Periodica Polytechnica Transportation Engineering, 53(1), pp. 7–15, 2025

Decomposition of Carbon Dioxide (CO_2) Emissions in Hungary

A Case Study Based on the Kaya Identity and LMDI Model

Ammar Al-lami[1,2*], Ádám Török[1,3]

[1] Department of Transport Technology and Economics, Faculty of Transportation Engineering and Vehicle Engineering, Budapest University of Technology and Economics, Műegyetem rkp. 3., H-1111 Budapest, Hungary
[2] Department of Civil Engineering, Faculty of Engineering, University of Misan, P. O. B. 132, 62001 Misan, Iraq
[3] Strategic, Research-Development and Innovation Directorate, KTI Nonprofit Ltd., Than Karoly str. 3-5., H-1119 Budapest, Hungary
[*] Corresponding author, e-mail: Al-lami1990@edu.bme.hu

Received: 27 May 2024, Accepted: 27 September 2024, Published online: 15 October 2024

Abstract

Elevated levels of global greenhouse gases (GHGs), primarily produced through fossil fuel combustion, present environmental risks such as prolonged droughts, global warming, and catastrophic floods. Despite raising awareness and international efforts to combat climate change, fossil fuel and GHGs demand persists. At this juncture, this study investigates Hungary's transportation sector, a notable CO_2 emitter. Using the Kaya Identity and Log Mean Divisia Index method, this study decomposes the primary components of CO_2 emissions in Hungary's transport sectors from 2001-2021. This analysis is done in two decomposition levels, annual and periodic decomposition analysis for each of the five years starting from 2001. The analysis reveals that the economic activity effect ΔC_{GPE} is the predominant driver of CO_2 emissions, while the energy intensity effect ΔC_{EIE} improvements have substantially mitigated these increases. Population changes affect ΔC_{POPE}, and the carbon emission intensity effect ΔC_{CEIE} has had minimal impacts. The study provides insights and recommendations for policy and strategic interventions to reduce emissions and promote sustainable transportation practices in Hungary.

Keywords

CO_2 emissions, energy consumption, Kaya identity, Hungary, decomposition, Log Mean Divisia Index

1 Introduction

The rising levels of global greenhouse gases (GHGs) and their adverse impacts on the environment and human life have heightened concerns about future natural threats such as prolonged droughts, global warming, and devastating floods. These threats primarily stem from the combustion of fossil fuels. Despite the growing global awareness and concern about global warming, the demand for fossil fuels and GHG emissions have continued to rise. Many countries lack effective environmental policies to reduce their fossil fuel consumption, and some are hampered by weak economic situations that limit their ability to address these issues effectively. The United States' decision to withdraw from the 2015 Paris Agreement on climate change mitigation has raised severe concerns recently. The U.S., the second-largest CO_2 emitter after China, significantly impacts global warming, and this withdrawal could have severe implications for global efforts to combat climate change (Solaymani, 2019). Road transport is the most popular mode of transport, which is the reason behind high-level carbon dioxide emissions. Passenger cars accounted for 73% of total emissions in 2022 (Khalaf Jabbar, 2022; Łuczyszyn, 2024).

Adherence to international agreements is crucial for reducing global warming. However, it is equally important to implement effective climate change policies that reduce fossil fuel consumption. Such policies are essential as they directly influence energy consumption and CO_2 emissions (International Panel on Climate Change (IPCC), 2022; Stern, 2007). The transport sector is a major energy consumer and a significant contributor to air emissions. This sector accounts for approximately 29% of the world's total energy consumption and 65% of global oil product consumption. It is responsible for about 24% of global CO_2 emissions due to fuel combustion, making it a key point

Cite this article as: Al-lami, A., Török, Á. (2025) "Decomposition of Carbon Dioxide (CO_2) Emissions in Hungary: A Case Study Based on the Kaya Identity and LMDI Model", Periodica Polytechnica Transportation Engineering, 53(1), pp. 7–15. https://doi.org/10.3311/PPtr.37552

for mitigating climate change, second only to emissions from electricity and heat production.

Countries worldwide have developed strategies to reduce fossil fuel consumption and greenhouse gas (GHG) emissions. The European Union, for instance, has a climate change package aimed at reducing GHG emissions by 20%, increasing renewable energy to 20%, and improving energy efficiency by 22% by 2020 (Hinrichs-Rahlwes, 2013). China, the largest CO_2 emitter, has also implemented numerous climate change strategies and participates in international climate policies (Liu et al., 2021). Turkey has implemented several policies to reduce reliance on internal combustion engine vehicles, such as introducing its own electric vehicle and promoting it as a suitable replacement for environmentally harmful vehicles (Alatawneh and Ghunaim, 2024). Furthermore, advancements in vehicle technologies can pave the way for more energy-efficient options, such as autonomous and shared autonomous vehicles, which are anticipated to be fully electric and designed to optimize driving patterns, thereby reducing congestion, and decreasing overall energy consumption (Alatawneh et al., 2023; Alatawneh and Torok, 2023; Matalqah et al., 2022).

However, many countries face challenges due to economic constraints. Enhancing energy efficiency, imposing carbon pricing, and developing renewable energy sources can be costly, leading to potential welfare losses. Reducing energy subsidies can further exacerbate poverty in some regions (Janic, 2014). Researchers advocate for policies that promote renewable energy and energy efficiency to improve energy security and meet environmental goals (Asmelash et al., 2020).

Transportation significantly contributes to energy consumption and CO_2 emissions, especially in industrialized nations. As the second-largest CO_2 emitting sector, it is crucial to implement climate change policies in this area. Identifying the main drivers of carbon emissions in transportation is essential for designing effective strategies.

In Hungary, the transportation sector's CO_2 emissions have fluctuated significantly from 2001 to 2021. The country's reliance on fossil fuels has increased despite efforts to use renewable energy. Economic growth and increased vehicle ownership have driven the rise in CO_2 emissions. These trends highlight the need for targeted policies to curb emissions and promote sustainable energy use in Hungary's transportation sector. Analyzing the trends and characteristics of energy consumption and CO_2 emissions in transport is essential for formulating effective policies. This study decomposes the main drivers of CO_2 emissions in Hungary's transportation sector, providing insights and recommendations for achieving low-carbon targets.

The primary objective of this study is to identify the main drivers of CO_2 emissions in Hungary's transportation sector and to assess the effectiveness of different strategies for reducing emissions. By understanding the contributions of economic activity, energy intensity, and other factors, this study aims to provide actionable insights to guide Hungary's efforts toward a more sustainable transportation sector. The structure of this paper is as follows: the introduction outlines the study's context and objectives, the literature review discusses relevant research, the methodology section details the data and methods used, the results section presents the findings, and the discussion and conclusion sections interpret the results and offer recommendations for policy and practice.

2 Literature review

A substantial body of research has utilized the Kaya Identity and LMDI method to decompose CO_2 emissions across various sectors and regions. These studies provide a robust foundation for understanding the factors influencing emissions and the effectiveness of different mitigation strategies.

Cansino et al. (2015) employed an extended Kaya Identity and LMDI method to analyze the driving forces of CO_2 emissions in Spain from 1995 to 2009. Their study identified economic activity and energy intensity as significant contributors to emission trends. Similarly, Chen et al. (2018) conducted a decomposition analysis of CO_2 emissions in OECD countries, finding that energy intensity and per capita GDP were crucial factors influencing emissions.

O'Mahony (2013) applied the Kaya Identity and LMDI method to decompose Ireland's carbon emissions from 1990 to 2010. The study revealed that while economic and population growth increased emissions, energy intensity and renewable energy adoption had mitigating effects. Liang et al. (2017) focused on China's transportation sector, demonstrating that economic development and energy efficiency were significant drivers of CO_2 emissions growth.

Su et al. (2020) analyzed CO_2 emissions in Henan's transportation industry using the LMDI method, identifying economic development and energy structure as critical factors. Zhang et al. (2019) examined the driving forces of CO_2 emissions in China's transport sector from both temporal and spatial perspectives, highlighting the importance of the income effect and energy intensity in emission trends.

Several studies have used decomposition analysis in public transportation to understand the factors driving CO_2 emissions and energy consumption. For instance, Liang et al. (2017) found that in China's transportation sector, economic development and improvements in energy efficiency played significant roles in shaping emission trends. Another study by Xu and Lin (2018) analyzed CO_2 emissions from Beijing's transportation sector, identifying economic growth, energy intensity, and population size as primary drivers of emissions.

In Europe, decomposition analysis has been applied to understand the impact of public transport policies on CO_2 emissions. For example, Abbes (2021) conducted a decomposition analysis on CO_2 emissions from transport systems in Eastern European countries, including Hungary. The study found that economic activity and the fuel mix by type and mode of transport were significant factors influencing emissions. Modal share and energy intensity also affected emission trends, albeit only slightly.

Public transport systems in Europe have been the focus of several studies using decomposition analysis to assess CO_2 emissions. For example, Papagiannaki and Diakoulaki (2009) conducted a decomposition analysis of CO_2 emissions from passenger cars in Denmark and Greece. Their study revealed that vehicle ownership, fuel mix, annual mileage, engine capacity, and technology influence emissions. These findings underscore the importance of improving vehicle efficiency and adopting cleaner energy sources to reduce emissions. The study highlighted the importance of optimizing the energy structure and improving energy efficiency in the transportation sector to mitigate emissions.

The LMDI method has been widely used to decompose CO_2 emissions in public transport, offering insights into the effectiveness of different policies and technologies. For example, Mavromatidis et al. (2016) used the LMDI method to analyze emissions from Switzerland's building sector and proposed a strategy for reducing emissions based on the Kaya Identity. Their study demonstrated how decomposition analysis can inform policy decisions and support the development of sustainable transportation systems.

This underscores the significance of economic activity, energy intensity, and energy structure in influencing CO_2 emissions. This study builds on these findings to explore the specific dynamics within Hungary's transportation sector, offering a detailed analysis that can guide policy and strategic interventions to mitigate emissions and promote sustainable transportation practices.

3 Research methodology and data collection

3.1 Yoichi Kaya and Log Mean Divisia Index (LMDI)

The research methodology outlined here aims to apply the LMDI method to decompose the Yoichi Kaya identity for analyzing CO_2 emissions and energy consumption trends in the transportation sector of Central Europe. The Yoichi Kaya identity provides a framework for understanding the drivers of CO_2 emissions, while the LMDI method allows for decomposing emissions and energy consumption changes into various factors. The approach breaks down combined figures to pinpoint the primary sources of carbon emissions within the transportation sector across specific nations. This method boasts precise decomposition without leftover factors, achieved with just a few time series variables. The decomposition formula employed is based on the Kaya identity devised by Yoichi Kaya, allowing for a thorough breakdown of carbon emissions.

$$F = (C/EC) \times (EC/G) \times (G/P) \times P \tag{1}$$

Equation (1) can help determine the drivers of CO_2 emissions by breaking down CO_2 emissions into various drivers, namely population (P) [inhabitant], GDP per capita (G/P) [USD/inhabitant], energy intensity (EC/G) [Mtoe/USD], and carbon intensity (C/EC) [$MtCO_2$/Mtoe] of energy use. The Kaya identity refers primarily to broad evaluations of a nation or region. However, it is used to scrutinize specific industrial sectors and energy varieties. According to the decomposed equations in Ang and Liu (2007); Liu et al. (2021); Solaymani (2019); Wang et al. (2011), based on Eq. (1), we reframe the Kaya identity as:

$$C = \sum_{ij} CO_{2ij}^{\,t} = \sum_{ij} \frac{C_{ij}}{EC_{ij}} \times \frac{EC}{G} \times \frac{G}{P^t} \times P = \sum_{ij} E_i LMA \tag{2}$$

From Eqs. (1) and (2) above, the three ratios on the right side of the equation (C/EC, EC/G, G/P) represent carbon intensity from fuel (E_i) [$MtCO_2$/Mtoe], energy intensity (L) [Mtoe/USD], GDP per capita (M) [USD/inhabitant], and Population effect (A) [inhabitant], from the transport sector.

Then, the (LMDI) method will be applied to decompose changes in CO_2 emissions and energy consumption into various factors, as specified by Yoichi Kaya identity. The shift in CO_2 emissions within the transportation sector from an initial year 0 to a designated target year t can be dissected into six distinct influences, as in Eq. (3).

$$\Delta C_{tot} = C_{ij}^t - C_{ij}^0 = \Delta C_{CEIE} + \Delta C_{EIE} + \Delta C_{GPE} + \Delta C_{POPE} \tag{3}$$

From Eq. (3), ΔC_{tot} is the total change in CO_2 between the current year and the base year, ΔC_{CEIE} is the carbon emission intensity effect, ΔC_{EIE} is the energy intensity effect, ΔC_{GPE} is the economic activity effect, and ΔC_{POPE} is the population effect. Each factor effect on the right-hand side of Eq. (3) can be calculated according to the general (LMDI) formulation:

$$\Delta C_{CEIE} = \sum_i \frac{C_{ij}^t - C_{ij}^0}{\ln C_{ij}^t - \ln C_{ij}^0} \times \ln\left(\frac{E^t}{E^0}\right) \tag{4}$$

$$\Delta C_{EIE} = \sum_i \frac{C_{ij}^t - C_{ij}^0}{\ln C_{ij}^t - \ln C_{ij}^0} \times \ln\left(\frac{L^t}{L^0}\right) \tag{5}$$

$$\Delta C_{GPE} = \sum_i \frac{C_{ij}^t - C_{ij}^0}{\ln C_{ij}^t - \ln C_{ij}^0} \times \ln\left(\frac{L^t}{L^0}\right) \tag{6}$$

$$\Delta C_{POPE} = \sum_i \frac{C_{ij}^t - C_{ij}^0}{\ln C_{ij}^t - \ln C_{ij}^0} \times \ln\left(\frac{A^T}{A^0}\right) \tag{7}$$

Where J represents the transport sector, i represents the fuel type, namely oil, gas, renewable, and waste, and t represents the time (in this study, $t = 2001$ to 2021). Equation (4) is used to calculate the carbon emission intensity effect (ΔC_{CEIE}), Eq. (5) to calculate the energy intensity effect (ΔC_{EIE}), Eq. (6) to calculate the economic activity effect (ΔC_{GPE}), and Eq. (7) to calculate the population effect ΔC_{POPE}.

3.2 Data collection and study area

The study utilizes secondary data from the International Energy Agency (IEA) and the World Bank. Emissions and energy consumption data are sourced from the IEA. In contrast, GDP and population data are obtained from the World Bank, The International Association of Public Transport (UITP), the World Bank Open Data, and Eurostat. To ensure consistency, all variables were converted into comparable units, such as CO_2 emissions in $MtCO_2$, energy consumption in TJ, and GDP in constant USD. Minor data gaps were addressed using linear interpolation, while larger gaps were excluded from the analysis to maintain data integrity. All data were normalized to the base year of 2001, allowing for consistent comparison across time. Outliers, such as those caused by the 2008 financial crisis and the 2020 COVID-19 pandemic, were retained and acknowledged due to their significant real-world impact on emissions and energy consumption. Given the time-series nature of the data, the Index Decomposition Analysis (IDA) method is employed, specifically the LMDI method. LMDI is advantageous for decomposition analysis as it provides perfect results without unexplained residuals (Ang and Liu, 2007).

4 Results and discussion

Table 1 shows the results of Kaya identity decomposition using the Additive LMDI method to analyze the change in CO_2 emissions in Hungary's transportation sector from 2001 to 2021 by decomposing the changes in CO_2 emissions into four contributing factors. Economic activity effect (ΔC_{GPE}), population effect (ΔC_{POPE}), energy intensity effect (ΔC_{EIE}), and carbon emission intensity effect (ΔC_{CEIE}) are included in Table 1. We gain insights into the dynamics driving these emissions.

4.1 Yearly decomposition analysis (2001-2021)

Table 1 illustrates that the economic activity effect consistently contributed positively to CO_2 emissions. Peaks were observed in 2002 (1.65 $MtCO_2$) and 2008 (1.73 $MtCO_2$), highlighting periods of significant economic growth. However, during the global financial crisis 2009, this effect dropped markedly to 0.64 $MtCO_2$. Despite fluctuations, the economic activity effect remained dominant, with an

Table 1 Decomposition of CO_2 emissions from 2001 to 2021 ($MtCO_2$)

year	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011
ΔC_{GPE}	1.65	1.36	1.23	1.27	1.59	1.19	1.73	0.64	1.16	1.15
ΔC_{POPE}	−0.03	−0.03	−0.02	−0.02	−0.02	−0.02	−0.02	−0.02	−0.03	−0.03
ΔC_{EIE}	−1.04	−0.87	−0.74	−0.38	−0.72	−0.76	−1.41	−0.68	−2.21	−1.90
ΔC_{CEIE}	0.03	−0.01	0.01	0.04	−0.04	−0.04	−0.38	−0.02	−0.08	−0.04
CO_2 total	0.61	0.45	0.48	0.91	0.80	0.37	−0.08	−0.08	−1.16	−0.82
year	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
ΔC_{GPE}	0.57	0.96	0.88	0.92	0.94	1.11	1.48	1.61	0.24	1.34
ΔC_{POPE}	−0.06	−0.03	−0.03	−0.03	−0.04	−0.03	−0.02	−0.01	−0.03	−0.05
ΔC_{EIE}	−0.86	−1.60	0.32	−0.02	−0.82	−0.41	−0.63	−0.81	−1.92	−0.09
ΔC_{CEIE}	0.02	−0.05	−0.04	0.13	−0.05	0.10	−0.03	0.02	−0.36	0.13
CO_2 total	−0.32	−0.71	1.14	1.00	0.03	0.77	0.80	0.81	−2.07	1.33

average yearly contribution of approximately 1.20 $MtCO_2$. The population effect showed a consistently slight negative contribution to CO_2 emissions, ranging from −0.03 to −0.06 $MtCO_2$ annually. This suggests that changes in population size had a minimal yet steady mitigating effect on emissions, likely due to Hungary's relatively stable population growth. Energy intensity improvements were significant in reducing CO_2 emissions. The most notable reductions occurred in 2010 (−2.21 $MtCO_2$) and 2011 (−1.90 $MtCO_2$), reflecting substantial gains in energy efficiency within the transportation sector. Over the two decades, the average annual reduction due to energy intensity improvements was about −0.92 $MtCO_2$, indicating persistent and practical efforts to reduce energy consumption per unit of GDP. The carbon emission intensity effect showed minor fluctuations, with both positive and negative contributions. The highest reduction was in 2008 (−0.38 $MtCO_2$), whereas slight increases occurred sporadically, such as in 2004 (0.01 $MtCO_2$) and 2015 (0.13 $MtCO_2$). On average, this effect had a negligible impact, suggesting that the carbon content of energy sources used in transportation did not change dramatically.

4.2 Periodic decomposition analysis

Fig. 1 shows the results of decomposition using the Additive LMDI method through four time periods, each five years from 2001.

4.2.1 2001-2006

In this period, the economic activity effect (ΔC_{GPE}) was the primary driver of emissions, contributing 7.22 $MtCO_2$. Energy intensity improvements (ΔC_{EIE}) significantly offset this increase, reducing emissions by 3.874 $MtCO_2$. The population effect was minor (−0.125 $MtCO_2$), and the carbon emission intensity effect was almost neutral (0.037 $MtCO_2$).

4.2.2 2006-2011

The economic activity effect remained substantial (ΔC_{GPE} 5.549 $MtCO_2$), but enhanced energy efficiency (ΔC_{EIE} −6.681 $MtCO_2$) led to a net reduction in emissions.

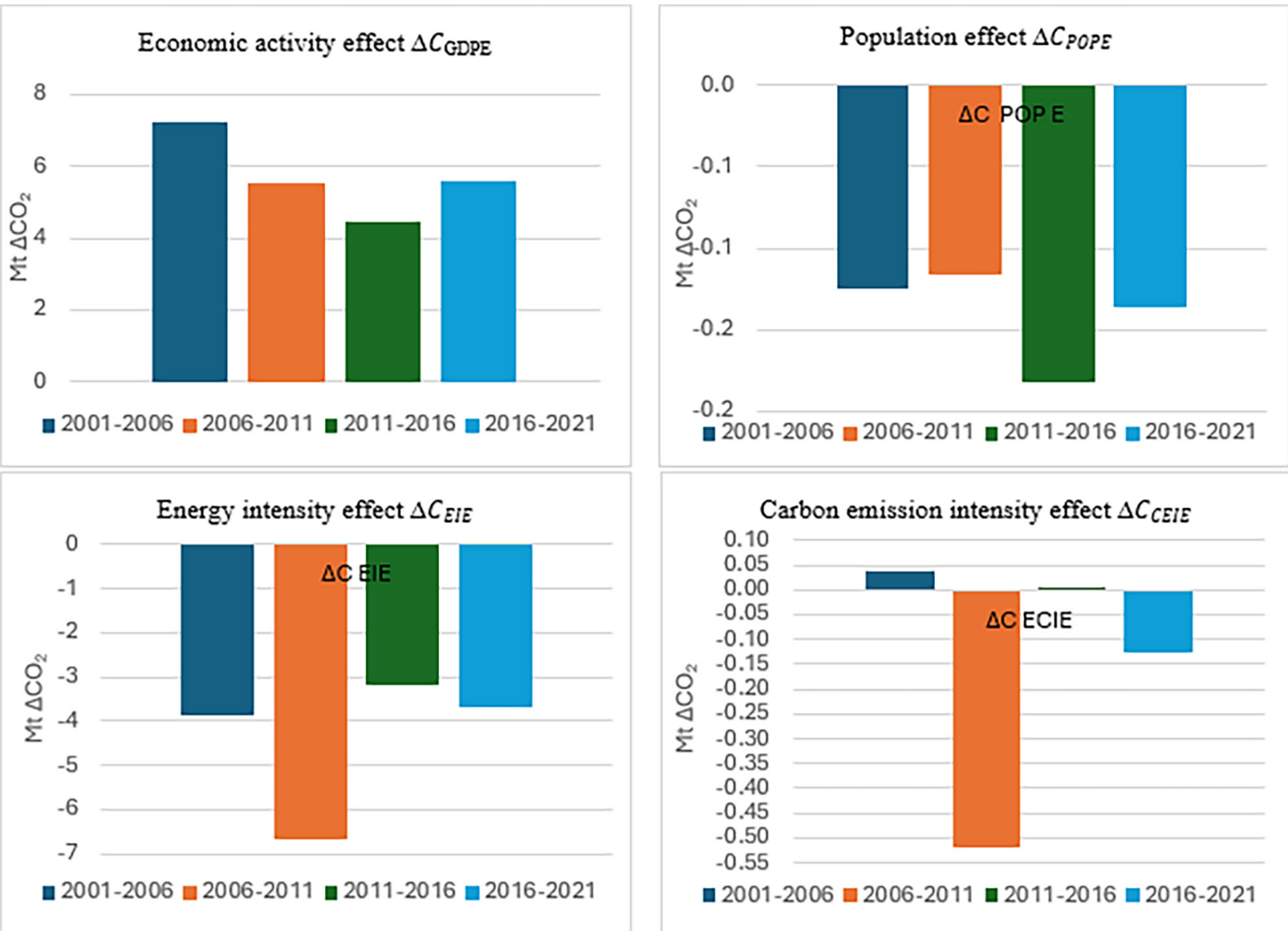

Fig. 1 Decomposition of CO_2 results in four time periods ($MtCO_2$)

The population effect continued its slight negative trend (−0.116 $MtCO_2$), while the carbon emission intensity effect showed a notable reduction (−0.519 $MtCO_2$).

4.2.3 2011-2016

During this period, economic activities continued to drive emissions (ΔC_{GPE} 4.471 $MtCO_2$), though at a reduced rate. Energy intensity improvements (ΔC_{EIE} −3.167 $MtCO_2$) and the population effect (−0.181 $MtCO_2$) again contributed to lowering emissions. The carbon emission intensity effect was minimal (0.005 $MtCO_2$).

4.2.4 2016-2021

Economic activity's impact in the most recent period increased (ΔC_{GPE}: 5.612 $MtCO_2$), reflecting robust economic growth. However, continued energy intensity improvements (ΔC_{EIE}: −3.708 $MtCO_2$) and a hostile population effect (−0.136 $MtCO_2$) helped mitigate this increase. The carbon emission intensity effect also contributed to the reduction (−0.126 $MtCO_2$), indicating progress in adopting cleaner energy technologies.

4.3 Discussion

According to the data in Table 1 and Fig. 2, the decomposition analysis reveals that economic activity was the predominant factor driving CO_2 emissions in Hungary's transportation sector from 2001 to 2021. However, substantial improvements in energy intensity have played a crucial role in offsetting these increases. The energy intensity effect consistently contributed to reducing emissions, particularly during periods of economic growth, demonstrating the effectiveness of energy efficiency measures. The population effect, while negative, had a minor impact on emissions, suggesting that population changes had a relatively small influence on overall CO_2 emissions. The carbon emission intensity effect fluctuated but generally showed a trend towards reducing emissions, reflecting gradual shifts towards cleaner energy sources and technologies. The findings indicate that while economic growth has increased transportation-related CO_2 emissions, energy efficiency, and carbon intensity improvements have effectively mitigated these increases. Future policies should continue to focus on enhancing energy efficiency and promoting low-carbon technologies to sustain the reduction in CO_2 emissions amidst economic growth.

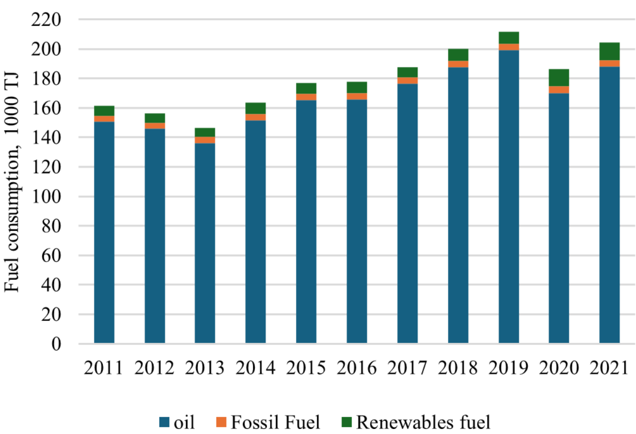

Fig. 2 Consumption of fuel in Hungary between 2011 and 2021

Analyzing the data from 2011 to 2021, we observe significant changes in the consumption patterns of fossil fuels, electric energy, and renewable fuels in Hungary's transportation sector (see Fig. 2). Fossil fuel consumption has shown variability over the decade. In 2011, the consumption was 150,485 TJ, decreasing to its lowest point in 2013 at 136,029 TJ. However, after 2013, there was a marked increase, peaking at 198,950 TJ in 2019. This rise could be attributed to economic growth, increased vehicle ownership, and possibly limited implementation of effective energy policies during these years.

In 2020, there was a notable drop to 170,150 TJ, likely due to the impact of the COVID-19 pandemic on transportation and industrial activities. By 2021, consumption rebounded to 187,897 TJ, indicating a recovery in transportation activities. Electric energy consumption remained relatively stable, with slight increases over the years. Starting at 4,021 TJ in 2011, it saw minor fluctuations, reaching 4,481 TJ by 2021. This stability suggests that integrating electric vehicles (EVs) and related infrastructure in Hungary has been gradual. Despite the global push towards electrification, Hungary's progress in adopting electric energy in transportation seems incremental rather than exponential. Renewable fuels have shown a more dynamic growth pattern. Beginning at 6,675 TJ in 2011, their consumption dipped to 5,728 TJ in 2013, like fossil fuels. Post 2013, there was a steady increase, culminating in a significant rise to 11,686 units in 2020 and slightly more to 11,931 units in 2021. This trend reflects Hungary's growing commitment to incorporating renewable energy sources in its transportation sector, aligning with global environmental goals.

Fig. 3 illustrates CO_2 emissions by sector in Hungary for 2021. The transport sector is the most significant contributor, accounting for 30% of total emissions. This is followed by electricity and heat production (22%), residential

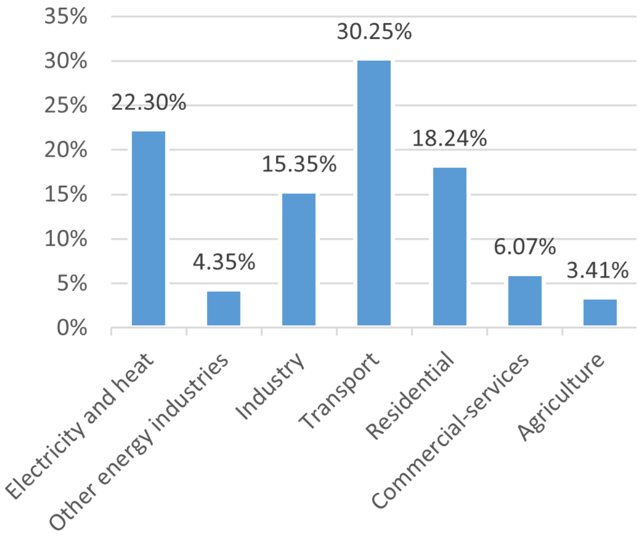

Fig. 3 CO_2 emissions by sector in Hungary in 2021

(18%), industry (16%), commercial services (11%), agriculture (4%), and other minor sources. The transport sector's dominance in CO_2 emissions (30%) underscores the critical need for interventions targeting this sector. Given its high reliance on fossil fuels, as seen from the consumption data, transitioning to electric and renewable energy sources is crucial for reducing emissions. Accounting for 22% of emissions, the residential (18%) and industry (16%) sectors are also significant contributors to CO_2 emissions.

Fig. 4 shows the total final energy consumption by sector in Hungary for 2021. The residential sector leads with 34%, followed by transport (26%), industry (25%), commercial services (11%), and agriculture (4%). With the highest energy consumption (34%), the residential sector offers significant energy savings and emission reduction

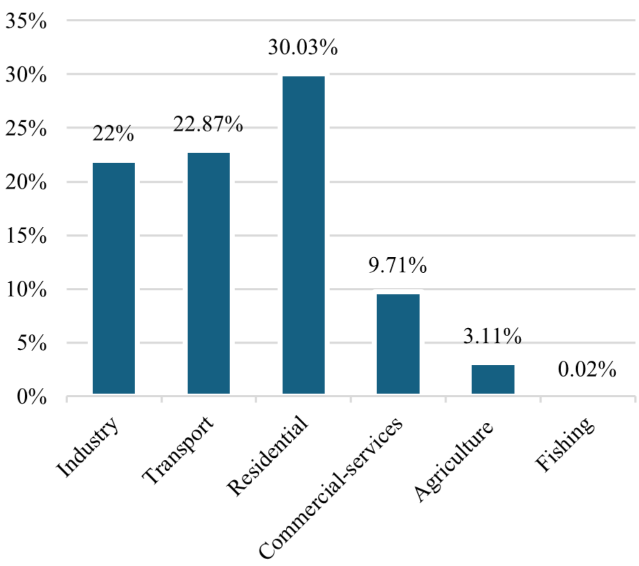

Fig. 4 Energy consumption by sector in Hungary in 2021

opportunities through energy-efficient appliances, better insulation, and increased use of renewable energy sources. Despite being the largest emitter, the transport sector consumes less energy (26%) than the residential sector. This discrepancy highlights the higher emission intensity of the transport sector due to its heavy reliance on fossil fuels.

5 Conclusions

The decomposition analysis of CO_2 emissions in Hungary's transportation sector from 2001 to 2021 highlights that economic activity is the primary driver of emissions, with significant fluctuations correlating with periods of economic growth and recession. Energy intensity improvements have consistently contributed to reducing emissions, demonstrating the effectiveness of energy efficiency measures in the transportation sector. The impact of population changes on emissions has been minimal. In contrast, the carbon emission intensity effect has shown fluctuations with a general trend towards reduction, indicating progress in adopting cleaner energy sources and technologies. The findings suggest that while economic growth has driven increases in transportation-related CO_2 emissions, improvements in energy efficiency and shifts towards cleaner energy sources have effectively mitigated these increases. Future policies should continue to focus on enhancing energy efficiency and promoting low-carbon technologies to sustain the reduction in CO_2 emissions amidst economic growth.

6 Recommendations and future work

This section outlines key recommendations to reduce CO_2 emissions in Hungary's transportation sector, focusing on energy efficiency, low-carbon technologies, and sustainable practices. These strategies aim to support future policy development and research for achieving low-carbon goals as follows:

1. Enhance Energy Efficiency: Implement policies that improve energy efficiency in the transportation sector, such as incentivizing energy-efficient vehicles and technologies.
2. Promote Low-Carbon Technologies: Invest in and encourage the adoption of low-carbon technologies, including electric and hybrid vehicles, to reduce the carbon intensity of the transportation sector.
3. Support Renewable Energy: Increase the integration of renewable energy sources in the transportation sector, ensuring a steady transition from fossil fuels to sustainable energy options.

4. Economic Incentives: Develop economic incentives and subsidies to support the transition to energy-efficient and low-carbon transportation options, making them more accessible and affordable.
5. Public Awareness Campaigns: Conduct public awareness campaigns to educate citizens on the benefits of sustainable transportation practices and the importance of reducing CO_2 emissions.
6. Monitor and Evaluate: Establish a robust monitoring and evaluation framework to assess the effectiveness of implemented policies and make necessary adjustments based on empirical data and trends.
7. International Collaboration: Engage in international collaborations to share best practices and leverage global advancements in sustainable transportation technologies and policies.

7 Limitations of study

The study has several limitations that should be noted. It relies on secondary data sources, with some gaps addressed through interpolation, which may introduce uncertainty. The analysis focuses on broad macro-level factors, such as economic activity and population, without fully considering the impact of technological advancements or policy interventions. Additionally, the study covers the period from 2001 to 2021, which may miss recent trends, such as the growth of electric vehicles and renewable energy adoption. Future research could focus on detailed modeling of technological changes, extend the analysis with more recent data, and explore cross-country comparisons within Central Europe.

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