's electricity sector experienced a reduction of 1.2 Mt in CO_2 emissions during the period 2002–2003. The primary contributing factors to this decline include the reduced share of coal in power generation, transmission and distribution losses, and improvements in the energy intensity of the industrial sector. Their respective contribution rate is 447.4%, 89.0%, and 1.9% (see Table 4). Among the positive contributors to emissions in 2002–2003, the coal consumption rate had the strongest impact. This is probably because the low-efficiency coal units were dispatched more heavily during the post-recovery period, which led to a higher consumption of fuel per unit of electricity. Transmission and distribution losses increased as a result of capacity overuse and inefficiency in aged grid hardware. Industrial electricity intensity also increased slightly, indicating that industries used more electricity per unit of output than they did under the 2001 economic slowdown.

Table 3. The year-by-year decomposition results of the driving factors in carbon emissions in the electricity sector from 2002 to 2019 (physical amount) (Unit Mt)

Year	ΔC_{EFS}	ΔC_{CR}	ΔC_{ES}	ΔC_L	ΔC_N	ΔC_{EI}	ΔC_S	ΔC_{AR}	ΔC_P	ΔC_{EIR}
2001–2002	0.964	1.784	0.634	0.281	0.006	0.243	-0.041	1.527	1.148	0.236
2002–2003	2.027	-5.291	0.332	-1.052	0.105	-0.022	0.114	1.119	0.587	0.082
2003–2004	1.515	-5.685	0.242	5.334	0.223	-2.839	0.567	7.395	3.037	−0.396
2004–2005	-0.671	4.401	-0.156	-1.115	0.586	-1.439	-0.457	8.634	5.647	0.381
2005–2006	0.387	-0.588	-0.003	0.515	0.348	-0.453	-0.079	1.352	0.677	0.176
2006–2007	1.53	0.742	0.38	-0.305	0.088	-0.038	-0.086	1.238	0.567	−0.039
2007–2008	-0.082	3.435	-1.005	1.161	-0.784	0.574	-3.642	2.402	9.406	−0.044
2008–2009	1.103	0.836	0.627	-0.721	-0.607	0.515	-0.154	-0.362	0.198	0.198
2009–2010	4.053	2.84	0.725	0.526	-0.051	0.354	0.377	3.902	1.332	0.12
2010–2011	1.266	-3.753	-1.842	3.673	-0.161	-0.521	-0.324	1.713	0.854	−0.339
2011–2012	0.455	-1.029	-0.472	-1.531	0.042	1.183	0.084	2.013	0.825	0.248
2012–2013	-2.101	-0.153	-1.148	0.239	-0.074	0.749	-0.108	2.164	2.26	0.324
2013–2014	-0.164	0.272	-0.807	-1.898	0.123	-0.407	0.057	1.254	0.487	−0.138
2014–2015	1.994	2.978	-1.364	-1.175	-0.003	-1.745	0.223	2.884	1.349	0.066
2015–2016	1.18	-1.457	-2.283	-0.085	0.423	4.597	0.604	4.317	2.221	1.31
2016–2017	2.569	4.767	-4.743	-0.602	0.294	-0.781	-0.106	1.803	0.509	−0.719
2017–2018	1.254	-2.203	0.739	0.815	0.24	1.027	-0.325	3.495	1.028	−1.315
2018–2019	-2.287	-2.001	0.513	0.111	0.106	-0.313	-0.373	2.585	0.283	0.223

Table 4. The year-by-year decomposition results of the driving factors in carbon emissions in the electricity sector from 2002 to 2019 (contribution) (Unit %)

Year	ΔC_{EFS}	ΔC_{CR}	ΔC_{ES}	ΔC_{L}	ΔC_{N}	ΔC_{EI}	ΔC_{S}	ΔC_{AR}	ΔC_{P}	ΔC_{EIR}
2001–2002	16.2	30	10.7	4.7	0.1	4.1	-0.7	25.6	19.3	4
2002–2003	-171.4	447.4	-28.1	89	-8.9	1.9	-9.6	-94.6	-49.6	-7
2003–2004	40.3	-151	6.4	141.7	5.9	-75.4	15.1	196.4	80.7	-10.5
2004–2005	-13.5	88.4	-3.1	-22.4	11.8	-28.9	-9.2	173.4	113.4	7.7
2005–2006	13.2	-20	-0.1	17.5	11.9	-15.4	-2.7	46.1	23.1	6
2006–2007	29.3	14.2	7.3	-5.8	1.7	-0.7	-1.6	23.7	10.8	-0.8
2007–2008	-1.7	71.7	-21	24.2	-16.4	12	-76	258.9	196.4	-0.9
2008–2009	32	24.2	18.2	-20.9	-17.6	14.9	-4.5	-10.5	5.8	5.8
2009–2010	29.7	20.8	5.3	3.9	-0.4	2.6	2.8	28.6	9.8	0.9
2010–2011	112.6	-333.9	-163.8	326.7	-14.3	-46.4	-28.8	152.3	76	-30.2
2011–2012	12.9	-29.1	-13.4	-43.3	1.2	33.5	2.4	57	23.4	7
2012–2013	-178.4	-13	-97.5	20.3	-6.3	63.6	-9.1	183.8	191.9	27.5
2013–2014	-18.3	30.4	-90.1	-211.9	13.8	-45.4	6.3	140	54.4	-15.4
2014–2015	38.9	58.2	-26.6	-23	-0.1	-34.1	4.4	56.3	26.3	1.3
2015–2016	22	-27.1	-42.5	-1.6	7.9	85.7	11.3	80.4	41.4	24.4
2016–2017	65.9	122.3	-121.7	-15.5	7.5	-20	-2.7	46.3	13	-18.4
2017–2018	24.8	-43.6	14.6	16.1	4.7	20.3	-6.4	69.2	20.3	-26
2018–2019	-125	-109.3	28.06	6.06	5.78	-17.13	-20.4	141.25	15.45	12.2

In contrast, some factors have negative effect on emission, such as power generation fuel mix -171.4%), electricity production structure (-28.1%), net electricity exports (-8.9%), industrial structure (-9.6%), per capita GDP (-94.6%), population (-49.6%), residential electricity intensity (-7.0%).

Between 2009 and 2011, CO_2 emissions from Malaysia's electricity sector increased by 13.7 Mt, and net electricity exports declined by just 0.4%. Nine factors accounted for the increase: power generation fuel mix (29.7%), coal consumption rate (20.8%), electricity production structure (5.3%), transmission and distribution losses (3.9%), industrial energy intensity (2.6%), industrial structure (2.8%), GDP per capita (28.6%), total population (9.8%) and residential electricity consumption intensity (0.9%) (see in Table 4). The dramatic increase in emissions from 2009 to 2011 arose primarily because of the strong rebound in the Malaysian economy after the crisis. After a reduction of -1.5% in 2009, GDP growth increased to 7.4 % percent in 2010, sparking an increase in the demand for electricity across all sectors. In response to this requirement, coal generation expanded in the context of fast-track national programmers. Limited penetration of renewables and energy efficiency improvements saw the increase in demand met predominantly using high-carbon fuels, leading to an increase in emissions.

CO_2 emissions of the Malaysian electricity sector declined slightly by 0.18 Mt between 2018 and 2019. The factors contributing to CO_2 reduction were the power generation mix (-1250%), coal consumption (-1093.6%), industrial energy intensity (-171.3%), and industrial structure (1204%). The factors contributing to increased emissions included electricity production structures (280.6%), transmission losses (60.6%), net electricity exports (57.8%), per capita GDP (1412.5%), total population (154.5%), and residential electricity intensity (122%) (see Table 4). The electricity production structure effect contributed 280.6% to the increase in emissions in 2018–2019, despite the overall emissions showing a slight decline. This outsized impact is primarily because air pollutants from the power sector are more prevalent where coal-fired generation has increased. Official energy statistics show that the proportion of coal in generating electricity increased, while cleaner sources like natural gas and hydropower were slightly down. The emission intensity of electricity was significantly raised, in view of the fact that coal has a higher carbon intensity than other natural resources. This also reveals the importance of emissions from power generation that can depend on how fuel is used, even when total electricity production stays constant.

Further analysis suggests Malaysia's electricity sector carbon emissions reached a high point in 2002. This peak was primarily due to the sharp rebound in electricity demand following the 2001 economic slowdown. As Malaysia's GDP recovered from 0.5% growth in 2001 to 4.4% in 2002, industrial and commercial activity surged. The increased electricity demand was largely met by coal-fired generation, including older, less efficient units, which raised the overall carbon intensity of electricity. Renewable energy penetration remained negligible at the time, and grid efficiency was relatively low, further compounding the emission impact [28].

A similar emissions peak was observed in 2010. The decline in Malaysia's GDP in 2009 was primarily due to the global financial crisis of 2008 [29]. As a trade-dependent economy, Malaysia faced sharp reductions in exports, industrial output, and investment. Manufacturing and energy-intensive industries contracted, leading to lower economic activity and electricity demand. This downturn explains the drop in GDP growth from 4.8% in 2008 to –1.5% in 2009, which corresponded with a temporary moderation in emissions.

Fluctuations in Carbon emissions during 2002–2003 and 2009–2011 were primarily driven by external shocks. Although such shocks are generally uncontrollable and difficult to predict, the economic slowdown in Malaysia during these periods had a counterintuitive impact on the electricity sector. These shocks resulted in improved electricity production structure, enhanced power generation efficiency, and industrial enterprise restructuring.

A. Classification Analysis of Driving Factors

We classify the ten driving factors into four groups based on positions along the electricity supply chain, power generation segment, Transmission and Distribution segment (T&D segment), international trade segment, and end-use consumption segment. The data are summarized in Tables 3 and 4. To facilitate a clearer understanding of the contribution of each factor, Table 4 presents the classification and the decomposition results for the period 2002–2019.

Table 4. Decomposition results of the driving factors for the changes in CO_2 emissions in Malaysia's electricity sector from 2002 to 2019

	Type of driving factors									
	Electricity generation segment			T&D segment	Trade segment	End-use consumption segment				
Symbol	ΔC_{EFS}	ΔC_{CR}	ΔC_{ES}	ΔC_L	ΔC_N	ΔC_{EI}	ΔC_S	ΔC_{AR}	ΔC_P	ΔC_{EIR}
Change (Mt)	21.35	2.44	5.45	3.16	0.71	0.028	0.033	2.25	1.17	0.026
rate（%）	30.54	−3.49	−7.8	4.52	1.01	−0.04	−0.05	3.22	1.67	0.04

1) Electricity generation segment

The power generation segment contains three primary driving factors: fuel structure effect (ΔC_{EFS}), coal consumption rate effect (ΔC_{CR}), and electricity production structure effect (ΔC_{ES}). Fig. 3 shows the fuel mix of Malaysia's power generation from 2002 to 2019.

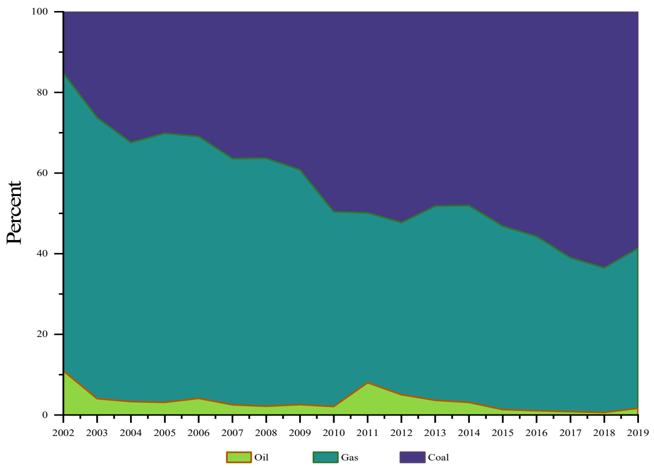

Fig. 3. Fuel mix in electricity generation in Malaysia from 2002 to 2019.

Fuel structure effect, year by year decomposition shows that ΔC_{EFS} increased electricity sector CO_2 emissions in 12 years and reduced emissions in 6 years (see Fig. 2). Interval decomposition for 2002–2019 shows 30.5% positive impact (see Table 4). This effect is primarily attributed to the rising share of coal in the fuel mix, which displaced lower-carbon alternatives such as natural gas in several years. As illustrated in Fig. 2, ΔC_{EFS} contributed to increased CO_2 emissions in 12 out of the 18 years analyzed. Fig. 3 further confirms that coal has maintained a dominant and growing role in Malaysia's electricity generation fuel structure, highlighting a long-standing structural dependence on coal within the national power sector. It is also a challenge observed in neighboring countries such as Indonesia and Vietnam [30, 31]. The coal consumption rate effect, $\Delta C_{CR,}$ raised emissions in 12 years, reduced emissions in 6 years (see Fig. 2). In full, it contributed a net increase of 3.5% (see Table 3). ΔC_{CR} is an index used to normalize the coal consumption amount per electricity generation unit. Over 12 years of the period, ΔC_{CR} had a positive impact on emissions largely due to higher coal use rates and load factors in inefficient power plants, as well as slowed retirement of older coal-fired units. By contrast, in 6 years, ΔC_{CR} has had negative effects for emissions, because the improvement in operational efficiency and slow shift toward more advanced combustion technology or partial conversion into natural gas/oil plants or efficient coal-fired power plants could have driven them down again. These shifts resulted in lower coal consumption per unit of electricity, thereby reducing emissions. The variability in ΔC_{CR} impact highlights the transitional nature of Malaysia's electricity generation system during this period.

The electricity production structure effect, $\Delta C_{ES,}$ increased emissions in 9 years (see Fig. 2), resulting in a net reduction of CO_2 emissions in 2002–2019. The positive contribution of ΔC_{ES} in 9 years reflects the expansion of coal-fired generation during those periods. Particularly in years when electricity demand rose rapidly, coal was favored for its availability and cost-effectiveness. In contrast, cleaner energy sources like natural gas and hydro saw reduced shares in the mix. These structural shifts in the generation portfolio led to higher carbon intensity, making ΔC_{ES} a significant positive driver of emissions in those years.

2) T&D segment

Transmission losses and distribution losses are the main contributors to increasing CO_2 emissions in the electricity sector. Interval decomposition data 2001–2019 show that it contributed 4.5% of the growth of CO_2 emissions in the sector. This is because more energy needs to be unaccounted for during transport and distribution, meaning that additional electricity has to be generated only for the purpose of "wasted". The inherent dependence of Malaysia on fossil fuels (coal and natural gas, primarily) means these losses contribute indirectly to emissions via increased fuel consumption at the generation stage. Thus, work to upgrade the grid and make it more efficient—such as adding storage, installing smart meters, conducting comprehensive residential retrofits, stimulating ubiquitous energy efficiency in industrial processes—should have a strong bearing on precipitable emissions.

3) International trade segment

Year-by-year decomposition reveals that the net electricity exports effect exerts both upward and downward influences on CO_2 emissions; however, the overall impact remains limited. Interval decomposition indicates that the net electricity exports effect has contributed to a net CO_2 increase of 1.0% between 2002 and 2019. Although Malaysia's electricity exports were relatively small during the study period, they were primarily supplied by fossil-fuel-based thermal plants. Electricity Exports Although so profitable, the mechanism of electricity exports raises domestic generation demand and thus additional fuel use, consequently contributing positively to CO_2 emissions. As Malaysia imported insignificant electricity, this asymmetry resulted in a net positive impact of 1.0% on national emissions because of the Net export factor (ΔC_N).

4) End-use consumption segment

End-use consumption segment consists of five key driving factors: Industrial energy intensity effect (ΔC_{EI}), Industrial Structure Effect (ΔC_S), GDP per capita effect (ΔC_{AR}), Population effect (ΔC_P), and Residential electricity consumption intensity effect (ΔC_{EIR}).

The industrial energy intensity effect (ΔC_{EI}) exhibited both positive and negative impacts on CO_2 emissions in the year-by-year decomposition, but the magnitudes were relatively small. The interval decomposition for 2001-2019 indicates a net reduction of 0.04%. The industrial structure effect (ΔC_S) increased emissions in certain years (e.g., 2003, 2005), but overall, it decreased emissions by 0.05% from 2002 to 2019, suggesting gradual structural optimization. The GDP per capita effect (ΔC_{AR}) was consistently positive from 2002 to 2019, contributing 248 kt of CO_2 equivalent, which accounted for a 3.2% increase in total emissions, indicating stable economic expansion. The population effect (ΔC_P) remained positive throughout the study period, contributing a total of 1.17 Mt (1.7%) to CO_2 emissions. This reflects the impact of steady demographic growth. The residential electricity consumption intensity effect (ΔC_{EIR}) fluctuated between positive and negative across years, but its impact was modest over the study period (0.026 Mt or 0.04 % growth) (see Tables 3–4).

These results suggest that although some structural and efficiency improvements were made during the period, their overall effects on decarbonization were limited. Technological innovation is key to breaking the structural rigidity in Malaysia's electricity sector. Hehe- Power Enhancement Technology: High-Efficiency-Low Emission (HELE) helps fuel conversion efficiency a lot for fossil power plants. Carbon Capture and Storage (CCS) provides a direct way to reduce greenhouse gas emissions from thermal generation. Greater penetration of renewable energy resources requires advanced battery storage systems. At the same time, smart grid deployment is an important condition for smoothing load curves and reducing losses in transmission. In addition, advanced digital management technologies on the demand side, such as smart meters, can help to shave peaks off electricity consumption peaks and thereby improve end-use efficiency. These are important in converting incremental improvements in the power system into comprehensive decarbonization.

V. Conclusion

This study analyzed the driving factors behind carbon emission changes in Malaysia's electricity sector using the Logarithmic Mean Divisia Index (LMDI) decomposition method. Based on the findings, five conclusions can be drawn:

The contribution of fossil fuels to rising carbon emissions is closely tied to the dominance of coal and natural gas, which accounted for over 75% of the electricity generated during the study period. The use of carbon-intensive fuels significantly contributed to the increase in carbon emissions, with the fuel structure effect accounting for 30.54%. Therefore, the transition to renewable energy sources is crucial for mitigating emissions.

Limited Progress in Efficiency Improvements, although technological advancements and operational enhancements have been implemented, the reductions in carbon emissions from the coal consumption rate and electricity production structure remained modest, at only −3.49% and −7.8%, respectively. This underscores the urgent need for more efficient energy generation technologies such as Carbon Capture and Storage (CCS) and smart grids.

Transmission and distribution losses contributed to a 4.52% increase in carbon emissions over the study period. This indicates that upgrading Malaysia's electricity infrastructure to reduce transmission and distribution losses can enhance efficiency and help lower carbon emissions.

Socioeconomic growth is a driving carbon emissions. The consistent positive contributions of GDP per capita (3.22%) and population growth (1.67%) to carbon emissions demonstrate a strong correlation between economic and population growth and increased energy demand. These findings highlight the need for policies that decouple economic growth from carbon emissions, such as energy-efficient technologies and sustainable urbanization.

Achieving a low-carbon electricity sector in Malaysia requires technological innovation, infrastructure development, and policy interventions to balance economic growth with environmental sustainability.

While these findings are insightful, it is also important to recognize the limitations of this approach. The most notable constraint is its assumption of a constant emission factor throughout the study period, which overlooks potential variations in fuel quality, advances in combustion efficiency, and the deployment of advanced low-carbon technologies. In addition, as a retrospective analytical method, LMDI is unable to capture the complex and evolving interactions among influencing factors over time.

To overcome these limitations, future research could incorporate scenario analysis or simulation approaches and employ analytical models such as system dynamics models, Computable General Equilibrium (CGE) models, or machine learning techniques. These methods can be used to explore carbon emission trajectories under varying policy, technological, and economic conditions, thereby further enhancing the foresight and policy relevance of studies on the low-carbon transition in the electricity sector.

VI. Policy Implications

To reduce carbon emissions from Malaysia's electricity sector and ensure sustainable growth, we propose the following policy recommendations based on our findings.

Accelerating renewable energy integration. The electricity sector's heavy reliance on coal and natural gas underscores the urgent need to expand renewable energy deployment. To achieve the target set in the Malaysia Renewable Energy Roadmap (MyRER)—40% renewable energy installed capacity by 2035—the government should strengthen incentives for solar, wind, and hydropower, such as tax exemptions, subsidies, and feed-in tariffs. At the same time, accelerating private investment and grid integration will make a meaningful contribution to Malaysia's progress toward the Sustainable Development Goals (SDGs).

Upgrading the Electricity infrastructure, Transmission, and distribution (T&D) losses have been identified as a significant contributor to carbon emissions. Modernizing the national grid through the adoption of smart grid technologies and high-efficiency T&D infrastructure can substantially reduce energy losses. This initiative aligns closely with the core objectives of Malaysia's National Energy Policy to strengthen energy security, while delivering both environmental and operational efficiency gains.

Fostering Technological Innovation, Malaysia's limited investment in R&D for clean energy technologies hinders the transition to a low-carbon economy. Increasing R&D funding to at least 2% of GDP, and collaborating with universities, private companies, and international organizations, could drive innovation in CCS, energy storage systems, and renewable energy.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Chen Chen conducted the research, performed the data analysis, and drafted the manuscript. Mohammad Nizamuddin Inamdar provided supervision, contributed to the conceptual framework, and revised the manuscript. Aiman Al-Odaini assisted with methodology design, literature review, and editing. All authors reviewed and approved the final version of the manuscript.

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References

[1] A. Pisor, J. Lansing, and K. Magargal, "Climate change adaptation needs a science of culture," *Philosophical Transactions of the Royal Society B, Biological Sciences*, vol. 378, no. 1889, 20220390, 2023.

[2] S. Yida *et al.*, "Emission accounting and drivers in East African countries," *Applied Energy*, vol. 312, 118805, 2022.

[3] W. Chuang *et al.*, "Minute-level ultra-short-term power load forecasting based on time series data features," *Applied Energy*, vol. 372, 123801, 2024.

[4] M. E. Farina *et al.*, "Reinvestigating the EKC hypothesis: Does renewable energy in power generation reduce carbon emissions and ecological footprint?" *Energy Strategy Reviews*, vol. 53, 101387, 2024.

[5] Z. W. Hou, Q. B. Di, and X. L. Chen, "Forecasting carbon emissions in Chinese coastal cities based on a gated recurrent unit model," *Energy Reports*, vol. 12, pp. 5747–5756, 2024.

[6] W. Ya and X. Bin, "When will China's carbon emissions peak? Evidence from judgment criteria and emissions reduction paths," *Energy Reports*, vol. 8, pp. 8722–8735, 2022.

[7] R. Asif *et al.*, "From growth to green: Navigating the complexities of economic development, energy sources, health spending, and carbon emissions in Malaysia," *Energy Reports*, vol. 10, pp. 4318–4331, 2023.

[8] S. Baoguo *et al.*, "District level decoupling analysis of energy-related carbon dioxide emissions from economic growth in Beijing, China," *Energy Reports*, vol. 8, pp. 2045–2051, 2022.

[9] D. Binoy *et al.*, "Analyzing the factors influencing the wind energy adoption in Bangladesh: A pathway to sustainability for emerging economies," *Energy Strategy Reviews*, vol. 50, 101265, 2023.

[10] Y. Li *et al.*, "Energy structure, digital economy, and carbon emissions: Evidence from China," *Environmental Science and Pollution Research*, vol. 28, pp. 64606–64629, 2021.

[11] W. Qiang, W. Lili, and L. Rongrong, "Does renewable energy help increase life expectancy? Insight from the linking renewable energy, economic growth, and life expectancy in 121 countries," *Energy Strategy Reviews*, vol. 50, 101185, 2023.

[12] X. V. Ngoc *et al.*, "Carbon dioxide emissions, population, foreign direct investment, and renewable energy nexus: New insights from Thailand," *Energy Reports*, vol. 11, pp. 4812–4823, 2024.

[13] K. Sarpong *et al.*, "Can environmental taxes and green-energy offer carbon-free E7 economies? An empirical analysis in the framework of COP-26," *Environmental Science and Pollution Research*, vol. 30, pp. 51726–51739, 2023.

[14] B. E. Antonio *et al.*, "Barriers to renewable energy expansion: Ecuador as a case study," *Energy Strategy Reviews*, vol. 43, 100903, 2022.

[15] L. Ting, S. Nick, and E. Mark, "Micro-macro multilevel analysis of day-to-day lifestyle and carbon emissions in UK multiple occupancy households," *Sustainable Production and Consumption*, vol. 39, pp. 13–29, 2023.

[16] F. M. Isaac *et al.*, "Malaysia's energy transition and readiness towards attaining net zero: Review of the potential, constraints, and enablers," *Renewable Energy Focus*, vol. 51, 100640, 2024.

[17] S. Pooja, "Role of energy efficiency in energy transition: A decomposition analysis of energy use," *Solar Compass*, vol. 12, 100086, 2024.

[18] H. Ali *et al.*, "Model predicting social acceptance behavior to implement ELV policy: Exploring the role of knowledge toward ELV policy on social acceptance in Malaysia," *Frontiers in Public Health*, vol. 10, 1093732, 2022.

[19] H. Khazaei and M. Tareq, "Moderating effects of personal innovativeness and driving experience on factors influencing adoption of BEVs in Malaysia: An integrated SEM–BSEM approach," *Heliyon*, vol. 7, no. 9, e08072, 2021.

[20] P. Teh, D. Adebanjo, and D. Kong, "Key enablers and barriers of solar paver technologies for the advancement of environmental sustainability," *Heliyon*, vol. 7, no. 10, e08189, 2021.

[21] L. Qingsheng, Y. Hongwei, and L. Zixiang, "Understanding China's CO_2 emission drivers: Insights from random forest analysis and remote sensing data," *Heliyon*, vol. 10, no. 7, e29086, 2024.

[22] X. Jing *et al.*, "Research on the spatial and temporal differences of China's provincial carbon emissions and ecological compensation based on land carbon budget accounting," *International Journal of Environmental Research and Public Health*, vol. 18, no. 24, 12892, 2021.

[23] M. Saleem, M. Aslam, and A. Janjua, "Uncovering the global ranking of greenhouse gases intensity, efficiency and structural transformation," *Scientific Reports*, vol. 13, 18040, 2023.

[24] O. I. Inah, F. I. Abam, and B. N. Nwankwojike, "Exploring the CO_2 emissions drivers in the Nigerian manufacturing sector through decomposition analysis and the potential of Carbon Tax (CAT) policy on CO_2 mitigation," *Future Business Journal*, vol. 8, 61, 2022.

[25] Z. Liu *et al.*, "Spatial heterogeneity and scenario simulation of carbon budget on provincial scale in China," *Carbon Balance and Management*, vol. 18, no. 20, 2023.

[26] X. Wu *et al.*, "Carbon emission of China's power industry: Driving factors and emission reduction path," *Environmental Science and Pollution Research*, vol. 29, pp. 78345–78360, 2022.

[27] G. A. Singh *et al.*, "Long-term energy system planning considering short-term operational constraints," *Energy Strategy Reviews*, vol. 26, 100383, 2019.

[28] A. Samina *et al.*, "Modeling the nexus between carbon emissions, energy consumption, and economic progress in Pakistan: Evidence from cointegration and causality analysis," *Energy Reports*, vol. 7, pp. 4642–4658, 2021.

[29] S. A. Abdul, M. A. Pahrol, and M. I. Mazeli, "Effects of population weighting on PM_{10} concentration estimation," *Journal of Environmental and Public Health*, vol. 2020, no. 1, 1561823, 2020.

[30] J. A. Ordonez *et al.*, "Coal, power and coal-powered politics in Indonesia," *Environmental Science & Policy*, vol. 123, pp. 44–57, 2021.

[31] N. Christoph *et al.*, "Can investors benefit from the early retirement of coal plants: A plant-level analysis of Chinese-sponsored coal stations in Vietnam and Pakistan," *Energy Policy*, vol. 193, 114291, 2024.