
Energy-Related Carbon Dioxide Emissions from Economic Growth in Poland: Decomposition and Decoupling Analysis

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Abstract:

Purpose: This paper addresses the conditions behind energy-related carbon dioxide emissions in Poland following its accession to the European Union. The study analyzed some energy, fossil fuel, economic, and environmental indicators, such as energy use, CO₂ emissions, driving factors and decoupling elasticity status.

Design/Methodology/Approach: This article is a contribution to the study of factors influencing climate change related to energy use. The analysis was based on descriptive statistics and decomposition methods. The Logarithmic Mean Divisia Index (LMDI), one of the most commonly used forms of index decomposition and index decoupling analysis, was used to identify the determinants of carbon dioxide emissions.

Findings: As the results showed, between 2004 and 2020, energy consumption in Poland grew at an average annual rate of 0.8% while fossil-fuel carbon emissions declined at 0.7% per year. Energy intensity was found to be the key force behind the reduction in CO₂ emissions, whereas rapid economic growth was the main driver of CO₂ emissions. While other factors, i.e. carbon intensity, energy mix and population, also contributed to reducing the emissions, they had a much smaller if not marginal effect. In turn, the decoupling elasticity analysis showed that Poland mostly witnessed strong decoupling states, which means a strong decoupling of CO₂ emissions from economic growth. Furthermore, it follows from the decoupling analysis that strong decoupling statuses prevailed throughout the study period, suggesting that the changes in the factors considered significantly contributed to reducing CO₂ emissions. However, the decoupling elasticity indices reveal the presence of an adverse trend. The above means that Poland witnesses a decline both in the strength of decoupling emissions from economic growth, and in the efficiency of policies and measures designed to reduce CO₂ emissions.

Practical implications: These considerations could help develop an active energy policy focused on climate neutrality.

Originality/value: This document broadens and updates knowledge on the determinants of CO₂ emissions in Poland. Also, these findings can provide grounds for accelerating energy transformation processes in Poland.

Keywords: CO₂ emissions, Poland, decomposition analysis, decoupling analysis.

JEL Classification: O44, P18, Q44.

Paper Type: Research study.

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1. Introduction

Some of the most important environmental challenges facing humanity today is the progressing global warming resulting from increased atmospheric emissions of greenhouse gases (GHGs), especially including carbon dioxide (CO₂) which contributes more than 60% to the greenhouse effect (Ozturk and Acaravci 2010; Chen *et al.*, 2018).

As confirmed by numerous studies and publications, human economic activities are a key source of greenhouse gases and CO₂ emissions are strongly linked primarily to the use of various fossil fuels and economic growth (Jiang *et al.*, 2019; Wang and Yan, 2022; Lv *et al.*, 2019).

The need to counteract climate change caused by excessive GHG emissions and to implement sustainable development principles is an increasingly urgent matter expressly addressed in Sustainable Development Goals (SDGs) and in the Paris climate agreement entered into in 2015 by 195 countries at the United Nations Framework Convention on Climate Change (COP21, 2015).

The key goal provided for therein is to limit global warming to 1.5–2.0°C by the end of this century (IPPC, 2018). Meeting that objective requires a considerable reduction in GHG emissions which, however, is not easy because their growth is strictly related to economic development. Therefore, the core issue in today's debates within political and academic communities is the degree to which emissions can be decoupled from economic growth (Lundquist, 2021; Pociovalisteanu *et al.*, 2010).

Decoupling emissions from economic growth is believed to be the key path of sustainable development which prevents environmental degradation with no adverse effects on economic development. However, it is extremely difficult to entirely decouple emissions from economic growth. It would be only possible in a situation where an increase in economic performance is accompanied by an absolute quantitative drop in emissions.

The scenario of compatibility between economic growth and reduced emissions is possible both theoretically and practically, as illustrated by numerous examples. In order for this to happen, innovative technologies must be deployed together with an effective economic and fiscal policy, adequate legal regulations, education efforts, and a reorientation of lifestyle focused on implementing the principles of low-carbon living.

However, it does not mean that decoupling emissions from growth—as one of the key paths to sustainable development—is not called into question. It is surrounded by different controversies, with negative economic growth being viewed as an enabler of environmental goals. Also, these controversies gave rise to a broad debate

on new terms such as “green growth,” “de-growth” and “agrowth” (Lundquist, 2021). Generally, even though each of these three approaches supports the concern for environmental sustainability, they differ in how they view the role of economic growth in attaining that goal.

“Green growth” supporters suggest that economic growth can be sustainable, whereas advocates of “de-growth” propose a fundamental shift away from seeking economic growth. On the other hand, supporters of “agrowth” seek both economic growth and environmental sustainability through a combination of political interventions and changes to economic practices (Van den Bergh, 2011; 2012; Kallis, 2011).

Decoupling is at the core of the debate on sustainable growth, which is expressed by a considerable number of research projects launched to investigate the decoupling trends and to identify the factors that affect them. However, as Lundquist (2021) emphasizes, the potential for a total decoupling of emissions remains unclear despite extensive research efforts.

The results of empirical studies on emissions decoupling differ between the countries, periods, pollution types and accounting methods. Also, they depend on the views on each country’s potential for decoupling. However, generally, the key conclusion is that the current levels of decoupling indicators are below what is needed to enable sustainable growth (Lundquist, 2021).

In some emerging economies, the growth rate of CO₂ emissions between 1990 and 2020 was noticeably above the worldwide average (World Bank data, 2023). For instance, it was 492.6%, 435.8%, 285.1%, 219.4% and 317.9% in China, India, Turkey, Brazil and Iran, respectively (World Bank data, 2023).

In turn, Poland saw a 35.7% decline in CO₂ emissions (without LULUCF), from 472.0 million tons in 1989 (base year) to 303.5 million tons in 2020, and a nearly 17% drop in emissions per capita, from 9.2 t to 7.7 t (World Bank data, 2023; UNFCCC, 2023). Despite the considerable reduction in CO₂ emissions, the most recent per-capita statistics for Poland continue to be above the European Union average level of 6.1 t.

Poland remains one of the largest CO₂ emitters, and is ranked second (2020) after Germany (EEA, 2023). These emissions mostly come from the energy sector, an important and complex part of the national economy. Also, Poland largely depends on coal in addressing its energy demand (coal-fired power stations account for most of the national production of electricity).

In addition to coal, Poland owns large reserves of natural gas used in producing both electricity and heat. Despite the quite dynamically developing sector of renewables in which wind and solar energy have an increasingly greater share in national

production of electricity fossil fuels continue to be the main source of energy and thus the main source of greenhouse gas emissions.

In view of the above, based on 2004-2020 data (a period where the Polish economy witnessed rapid development), this paper investigates the contribution of adjustments to the energy mix, technological progress, economic growth, and population change to CO₂ emissions.

Second, in addition to analyzing CO₂ emissions, trends and causative factors, the next part of the paper addresses the decoupling status, the decoupling effort and the efficiency of economic growth and CO₂ emission policies by decomposing the decoupling indicator with a combination of the LMDI method and the Tapio model.

This study contributes to research on relationships between carbon emissions and economic growth in two major aspects. Firstly, this paper built a comprehensive consistent framework by combining the Kaya identity, the Tapio decoupling model and the LMDI method to investigate the relationship between CO₂ emissions and economic growth in Poland, the second largest carbon emitter in the EU.

Secondly, the Tapio decoupling model was chosen to identify the decoupling states. The results of this analysis can contribute to a broader debate on the Polish energy policy whose instruments should place greater focus on significantly reducing the use of fossil fuels in energy production, and on intensifying the efforts made to accelerate the development of renewables.

2. Literature Review

There is ample literature on decoupling growth from emissions CO₂. This topic sparks growing interest from scientists because of the increasing global warming mostly caused by CO₂ emissions which threaten the global climate and considerably affect both the environment and human health (Wang and Su, 2020; Li and Jiang 2017; Thalassinos *et al.*, 2022).

The decoupling of economic development from CO₂ emissions has become the subject matter of a number of studies, especially in the last decades (Pao and Chen, 2019; Wang *et al.*, 2019). The OECD and Tapio models are the most widely used among the variety of decoupling approaches (Chen *et al.*, 2018; Wang *et al.*, 2019; Wu, 2018; Xie *et al.*, 2019).

In the vast literature on decoupling processes, most studies focus on identifying the decoupling states between CO₂ emissions and economic growth, and on examining the factors affecting the decoupling states.

Research on decoupling processes is conducted from different angles and at different levels of data aggregation, e.g., at the global, regional, country group, country, sector

and sub-sector levels. Chen *et al.* (2018) used the Tapio model to examine the decoupling relationships between influencing factors and CO₂ emissions in OECD countries from 2001 to 2015.

The results indicate that the decoupling states between fossil fuel CO₂ intensity, energy mix, energy intensity, GDP per capita, population size and CO₂ emissions during that period are: recessive decoupling, weak negative decoupling, and strong decoupling, respectively. In turn, Dai *et al.* (2016) examined the occurrence of decoupling between economic growth and energy-related CO₂ emissions in BRICS countries.

It follows from their research that Brazil, Russia and South Africa experienced five decoupling statuses during the study period. However, only three of them occurred in China and India. Moutinho *et al.* (2020) used the Tapio model and the decoupling effort analysis in a study investigating the underlying driving forces behind energy-related per-capita CO₂ emissions over the 1993-2017 period in a panel of 16 South American countries.

Their study found that this group of countries shifted from the weak state to the strong decoupling state after the signing of the Kyoto Protocol. In addition, it demonstrated that “strong decoupling” was mainly achieved due to a group of economic drivers, with the negative changes in energy intensity and in domestic investment playing the strongest role in reducing CO₂ emissions per capita.

In turn, Zhang *et al.* (2020) analyzed the decoupling elasticity between carbon dioxide, GDP and energy consumption in China and ASEAN countries over the period 1990-2014. As shown in their study, in light of the Tapio model, only three decoupling statuses occurred during the period considered, i.e., weak decoupling, expansive coupling, and expansive negative decoupling.

Ozturk *et al.* (2021) examined the decoupling of CO₂ emissions from economic growth for Pakistan, India and China over the period 1990-2014. The results of the Tapio elasticity analysis showed that these countries experienced a decoupling of environmental impacts from economic growth.

However, relatively speaking, it was a costly negative decoupling in Pakistan; mostly weak decoupling and costly coupling in India; and a weak decoupling in China over many years. In addition, the decoupling elasticity analysis showed that energy intensity was a key enabler of decoupling in these countries, while population, wealth and energy mix undermined its progress.

In turn, Li and Jiang (2020) attempted to study the impact of R&D on reducing environmental pressures based on an empirical analysis of the world’s six largest carbon emitters. The main results from the Tapio model and the LMDI technique

showed that over the period 1996-2014, the developed countries enjoyed better and more stable decoupling statuses than developing ones.

Another conclusion is that the effect of per-capita R&D expenditure was the main inhibitor of decoupling CO₂ emissions from economic development. However, the energy intensity effect and R&D efficiency effect related to technological progress were the main driving forces for the decoupling process.

A number of studies have also been carried out in EU countries. Papież *et al.* (2021) analyzed the impact of EU energy policy on decoupling GHG emissions from economic growth between 1996 and 2017. They relied on the Tapio model in carrying out two types of GHG measurements, i.e. production-based and consumption-based accounting.

Although the results show a decoupling of emissions from economic growth in almost all countries, regardless of the type of GHG measurement, it occurs faster in the case of production-based emissions. As regards EU countries (EU-15), the decoupling processes were analyzed by Madaleno and Moutinho (2018) who examined the decoupling states and decoupling effort in the context of changes in the evolution of carbon emissions over the period 1995–2014.

The study showed that the most significant CO₂ reductions occurred in the years following the signing of Kyoto commitments, due to a negative and significant impact of carbon intensity of petroleum products, energy intensity and conversion efficiency. Furthermore, the authors found that the effects of flexibility and of the decoupling effort were not controlled for by internal CO₂ factors.

Also, the drivers of CO₂ emissions from electricity generation and decoupling processes in the EU were analyzed by Karmellos *et al.* (2021). According to their results, in the last five years of the study period (2000-2018), a significant number of EU countries moved into a state of strong decoupling, implying successful implementation of relevant energy and environmental policies.

Another research among EU countries was carried out by Diakoulaki and Mandaraka (2007). They used the decomposition analysis to explain the changes in industrial CO₂ emissions, and to comparatively evaluate the progress made in EU-14 countries in decoupling emissions from industrial growth between 1990 and 2003. The decomposition results they obtained were further used to assess the real efforts undertaken in each country and their effectiveness.

On these grounds, the authors concluded that most EU countries made a significant (though not always sufficient) decoupling effort, but no significant acceleration was observed in the post-Kyoto period.

Wang *et al.* (2018) compared the decoupling performance between China and the U.S. They quantified the decoupling statuses using the Tapio indicator, and decomposed the decoupling index to explore the driving factors behind the decoupling using the LMDI technique. They found that in most years between 2000 and 2014, China experienced expansive coupling and weak decoupling whereas the U.S. mostly saw weak and strong decoupling.

Moreover, the authors proved that income and population had a restrictive effect on decoupling, whereas energy intensity and energy mix effects promoted the decoupling process. In addition, the carbon intensity effect exerted negative and positive effects on decoupling in China and the U.S., respectively. Changes in decoupling processes and energy-related CO₂ emissions in the U.S. were also analyzed by Jiang and Li (2017).

In light of the decoupling effort index, they found that the lack of decoupling prevailed in most of the surveyed years of the 1990-2014 period, whereas strong decoupling was the least frequent state. In turn, Wang and Wang (2019) analyzed the decoupling states and the effectiveness of decoupling efforts in the U.S. from 1998 to 2015. Their study used the Tapio model and the decoupling effort model.

The analysis of decoupling efforts revealed that energy intensity, R&D intensity, R&D efficiency and sectoral CO₂ intensity contributed to decoupling economic growth from carbon emission, whereas investment intensity, population size and sectoral energy mix did not. Freitas and Kaneko (2011) used the OECD method in examining the occurrence of decoupling between growth rates in economic activity and CO₂ emissions from energy consumption in Brazil between 2004 and 2009.

In general, they identified several periods of relative decoupling in Brazil, but also noted that the decoupling processes did not occur smoothly. Based on the Tapio model, Wang *et al.* (2015) presented a new way to study the change in decoupling rates in China, making it possible to answer the question: why does the decoupling rate change over time? Their research found that only three states of CO₂-GDP decoupling (weak and expansive decoupling and negative expansive decoupling) occurred during the period studied.

In addition, the researchers showed that the energy-GDP decoupling effect played a significant role in changing the CO₂-GDP decoupling rate, followed by the energy-fossil decoupling effect. In contrast, the CO₂-energy decoupling effect played a minor role in changing the CO₂-GDP decoupling rate. Zhang and Da (2015) introduced the Tapio index to analyze the decoupling relationship between CO₂ emissions and economic growth in China between 1996 and 2010.

The results indicate that a relative decoupling effect between carbon emissions and economic growth was recorded in most years during the study period. This suggests that the reduction effect of CO₂ emission inhibitors was less than the driving effect

of economic growth, and the economy grew with increased carbon emissions. Xu *et al.* (2017) used the Tapio model in decomposing the indicator of the decoupling of fossil-energy carbon emissions from economic growth in China over the period 1995-2012.

Their research showed that decoupling varied due to changes in economic growth and energy intensity between different sub-periods. The economic output effect significantly boosted the decoupling, whereas the energy intensity effect strongly decreased it. In turn, a comparative analysis across different sectors and industrial sub-sectors revealed that industrial growth determined the status of decoupling CO₂ emissions from economic growth.

In addition, energy-intensive sub-sectors strongly contributed to the decoupling of carbon emissions, whereas non-energy-intensive ones had a relatively slight impact on it. In turn, Engo (2018) used the Tapio model to assess the decoupling and factors that influenced the relationship between economic growth and CO₂ emissions in Cameroonian industrial and service sectors between 1990 and 2015.

The results showed that Cameroon experienced weak decoupling throughout the study period because weak and strong negative decoupling and strong decoupling were witnessed in most years, whereas strong decoupling was recorded in only three periods.

Roinioti and Koroneos (2017) used the decomposition technique and the decoupling index in identifying the driving forces of energy-related CO₂ emissions in the Greek economy between 2003 and 2013. Their research shows that the effects of decoupling varied over time. Weak decoupling was experienced in most years, whereas strong decoupling was recorded in only three periods.

Moreover, as a result of the recession, no decoupling was found in the last years of the period considered. Yasmeen and Tan (2021) used the Tapio method in analyzing the decoupling relation between environmental degradation, energy use, and economic progress in Pakistan based on data from 1972-2017. Based on the decoupling analysis, they identified the decoupling linkage between energy use and CO₂ emissions (growth negative decoupling).

Conversely, a weak decoupling relation was observed between carbon emissions and economic progress. Furthermore, a similar weak decoupling relationship was found to exist between energy use and economic progress.

Also many studies have focused on the transport sector. Tapio (2005) presented a theoretical framework for decoupling, and applied it in analyzing the relationships between GDP, traffic volumes and CO₂ emissions from transport in EU countries between 1970 and 2001.

Aggregate data showed a shift from expansive negative decoupling to expansive coupling in passenger transport, and a shift from weak decoupling to expansive negative decoupling in freight transport.

In addition, he discovered a weak decoupling of transport CO₂ emissions from GDP. Next, Engo (2019) examined the decoupling relationship between energy-related CO₂ emissions and economic growth in the Cameroonian transportation sector between 1990 and 2016. The decoupling rates were decomposed into five factors with four fuels consumed in this sector.

The empirical results derived from the Tapio model showed that only four decoupling states emerged during the study period, i.e. weak and strong decoupling, weak negative decoupling and strong negative decoupling. Meanwhile, scale effects, the energy mix effect and the energy intensity effect prevented decoupling, while the economic structure effect played an important role in decoupling.

In the transport sector, similar research was also conducted by Zhao *et al.* (2016) who analyzed the main drivers of energy-related CO₂ emissions in Guangdong, China's richest and most populous province.

The results showed that in general, the decoupling level between transport output and CO₂ emissions during the period 1995–2012 was relatively low. Also, the optimization of the tertiary industry structure was the main inhibitor of CO₂ increase.

However, the province experienced rapid growth of GDP per capita and population, which was more powerful at boosting CO₂ and resulted in the elasticity index rising directly. Moreover, the research shows that reducing energy intensity can be one of the most important ways to increase the decoupling effort. In turn, Li *et al.* (2019) examined the relationship between the development of the transport sector and its CO₂ emissions from the perspective of 30 Chinese provinces.

The results showed that underdeveloped provinces were more likely to present a weak decoupling state than developed and coastal ones. The researchers also found that income level was the major influential factor limiting the development of decoupling in the transport sector, and that the population scale played a very small negative role in the development of decoupling.

Decoupling processes have also been explored in the agricultural sector. Han *et al.* (2018) investigated the interactions between agricultural carbon emissions and growth in 30 Chinese provinces from 1997 to 2015. Based on this data, the coupling and decoupling effects of CO₂ emissions and the underlying driving factors were examined using the Tapio model.

From these studies, it appears that at the regional scale, the degree of coupling between CO₂ emissions and agricultural growth was high in the central region of

China and low in the western region. At the provincial scale, the coupling effects of carbon emissions exhibited four levels, minimal, low, moderate, and high coupling.

In turn, in most other provinces, CO₂-growth relations indicated a weak decoupling state. The relationship between agricultural development and energy-driven agricultural CO₂ emissions was also studied by Hossain and Chen (2020). Their results showed that the agricultural sector of Bangladesh was strongly and weakly decoupled from agricultural growth in most years of the period 1990-2017.

Research in agriculture was also carried out by Huang and Zhang (2022) in Heilongjiang, China's largest grain-producing province. The study estimated its grain production-induced CO₂ emissions, and examined the nexus between grain production and emissions from 2000 to 2018, using decoupling and decomposition analyses.

The decoupling analysis showed that weak decoupling occurred for half of the study period; however, the decoupling and coupling states occurred alternately, and there was no definite evolving path from coupling to decoupling. In turn, Liu and Feng (2021) attempted to explain the mechanism behind the decoupling of economic growth and CO₂ emissions in the agricultural sector in mainland China from 2005 to 2016.

The results obtained from the Tapio model showed that the decoupling efficiency was not perfect. Their study found that the most important factors affecting the decoupling status were investment and investment efficiency, and the main obstacle was investment in productivity growth being greater than investments in energy saving and carbon reduction. In addition, the decoupling status and investment orientation of decoupling activities varied across regions.

At the national level, the dominant decoupling status changed from weak to expansive. Luo *et al.* (2017) also studied the decoupling of carbon emissions from agricultural growth in China from 1997 to 2014. Their results indicate that decoupling in the agricultural sector generally followed a favorable trend. Strong negative decoupling prevailed in the early years of the period studied, while weak or strong decoupling was recorded in subsequent years.

Also, a significant number of studies have been carried out in Chinese provinces and counties. Based on the Tapio model and the LMDI method, Huang *et al.* (2021) analyzed the evolution of energy-related carbon emissions as well as the decoupling relationship and its driving factors in the Qinghai province between 1997 and 2017.

The results indicated that the relationship between CO₂ emissions and economic growth was represented by four types: weak and strong decoupling; expansion negative decoupling; and expansion coupling. Among them, strong decoupling was achieved in only five sub-periods. Qin *et al.* (2022) used the Tapio index to

decompose the driving forces of decoupling, and measured the states of the sector's decoupling from carbon emissions in the Chinese province of Xinjiang between 2000 and 2017.

These studies found the occurrence of four decoupling states in this period, i.e. weak decoupling, expansive coupling, expansive negative decoupling and strong negative decoupling. Most industries in this province failed to reach the ideal decoupling state, with GDP per capita elasticity having the major inhibitory effect on the decoupling of carbon emissions.

In turn, energy intensity elasticity was a major driver of decoupling. Based on the Tapio model, Shi *et al.* (2022) analyzed the decoupling status of CO₂ emissions from economic growth in 16 districts of Beijing during the period of 2006-2017.

Their decoupling states demonstrated some phased improvement characteristics. In 2017, over 93% of districts achieved a decoupling state (whether strong or weak); 37% districts achieved strong decoupling, the most desirable state.

The authors believe these favorable changes to be caused by urban functional zones and the transformation of the industrial structure, as well as by the direct impact of the national environmental policy. In turn, You *et al.* (2021) analyzed the decoupling relationship between coal-related CO₂ emissions and economic growth in China from national and provincial perspectives between 1997 and 2016 through the Tapio index.

The results reflect the inverted "U" shape of the decoupling curve, and demonstrate that the vast majority of provinces achieved a strong decoupling of economic growth from coal-related carbon emissions by 2016. Furthermore, they prove that activity and energy-intensity effects were the dominant factors driving and curbing the increase in the decoupling indicator, respectively.

Wang *et al.* (2013) used the decoupling effort index to analyze the contribution of factors which influence energy-related CO₂ emissions in the Chinese province of Jiangsu over the period 1995-2009. The results show that during the period considered, strong decoupling was recorded only twice, and a weak decoupling effect prevailed in most of the remaining time intervals.

The decoupling analyses have also been frequently applied to a number of other sectors and sub-sectors of the Chinese economy. Li *et al.* (2015) studied the decoupling relationship and its influencing factors between economic growth and CO₂ emissions in China in the manufacturing and household sectors over the period 1996-2012.

The results showed that the decoupling status of the manufacturing sector remained mainly at the level of weak decoupling, while that of households generally indicated

strong decoupling. Luo *et al.* (2022) exploited the Tapio method to analyze the decoupling processes in 28 Chinese industries between 2002 and 2017. In these sectors, economic growth and CO₂ emissions were slowly decoupling.

In addition, researchers proved that energy intensity promoted the decoupling, whereas economic growth had an opposite effect. Other factors showed little impact on the decoupling of CO₂ emissions. Wang *et al.* (2020) constructed a decoupling effort index for the Chinese iron and steel industry.

Based on the results, they found that the decoupling efforts of the industry gradually changed from weak to strong, and that environmental regulations and technological developments particularly contributed to decoupling. In turn, Wan *et al.* (2016) used the Tapio method in investigating the decoupling relationship between carbon emissions and economic growth of the equipment manufacturing industry in China from 2000 to 2014.

Based on the results, the authors found this relationship to be weak, which means the industry grew faster than carbon emissions. The indicators of the industry's decoupling effort were all below 1.0, suggesting that weak decoupling prevailed during the study period.

Meanwhile, Wu *et al.* (2018) used the Tapio model to investigate the decoupling relationship between economic output and CO₂ in the Chinese construction industry from 2005 to 2015. Their results show that there existed an expansive decoupling relationship between growth and construction-related carbon emissions in most Chinese provinces during that period.

The researchers also found that economic output played the most significant role in inhibiting the decoupling at both national and provincial levels, while indirect carbon intensity was the main driver for promoting nationwide decoupling. In turn, Wang *et al.* (2022) explored the decoupling relationship between CO₂ emissions and power generation of the Chinese power sector and the driving factors of the decoupling index at provincial level between 2000 and 2019 using the Tapio and LMDI methods.

The decoupling analysis showed that five provinces achieved decoupling, and most provinces were in expansive coupling states in this period. The decomposition analysis also indicated that per-capita GDP and population size were responsible for inhibiting the decoupling process, whereas thermal power generation efficiency and electricity intensity promoted it.

In turn, Yang *et al.* (2018) used the LMDI method and the Tapio index to analyze the decoupling elasticity and effort index of industrial growth and CO₂ emissions in China from 1996 to 2015. They found that industry-related CO₂ emissions increased

about 1.5 times during the study period, with the manufacturing sector contributing the most, followed by the transport sector.

Furthermore, their research found that the manufacturing sector witnessed a reverse U of decoupling progression, moving from strong decoupling to weak decoupling and then turning back to strong decoupling.

In addition, they noted that expansive decoupling and strong negative decoupling emerged in the construction, transport and commercial sectors; provinces with high energy demand and heavy industry were able to achieve strong decoupling, while those with lower energy demand witnessed a clear trend towards decoupling.

3. Materials and Methods

3.1 LMDI Decomposition Analysis

The starting point for these analyses is the Kaya identity (1990) which links anthropogenic CO₂ emissions to demographic and economic parameters and technological aspects of energy (Yamaji *et al.*, 1991). Accordingly, total emissions can be expressed as the product of four factors, i.e. population, GDP per capita, energy intensity and CO₂ content of energy consumption.

Both the equation itself and its extended versions are widely used in analyzing and simulating global CO₂ emissions under the policy for fighting against global warming. In view of these analyses, the identification of driving forces behind energy-related CO₂ emissions in Poland relied on the Index Decomposition Analysis (IDA) which exhibits completeness (does not leave a residual term) and zero-value robustness, passes the time-reversal test (Roinioti and Koroneos, 2017; Baležentis *et al.*, 2011; Ang *et al.*, 1998; Hoekstra and van den Bergh, 2003), and offers a broader variety of indexes, their forms and mathematical specifications (Baležentis *et al.*, 2011).

Considering these properties, the study used the weighted logarithmic mean Divisia index (LMDI) developed by Ang *et al.* (1998). It is the most widely adopted and broadly recommended IDA method which proved its efficiency in a number of research projects addressing energy and emissions (Ang, 2004). This paper decomposed CO₂ emissions in Poland using a 5-factor model underpinned by the Kaya identity and the LMDI method in the following form:

$$CO_2 = \frac{CO_2}{FE} \times \frac{FE}{E} \times \frac{E}{GDP} \times \frac{GDP}{POP} \times POP \quad (1)$$

Using the following designations: $CI = \frac{CO_2}{FE}$, $ES = \frac{FE}{E}$, $EI = \frac{E}{GDP}$, $GP = \frac{GDP}{POP}$, $P = POP$ equation (1) can be written as follows:

$$CO_2 = CI \times ES \times EI \times GP \times P \quad (2)$$

Equation (1) links CO₂ emissions to the consumption of fossil fuels (FE), total supply of primary energy (E), economic activity measured as GDP per capita (GDP), and population size (POP). It provides a basis for identifying five determinants of carbon dioxide emissions:

$CI = CO_2/FE$: means CO₂ emissions per unit of fossil fuels (coal, oil, natural gas), i.e., measures the impact of emission intensity, and reflects technological and qualitative changes and the restructuring of the fuel mix;

$ES = FE/E$: means the impact of fossil fuel intensity, i.e. indicates the share of energy derived from fossil fuels in primary energy consumption, and indirectly reflects the penetration effect of emission-free energies;

$EI = E/GDP$: measures the impact of energy intensity of economic activity whose levels depend on energy use efficiency and economic structure;

$GP = GDP/POP$: represents the impact of economic growth or, in other words, the impact of the increase in wealth measured as gross domestic product per capita;

$P = POP$: means the population size whose growth entails an increase in energy consumption and in CO₂ emissions.

The indicators used in Equation (2) enable the analysis of changes in carbon dioxide emissions (ΔCO_2) from energy use in the context of impacts of five changing factors, i.e. emission intensity (ΔCI), substitution (structure) of fossil fuels (ΔES), energy intensity (ΔEI), economic growth (ΔGP) and population size (ΔP). Using the additive specification, the changes in CO₂ emissions in the context of impact of those changing factors can be presented as:

$$\Delta CO_2 = CO_2^t - CO_2^{t-1} = \Delta CI + \Delta ES + \Delta EI + \Delta GP + \Delta P \quad (3)$$

The use of LMDI translates into the following formulas (Equations 4–8) that specify the impact of each factor on changes in CO₂ emissions:

$$\Delta CI = L(CO_2^{t-1}, CO_2^t) \times \ln(CI^t / CI^{t-1}) = \frac{CO_2^t - CO_2^{t-1}}{\ln(CO_2^t / CO_2^{t-1})} \times \ln(CI^t / CI^{t-1}) \quad (4)$$

$$\Delta ES = L(CO_2^{t-1}, CO_2^t) \times \ln(ES^t / ES^{t-1}) = \frac{CO_2^t - CO_2^{t-1}}{\ln(CO_2^t / CO_2^{t-1})} \times \ln(ES^t / ES^{t-1}) \quad (5)$$

$$\Delta EI = L(CO_2^{t-1}, CO_2^t) \times \ln(EI^t / EI^{t-1}) = \frac{CO_2^t - CO_2^{t-1}}{\ln(CO_2^t / CO_2^{t-1})} \times \ln(EI^t / EI^{t-1}) \quad (6)$$

$$\Delta GP = L(CO_2^{t-1}, CO_2^t) \times \ln(GP^t / GP^{t-1}) = \frac{CO_2^t - CO_2^{t-1}}{\ln(CO_2^t / CO_2^{t-1})} \times \ln(GP^t / GP^{t-1}) \quad (7)$$

$$\Delta P = L(CO_2^{t-1}, CO_2^t) \times \ln(P^t/P^{t-1}) = \frac{CO_2^t - CO_2^{t-1}}{\ln(CO_2^t/CO_2^{t-1})} \times \ln(P^t/P^{t-1}) \quad (8)$$

where: $L(CO_2^{t-1}, CO_2^t)$ is the logarithmic average of two positive numbers is define as:

$$L(CO_2^{t-1}, CO_2^t) = \begin{cases} \frac{CO_2^t - CO_2^{t-1}}{\ln CO_2^t - \ln CO_2^{t-1}}, & CO_2^t \neq CO_2^{t-1} > 0 \\ CO_2^{t-1}, & CO_2^{t-1} = CO_2^t > 0 \end{cases} \quad (9)$$

3.2 Decoupling Elasticity Analysis

The decoupling elasticity index ($\varepsilon_{(CO_2, GDP)}$), developed by Tapio (2005) to assess the sensitivity of GDP to changes in CO₂ emissions, was used in identifying the decoupling states as per the formula below:

$$\varepsilon_{(CO_2, GDP)} = \frac{\Delta CO_2 / CO_2}{\Delta GDP / GDP} \quad (10)$$

Also, the decomposition results (Equation 3) can be combined with the decoupling index (Equation 10) to determine the impact of each factor on the relationship between economic growth and CO₂ emissions. It was measured by decomposing ($\varepsilon_{(CO_2, GDP)}$) as follows (Madaleno and Moutinho, 2018; Karakaya *et al.*, 2019):

$$\begin{aligned} \varepsilon_{(CO_2, GDP)} &= \frac{\Delta CO_2 / CO_2}{\Delta GDP / GDP} = \Delta CO_2 \times \frac{GDP}{CO_2 \times \Delta GDP} = (\Delta CI + \Delta ES + \Delta EI + \Delta GP + \Delta P) \times \\ \frac{GDP}{CO_2 \times \Delta GDP} &= \frac{CO_2}{\Delta GDP} + \frac{CO_2}{GDP} + \frac{CO_2}{\Delta GDP} + \frac{CO_2}{\Delta GDP} + \frac{CO_2}{\Delta GDP} = \varepsilon_{CI} + \varepsilon_{ES} + \varepsilon_{EI} + \varepsilon_{GP} + \varepsilon_P \end{aligned} \quad (11)$$

where: ε_{CI} , ε_{ES} , ε_{EI} , ε_{GP} , ε_P are the decoupling elasticity values of carbon intensity, energy structure, energy intensity, economic growth, and population growth, respectively. The decoupling states between economic growth and CO₂ emissions can be split in eight categories, as shown in Table 1.

Table 1. Descriptions of decoupling elasticity states (adapted from Tapio (2005)).

ΔCO_2	$\frac{\Delta GDP}{P}$	$\varepsilon_{(CO_2, GDP)}$	States	Descriptions
Decoupling				
< 0	> 0	$\varepsilon < 0$	strong decoupling (SD)	GDP grows and CO ₂ decreases
> 0	> 0	$0 < \varepsilon \leq 0.8$	weak decoupling (WD)	GDP and CO ₂ grow; GDP grows at a faster rate
< 0	< 0	$\varepsilon > 1.2$	recessive decoupling (RD)	GDP and CO ₂ decrease; CO ₂ decreases at a faster rate

2004	3800	100	2353	61.9	833	21.9	471	12.4	179	4.7	-36.6	-1.0	0.0	0.00
2005	3811	100	2268	59.5	892	23.4	497	13.1	186	4.9	-33.5	-0.9	0.5	0.01
2006	3858	100	2288	59.3	903	23.4	512	13.3	194	5.0	-40.3	-1.0	0.5	0.01
2007	4054	100	2389	58.9	969	23.9	527	13.0	208	5.1	-39.5	-1.0	0.6	0.01
2008	4037	100	2329	57.7	992	24.6	523	13.0	212	5.2	-19.3	-0.5	0.7	0.02
2009	4092	100	2298	56.2	1027	25.1	526	12.9	243	5.9	-2.4	-0.1	0.6	0.01
2010	3935	100	2155	54.8	1006	25.6	505	12.8	276	7.0	-7.9	-0.2	0.2	0.01
2011	4208	100	2292	54.5	1064	25.3	536	12.7	321	7.6	-4.9	-0.1	0.6	0.01
2012	4228	100	2287	54.1	1071	25.3	537	12.7	351	8.3	-18.9	-0.4	0.9	0.02
2013	4086	100	2125	52.0	1019	24.9	573	14.0	378	9.3	-10.2	-0.3	0.7	0.02
2014	4089	100	2221	54.3	930	22.8	575	14.1	378	9.2	-16.3	-0.4	0.9	0.02
2015	3937	100	2064	52.4	921	23.4	561	14.3	382	9.7	7.8	0.2	1.2	0.03
2016	3974	100	2024	50.9	976	24.6	577	14.5	397	10.0	-1.2	0.0	1.2	0.03
2017	4157	100	2059	49.5	1080	26.0	613	14.7	398	9.6	7.2	0.2	0.5	0.01
2018	4348	100	2069	47.6	1215	28.0	647	14.9	408	9.4	8.2	0.2	0.7	0.02
2019	4426	100	2068	46.7	1245	28.1	675	15.3	418	9.4	20.5	0.5	0.5	0.01
2020	4301	100	1842	42.8	1263	29.4	709	16.5	449	10.4	38.2	0.9	0.5	0.01
\bar{x}	4079	100	2155	53,0	1034	25,3	571	14,0	324	7,9	-5,6	-0,2	0,6	0,02
ΔR (%)	0,8	-	-1,5	-2,3	2,6	1,9	2,6	1,8	5,9	5,1	-21,9	-20,5	-4,3	-25,6

Note: \bar{x} : average value; ΔR : average annual growth in %.

Source: Own study.

As Table 3 suggests, although coal was the main source of energy in Poland throughout the period considered, its importance declined steadily ($\Delta R = -1.5\%$). In 2004–2014, coal-derived energy amounted to an average of ca. 2270 PJ, but it was ca. 2050 PJ in 2015–2019, and only 1842 PJ in 2020 (the pandemic period). These trends translated into considerable changes in the energy mix. The share of coal energy declined from 59–62% (2004-2007) to 43% (2020).

Conversely, the changes in the consumption of energy derived from oil and natural gas seem to follow an opposite trend. The supply of these energies grew at the same rate ($\Delta R=2.6\%$), and their share in total energy supply went up from 21.9% to 29.4% and from 12.4% to 16.5%, respectively. From the perspective of emissions, these are generally favorable trends, Poland saw a gradual shift from high-emission energies to lower-carbon sources.

As shown in Table 3, CO₂ emissions from coal combustion dropped at an average annual rate of 2.2%, going down by nearly 30% between 2004 (221.5 Mt) and 2020 (156.3 Mt). However, at the same time, oil and natural gas-derived emissions grew at a comparable rate (of $\Delta R = 2.1\%$ and $\Delta R = 2.3\%$, respectively), translating into a

generally slow reduction in total CO₂ emissions from fossil fuels. Indeed, total emissions declined at an annual average rate of barely 0.7% over the study period.

As a consequence, the level recorded in 2020 (266 Mt CO₂) was only ca. 11% lower than that witnessed in 2004 (300 Mt CO₂). The above means that changes in the fossil fuel mix are not enough to radically reduce CO₂ emissions, and must be more tightly related to the development of other energy sources. In Poland, the development of nuclear energy and renewables is of crucial importance.

However, nuclear energy—as an alternative to fossil fuels—is only at the conceptual stage and therefore cannot be expected to affect the restructuring of energy supply (and the resulting reduction in emissions) in the medium term. Conversely, considerable and untapped resources of energy can be provided by renewables (RE). Although the supply of RE went up from ca. 180 PJ (2004-2005) to ca. 450 PJ (2020), i.e., increased 2.5 times, and demonstrated the highest average growth rate ($\Delta R=5.9\%$), data in Table 1 also shows a clear slowdown in that favorable trend.

After 2015, RE supply grew at a much slower rate ($\Delta R = 2.8\%$), and their share in total energy supply fluctuated slightly, falling into a narrow interval of 9.4-10.4%. Accelerating the development of RE in Poland will be a tremendous challenge in the years to come. The Directive of the European Parliament and of the Council of 2021 sets forth a binding target of 32% for the amount of RE in the Union's final energy consumption by 2030. This means that, as part of the plan for climate goals, the share of RE in final gross energy consumption would need to increase to 40% by 2030 to enable attaining the Union's goal for reducing gaseous emissions.

However, as it is unrealistic for Poland to reach that level within 10 years, the national Ministry of Climate and Environment declared that the share of RE in final gross energy consumption would grow to 21% by 2030. This is much below the level planned for the EU (40%) but nearly twice what was recorded in 2020.

Table 3. Emissions from fossil fuel combustion in Poland in 2004–2020 (Mt CO₂ eq.)¹.

Years	Total	Coal	Crude	Gas	Total	Coal	Crude	Gas
	Mt CO ₂ eq.				%			
2004	300.0	221.5	56.1	22.4	100	73.8	18.7	7.5
2005	299.6	218.8	57.6	23.2	100	73.0	19.2	7.8
2006	311.1	228.5	59.2	23.5	100	73.4	19.0	7.5
2007	309.4	223.4	62.3	23.7	100	72.2	20.1	7.6
2008	304.8	217.5	63.5	23.8	100	71.4	20.8	7.8
2009	294.2	206.8	63.6	23.8	100	70.3	21.6	8.1
2010	310.5	218.5	66.4	25.5	100	70.4	21.4	8.2
2011	305.5	214.3	65.8	25.4	100	70.1	21.5	8.3
2012	299.4	210.3	62.7	26.5	100	70.2	20.9	8.8

2013	294.5	210.1	57.8	26.5	100	71.4	19.6	9.0
2014	280.7	198.0	57.4	25.3	100	70.5	20.5	9.0
2015	284.1	196.7	61.3	26.2	100	69.2	21.6	9.2
2016	294.0	197.3	68.5	28.1	100	67.1	23.3	9.6
2017	306.1	199.0	77.4	29.7	100	65.0	25.3	9.7
2018	303.5	193.6	79.6	30.4	100	63.8	26.2	10.0
2019	286.0	173.0	81.1	31.8	100	60.5	28.4	11.1
2020	266.3	156.3	77.8	32.1	100	58.7	29.2	12.1
\bar{x}	297.0	204.9	65.8	26.3	100	68.9	22.2	8.9
ΔR (%)	-0.7	-2.2	2.1	2.3	-	-1.4	2.8	3.1

Note: ¹ \bar{x} : average value; ΔR : average annual growth in %.

Source: Own study.

4.2 Decomposition Analysis

This Section presents the results of the LMDI decomposition which served as a basis for analyzing the key conditions affecting the volume of CO₂ emissions in Poland as per the methodology presented earlier. Changes in CO₂ emissions were considered in a 17-year perspective (2004-2020, i.e., after Poland's accession to the EU) and in the context of five factors (Equations 1 and 2). The decomposition was preceded by an analysis of changes in these factors over the study period.

According to data shown in Table 4, the factors changed at different paces over the study period, and therefore differed in their impact on changes in CO₂ emissions. It can be observed that emission (carbon) intensity (CI) remained very stable across the study period. In most years, the volume of CO₂ emissions from fossil fuels was ca. 80 kt/toe; a relatively smaller level (ca. 75 kt/toe) was recorded at the end of the analysis. The small extent of these changes is also corroborated by descriptive statistics.

Each year, emission intensity deviated only slightly from the average of 79 kt/toe, and the average annual growth rate (ΔR) was only -0.44%. These low levels clearly suggest that carbon intensity remained virtually unchanged between 2004 and 2020. Similar conclusions can be drawn from the analysis of changes in the share of energy derived from fossil fuels in total energy supply (ES).

According to Table 4, that factor also remained quite stable (0.88–0.96), and thus exhibited little variation over time ($\Delta R = -0.55\%$). It is worth noting that it remained virtually constant (0.88-0.90) from 2014, which means that in practice no changes occurred in the energy mix.

The above also suggests that renewable energies continue to be of minor importance in Poland, and their penetration is a sluggish process. From the perspective of statistical metrics used ($\Delta R = -3.11\%$), much greater changes were recorded in

energy intensity (EI) which dropped from 11-12 (in 2004–2008) to ca. 7.5 (in 2019–2020), i.e., by 35%.

However, a more detailed insight into Table 5 data suggests that a considerable drop in energy intensity occurred only in 2014–2020 when energy consumption per GDP unit decreased to 7.5–8.5. In turn, GDP per capita (GP) is the factor that changed the most over the study period. The average annual economic growth rate per capita was as high as 3.71%; as a consequence, the values recorded in 2019–2020 (14.64–15.01) were by as much as ca. 76% greater than those seen in 2004–2005 (8.27–8.57).

In Poland, rapid growth of GDP per capita was mostly due to growth in GDP. Indeed, as shown in Table 4, the Polish population (P) varied only to a marginal extent ($\Delta R = -0.04\%$) and fell within the narrow interval of 38.19–37.96 million throughout the study period.

Table 4. Changes in the factors of the decomposition model for Poland from 2004 to 2020^{1,2}.

Years	CI=CO ₂ /FE	ES=FE/ E	EI=E/GDP	GP=GDP/POP	P=POP
	[tons CO ₂ /TJ]	[TJ/TJ]	[PJ/USD mln 1000] x	[USD thous. per person]	[mln]
2004	82.03	0.960	12.06	8.27	38.19
2005	80.91	0.961	11.80	8.57	38.17
2006	80.09	0.958	11.68	9.10	38.16
2007	80.49	0.952	10.86	9.75	38.13
2008	79.15	0.941	10.57	10.16	38.12
2009	80.26	0.932	9.88	10.44	38.14
2010	79.78	0.935	10.19	10.86	38.02
2011	78.43	0.921	9.77	11.37	38.06
2012	80.55	0.910	9.32	11.52	38.06
2013	79.03	0.911	9.22	11.65	38.06
2014	79.17	0.901	8.59	12.06	38.02
2015	79.44	0.900	8.32	12.57	38.01
2016	78.35	0.903	8.44	12.98	37.97
2017	77.86	0.904	8.42	13.61	37.97
2018	76.13	0.901	8.13	14.33	37.98
2019	74.98	0.887	7.54	15.01	37.97
2020	75.09	0.877	7.38	14.64	37.96
\bar{x}	78.93	0.92	9.54	11.58	38.06
ΔR	-0.44	-0.55	-3.11	3.71	-0.04

Note: ¹CI: emission coefficient for fossil fuel *i*; ES: share of fossil energy from fuel type *i* in total energy; EI: energy intensity; GP: GDP per capita; P: population size; ² \bar{x} : average value; ΔR : average annual growth in %.

Source: Own study.

The direction and pace of changes in factors covered by the decomposition model, as presented above, clearly show that the factors considerably differed in the direction and strength of impact they had on carbon dioxide emissions in Poland (which is corroborated by the results of CO₂ emissions decomposition).

It can be noticed (Table 5, Figure 1) that despite the extremely slow reduction in emission intensity (ΔCI), its changes between 2004 and 2020 contributed to a reduction in CO₂ emissions.

A slight drop in emission intensity caused a nearly 23 Mt total reduction in CO₂ emissions over that period. Table 6 data also suggests that this factor had a restrictive effect on emissions in ten sub-periods, especially in those where the decline in CO₂ emissions per energy unit was relatively faster (2004-2005, 2007-2008, 2011-2020, 2012-2013 and 2017-2018). The data presented above also shows that even a relatively small drop in emission intensity translated into a significant reduction in emissions.

However, considering the structure of deviations, it can be easily seen that emission intensity did not exert any significant impact on changes in CO₂ emissions. Compared to other factors, it had a relatively small share in total variation (ΔCO_2), with 87.4% over the entire study period.

Similar conclusions can be drawn from the impact analysis of the energy mix (ΔES) on CO₂ emissions. The decomposition results prove that aggregate changes in that factor generally had a restrictive effect on emissions ($\Delta ES = -27.80$ Mt CO₂).

However, just like in the case of emission intensity, changes in the energy mix also played a relatively small role in reducing carbon dioxide. In the entire period from 2004 to 2020, its average share in total variation (ΔCO_2) was 106.2%, i.e. only slightly more than that of carbon intensity (87.4%).

Table 5. *Decomposition of changes in fossil-energy CO₂ emissions in Poland between 2004 and 2020.*

Periods	Mt CO ₂						percentage weights of factors (%)					
	ΔCI	ΔES	ΔEI	ΔGP	ΔP	ΔCO_2	ΔCI	ΔES	ΔEI	ΔGP	ΔP	ΔCO_2
2004/2003	3.77	-0.83	-13.62	14.71	-0.22	3,81	98.9	-21.9	-357.8	386.5	-5.7	100
2005/2004	-4.10	0.04	-6.65	10.47	-0.13	-0,38	1076.8	-10.4	1747.3	-2748.3	34.6	100
2006/2005	-3.10	-0.54	-3.01	18.30	-0.13	11,51	-26.9	-4.7	-26.2	159.0	-1.2	100
2007/2006	1.54	-1.97	-22.46	21.43	-0.26	-1,71	-90.1	114.9	1311.1	-1250.9	15.0	100
2008/2007	-5.17	-3.58	-8.50	12.71	-0.08	-4,61	112.1	77.7	184.3	-275.8	1.7	100
2009/2008	4.17	-3.01	-20.12	8.21	0.16	-10,59	-39.4	28.4	190.0	-77.5	-1.5	100
2010/2009	-1.82	1.27	7.22	10.45	-0.90	16,22	-11.2	7.8	44.6	64.5	-5.6	100
2011/2010	-5.23	-1.15	-12.88	13.99	0.32	-4,94	105.7	23.3	260.6	-283.1	-6.5	100
2012/2011	8.03	-3.79	-14.34	3.97	0.01	-6,12	-131.3	62.0	234.4	-64.9	-0.1	100
2013/2012	-5.64	0.52	-3.10	3.33	-0.01	-4,90	115.2	-10.6	63.3	-68.1	0.2	100
2014/2013	0.50	-3.40	-20.43	9.89	-0.34	-13,77	-3.6	24.7	148.3	-71.8	2.5	100

2015/2014	0.97	-0.22	-9.07	11.81	-0.09	3,40	28.6	-6.5	-266.7	347.2	-2.7	100
2016/2015	-3.98	0.81	4.07	9.23	-0.29	9,85	-40.5	8.3	41.4	93.8	-3.0	100
2017/2016	-1.89	0.56	-0.71	14.11	0.05	12,11	-15.6	4.6	-5.9	116.5	0.4	100
2018/2017	-6.86	-1.15	-10.42	15.87	0.03	-2,54	270.5	45.2	410.8	-625.3	-1.2	100
2019/2018	-4.46	-4.66	-22.13	13.69	-0.03	-17,59	25.3	26.5	125.8	-77.8	0.2	100
2020/2019	0.38	-3.16	-6.01	-7.04	-0.11	-15,95	-2.4	19.8	37.7	44.2	0.7	100
2004/2020	-22.89	-27.80	-160.16	186.68	-2.02	-26,19	87.4	106.2	611.6	-712.9	7.7	100

Note: ΔCI : effect of changes in emission intensity; ΔES : effect of energy structure changes; ΔEI : effect of changes in energy intensity; ΔGP : effect of changes in economic growth; ΔP : effect of changes in population; ΔCO_2 : increase in emissions.

Source: Own study.

In turn, changes in energy intensity (ΔEI) can be observed to be a strong determinant of changes in CO₂ emissions. Data presented in Table 5 suggests that a significant reduction in energy consumption per GDP unit brought CO₂ emissions down by a total of 160.16 Mt over the study period, and the importance of that factor is strongly emphasized by its contribution to total variation in emissions (nearly 612%).

In light of decomposition results, favorable changes in energy intensity were of key importance to reducing growth in CO₂ emissions virtually throughout the study period, except for two sub-periods, i.e. 2009–2010 and 2015–2016 where Poland experienced an increase in energy intensity (though to a small degree).

Conversely, the next factor, GDP per capita (ΔGP), contributed the most to increasing CO₂ emissions in Poland over the study period. On an aggregate basis (2004–2020), rapid growth in GDP per capita resulted in increasing CO₂ emissions by as much as 186.68 Mt, which translated to it having the greatest contribution to total variation in emissions ($\Delta GP = -712.9\%$).

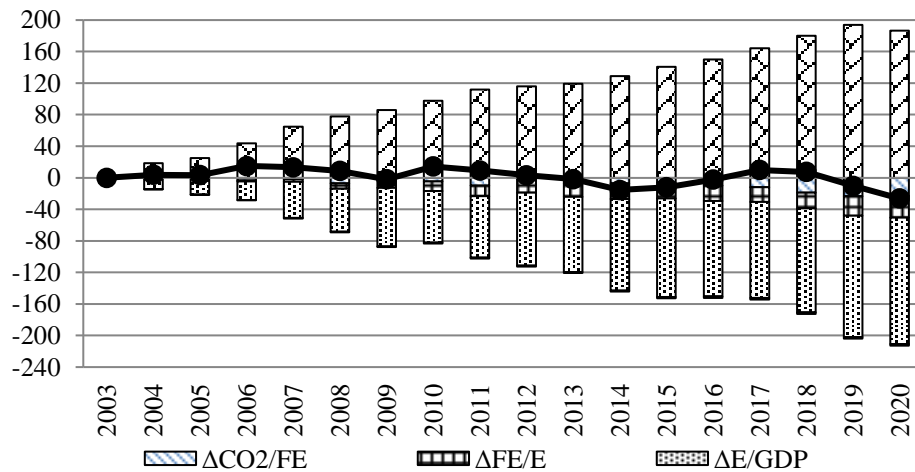
This makes economic growth the factor which the strongest and negative impact on reducing CO₂ emissions in Poland in the study period.

Also, as emphasized earlier, the dynamic growth in GDP per capita was only marginally related to changes in population size. Indeed, the Polish population declined to a small extent (from 38.2 million to 38 million), i.e. by less than 1%.

The marginal (though having a beneficial effect on emissions reduction) changes in population size translated into favorable, though also marginal, changes in carbon dioxide emissions.

In light of decomposition results, the population factor (ΔP) can be viewed as accountable for reducing CO₂ emissions by 2.02 Mt, which in relative terms means a share of only 7.7% in reducing Polish CO₂ emissions between 2004 and 2020.

Figure 1. Aggregate decomposition of changes in fossil-energy CO₂ emissions in Poland between 2004 and 2020



Source: Own study.

4.3 Decoupling Analysis Results

This Section presents the results of the decoupling analysis, which was combined with the results of LMDI decomposition in order to examine the relationship between CO₂ emissions, on one side, and fossil-fuel CO₂ emission intensity, energy intensity, GDP per capita, and population size, on the other. The investigation into these dependencies was underpinned by the Tapio's decoupling elasticity model.

The decoupling states (calculated as per Equation 11) between CO₂ emission intensity of fossil energy, energy structure, energy intensity, GDP per capita, and population size, on one side, and CO₂ emissions in Poland, on the other, between 2004 and 2020 are shown in Table 6 and Figure 2. It follows from the analysis that aggregated decoupling elasticity indices ($\epsilon_{(CO_2, GDP)}$) are negative, which generally is indicative of a strong decoupling of economic growth from the amount of CO₂ emissions.

Table 6. Decoupling elasticity indices and decoupling states for Poland (annual changes)^{1,2}

Periods	ϵ_{CI}	ϵ_{ES}	ϵ_{EI}	ϵ_{GP}	ϵ_P	$\epsilon_{(CO_2, GDP)}$	Decoupling states
2004-2005	-0.390	0.004	-0.632	0.995	-0.013	-0.036	SD
2005-2006	-0.169	-0.030	-0.164	0.996	-0.007	0.627	WD
2006-2007	0.070	-0.090	-1.022	0.975	-0.012	-0.078	SD
2007-2008	-0.398	-0.276	-0.654	0.978	-0.006	-0.355	SD
2008-2009	0.483	-0.348	-2.330	0.950	0.018	-1.227	SD

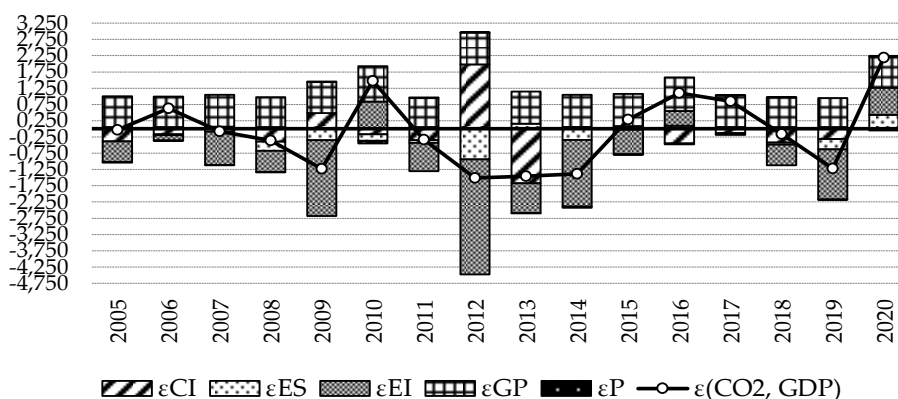
2009-2010	-0.166	-0.206	0.837	1.090	-0.082	1.474	END
2010-2011	-0.354	-0.078	-0.872	0.947	0.022	-0.335	SD
2011-2012	1.984	-0.937	-3.542	0.981	0.002	-1.511	SD
2012-2013	-1.674	0.154	-0.920	0.989	-0.003	-1.453	SD
2013-2014	0.050	-0.342	-2.053	0.994	-0.034	-1.384	SD
2014-2015	0.082	-0.019	-0.763	0.993	-0.008	0.286	WD
2015-2016	-0.446	0.091	0.456	1.034	-0.033	1.103	EC
2016-2017	-0.133	0.039	-0.050	0.993	0.003	0.853	EC
2017-2018	-0.419	-0.070	-0.636	0.968	0.002	-0.155	SD
2018-2019	-0.309	-0.323	-1.537	0.951	-0.002	-1.221	SD
2019-2020	-0.052	0.435	0.827	0.970	0.015	2.194	RD
2004-2020	-0.153	-0.154	-0.835	0.988	-0.011	-0.166	SD

Notes: ¹ ϵ_{CI} : decoupling elasticity values for carbon intensity; ϵ_{ES} : decoupling elasticity values for the energy mix; ϵ_{EI} : decoupling elasticity values for energy intensity; ϵ_{GP} : decoupling elasticity values for economic growth; ϵ_P : decoupling elasticity values for population growth; $\epsilon_{(CO_2, GDP)}$: values of the overall decoupling elasticity index.

²Abbreviations for the decoupling states: SD: strong decoupling, WD: weak decoupling, END: expansive negative decoupling, EC: expansive coupling, RD: recessive decoupling.

Source: Own study.

Figure 2. Decoupling elasticity indices in Poland in 2005–2020.



Source: Own study.

In the years of strong decoupling, the elasticity index varied broadly, with the highest levels being recorded in 2011–2014 (–1.384 and –1.511) and the relatively lowest in 2004–2007 (–0.036 and –0.078).

In turn, when considering the factors separately, it may be noticed that they differed quite importantly in the strength (and, though to a smaller degree, in the direction) of their impact on the overall decoupling index. However, what the data generally

shows is that strong decoupling states were mostly determined by energy intensity (ε_{EI}) and economic growth per capita (ε_{GP}). In the case of energy intensity, the decoupling elasticity value (ε_{EI}) fell into the interval of -0.632 (2004-2005) to -3.542 (2011-2012), and its average level in years of strong decoupling was -1.420 .

In turn, as regards economic growth per capita, the values of decoupling elasticity (ε_{GP}) varied moderately (0.947 – 0.995), with an average level of 0.973 in years of strong decoupling. Compared to these two, other factors generally had a much smaller or marginal impact on the decoupling processes.

Although their changes contributed to strong decoupling, their effect was not as powerful as that of energy intensity and GDP per capita. This is because the decoupling elasticity for emission intensity ($\varepsilon_{CI}=-0.096$), energy mix ($\varepsilon_{ES}=-0.231$) and population change ($\varepsilon_P=-0.003$) was negative in years of strong decoupling.

While other decoupling states were also witnessed between 2004 and 2020, their were either sporadic or much less frequent than strong decoupling. In two sub-periods (2005–2006, 2014–2015), a weak decoupling state was recorded as a consequence of rapid economic growth combined with a small increase in CO₂ emissions. In turn, the last sub-period covered by the analysis (2019-2020) saw recessive decoupling.

It was caused by a decline in GDP and a reduction in emissions, with GDP decreasing much slower than CO₂ emissions. Data shown in Table 6 also suggests that other identified decoupling states were extremely rare. The expansive negative decoupling state was recorded only once (2009-2010), and was caused by CO₂ emissions growing faster than GDP.

In turn, the expansive coupling state was experienced in 2015–2016 and 2016–2017 due to the emissions and GDP growing at a similar rate. The presence of these states was determined by different factors. In the case of the relatively beneficial weak decoupling state, positive values of overall decoupling indexes (0.627 and 0.286) were due to a considerable weakening of favorable changes in emission intensity (ε_{CI}), energy structure (ε_{ES}) and energy intensity (ε_{EI}), accompanied by a stable and important role of economic growth per capita (ε_{GP}) and marginal changes in population size (ε_P).

In turn, the expansive coupling state recorded in 2015-2016 and 2016-2017 demonstrated quite similar characteristics. The common trait of these sub-periods was the negative impact exerted on the decoupling processes by adverse changes in the energy mix (ε_{ES}), growth in energy intensity (ε_{EI}) in 2015-2016 or the lack of progress in that respect in 2016-2017, and the slowdown in the reduction of fossil-fuel emissions (ε_{CI}).

Compared to these rare decoupling states, a truly disadvantageous state was witnessed the last year of the analysis. The recessive decoupling state recorded in 2020 was mostly determined by two factors, i.e. the energy mix ($\varepsilon_{ES} = 0.435$) and energy intensity ($\varepsilon_{EI} = 0.827$). Given the relatively stable GDP per capita (ε_{GP}) and marginal impacts of emission intensity (ε_{CI}) and population size (ε_P), these factors largely determined the high positive level of the overall index ($\varepsilon_{(CO_2, GDP)} = 2.194$) and thus the recessive nature of the decoupling.

In summary, strong decoupling states prevailed in Poland between 2004 and 2020. The overall decoupling index for the whole period ($\varepsilon_{(CO_2, GDP)} = -0.166$) also suggests that it was a time dominated by processes of strong decoupling of CO₂ emissions from economic growth. When comparing the impacts of five factors on these processes, it may be concluded that they were mostly determined by growth in GDP per capita ($\varepsilon_{GP} = 0.988$) and the reduction in energy intensity ($\varepsilon_{EI} = -0.835$).

Against that background, the impacts of emission intensity ($\varepsilon_{CI} = -0.153$) and energy mix ($\varepsilon_{ES} = -0.154$) were much weaker (though also positive), whereas the changes in population size played a marginal role ($\varepsilon_P = -0.011$). Note however that the linear trend (Figure 6) reflects a negative trend followed by the overall decoupling elasticity index ($0.039t$).

In light of the trend's parameters, the overall decoupling elasticity was increasing, mostly due to growth in ε_{ES} and ε_{EI} . It means that the decoupling of CO₂ emissions from economic growth was becoming weaker, and that the beneficial decoupling processes may come to a halt if the energy mix is not radically restructured and if less energy-intensive technologies are not developed.

5. Conclusions

Based on the empirical results, the main findings of this paper are as follows:

- 1) In light of the results brought by the decomposition analysis, the energy intensity effect and the effect of economic activity were the key determinants of CO₂ emissions in Poland, both on an aggregate basis and in the vast majority of years covered by the study. The energy intensity effect contributed the most to reducing CO₂ emissions.

The reduction in energy intensity over that period translated into 160 Mt of total reduction in emissions, which suggests that more efficient technical and technological solutions were put in place. Conversely, economic growth contributed the most to increasing CO₂ emissions in Poland. On an aggregate basis (2004–2020), the rapid growth in GDP per capita entailed an increase in fossil-fuel CO₂ emissions by as much as over 187 Mt.

- 2) Compared to the impacts of energy intensity and economic growth, changes in emission intensity and energy mix contributed much less to decarbonization processes. Over the study period, the small but generally beneficial decline in emission intensity and the generally favorable changes in the energy mix reduced CO₂ emissions by as little as 23 Mt and 28 Mt, respectively. The weak impact these factors had on reducing CO₂ emissions in the Polish economy was mostly due to the extremely high (though declining) consumption of coal and lignite in energy production, and to the sluggish development of renewables.
- 3) In light of decomposition results, population change played a very limited role in determining the amount of carbon dioxide emissions, because the Polish population varied to a small extent during the study period (declined by less than 1%). As a consequence, the marginal (though having a beneficial effect on emissions reduction) changes in population size translated into favorable, though also marginal, changes in carbon dioxide emissions. On an aggregate basis, the population factor is accountable for an extremely small reduction (2 Mt) in CO₂ emissions.
- 4) Strong decoupling states prevailed in Poland between 2004 and 2020, which suggests that it was a period dominated by processes of strong decoupling of CO₂ emissions from economic growth. The processes were mostly determined by growth in GDP per capita (which increased carbon emissions) and a reduction in energy intensity (which decreased them). Also recorded was a beneficial, though considerably smaller, impact of changes in emission intensity and energy mix. In turn, changes in population size played a marginal role. Note however the presence of a negative linear trend followed by the overall decoupling elasticity index. In light of the trend's parameters, the index was increasing, mostly due to the favorable changes in energy structure and energy intensity becoming slower at the end of the study period. It means that the decoupling of CO₂ emissions from economic growth becomes weaker, and that the beneficial decoupling processes may come to a halt if the energy mix is not radically restructured and if less energy-intensive technologies are not developed.

The results of this analysis indicate that a reduction in CO₂ emissions may coexist with economic growth. However, in order for this process to continue, political decision-makers must consistently develop and effectively implement new instruments that promote CO₂ reduction.

As regards Poland, the decisions in the following areas are of core importance: developing, implementing and stabilizing a long-term development strategy for the energy sector; reducing the intensity of emissions through the optimization of the energy mix; making renewable energies go mainstream; the development of the renewables sector must be combined with the development of nuclear energy which

provides a stable source of power; energy efficiency and carbon reduction should be strictly related to promoting, implementing and raising awareness of the principles of low-emission living.

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