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RESEARCH ARTICLE

The drivers of energy-related CO_2 emission changes in Indonesia: structural decomposition analysis

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Abstract
This study aims to decompose the changes in CO_2 emission, in 1990–1995 and 2010–2015, to identify the main drivers of those changes at the sectoral level. Using energy input and input-output table, the emission changes were decomposed into six factors: energy intensity, carbonization factor, technology, structural demand, consumption pattern effect, and scale effect. This model would allow a given country to identify the impacts of energy consumption, energy mix, and production efficiency (as direct sources of emission) while paying close attention to their linkages with both the economic structure and the accretion of final demand. This research was the first attempt to decompose CO_2 emission changes using the input-output framework in Indonesia. The results revealed that the scale effect was the main driving factor of emission in 1990–1995. In 2010–2015, embodied emission in the chemical industry, mining, rubber, and plastic industry significantly rose due to an increase in energy intensity. Meanwhile, the embodied emission in electricity, road and air transportations, and non-metallic mineral production rose due to inefficiency in production. The energy policy to improve efficiency and diversified primary energy seemed to be negative between 2010 and 2015. Consequently, the embodied emission from energy intensity factor in several energy-intensive sectors increased along with a lack of contribution to changes in primary energy composition. This study also demonstrated that there was a decline in structural demand for electricity and mining between 2010 and 2015, which contributed negatively to the emission and yet outdrew with the rise from scale effect.

Keywords Structural decomposition analysis · Energy input-output · Emission growth · Energy intensity · Energy mix · Sectoral analysis

Introduction

Indonesia is the second-largest contributor to energy-related emission in the Asia non-China region, after India (IEA 2017). The emission grew way faster (230%) than the global level (56.5%) in 1990–2015 (Olivier et al. 2017). In the meanwhile, the total energy consumption in Indonesia increased by 7.10% per year on average in the same period (Kartiasih et al. 2012).

As a highly emerging market, energy demand naturally increased due to the positive relationship between energy consumption and economic growth (Hwang and Yoo 2014; Wahid et al. 2013). This aspect was compounded by the usage of oil fuel, which has high emission as the primary source of energy consumption in Indonesia (Ministry of Energy and Mineral Resources (MEMR) 2016).

Indonesia has issued various energy and emission policies to regulate energy consumption and its relation to emission. Initially, Indonesia focused on increasing the utility of energy resources and created energy security to support the economy with energy intensification, diversification, and conservation policies. This aspect was stated in the General Policy on Energy (*Kebijakan Umum Bidang Energi*, KUBE) implemented and gradually in 1981, 1987, 1991, and 1998. Even so, these policies are considered to be partial, with no definite targets (Bappenas 2012). In the 2003s, the government policies began to recognize the importance of environmental aspects, such as setting energy efficiency targets and the

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composition of renewable energy, as stated in National Energy Policy (*Kebijakan Energi Nasional*, KEN). The implementation of the long-term objectives started in 2010–2025. The policy difference between these two periods should have resulted in different impacts on Indonesia since the considerations of the environmental aspects in the second period might have declined the emission level compared with the first period. Nonetheless, the overall energy-related emissions in Indonesia have increased significantly since 1990 (Olivier et al. 2017).

Due to the high emission from Indonesia, the progress to reduce emission is of global interest (Yusuf and Resosudarmo 2015). Thus, it is also vital to investigate historical changes in energy-related emissions to analyze the reasons why emissions have increased in Indonesia. One primary tool, widely used to disintegrate the growth of a specific variable over time into several indicators, is the decomposition (Dietzenbacher and Los 1998). The decomposition method can investigate the changes in embodied emission in energy consumption by assessing the driving factors underlying these changes. The result could be an essential suggestion to designing an effective energy policy to attain Indonesia National Determined Contribution (NDC) for Paris Agreement, reducing GHG emission by 29.1% below Business as Usual (BAU) or 37.7% below the BAU in 2030 when receiving international assistance (the Republic of Indonesia 2019).

Various existing studies reported decomposition analysis on energy or emission issues. Most studies used the Index Decomposition Analysis (IDA) model to decompose changes in CO_2 emission because the required data are relatively available and the formulations flexible (Cansino et al. 2016; Su and Ang 2015). However, the IDA method has disadvantages since it only covers direct effects. It is also unable to distinguish between the impact of technology and the impacts of final demand factors (Hoekstra et al. 1994). Utilizing requisite input-output (I-O) data, structural decomposition analysis (SDA) method has been commonly used to identify driving factors of carbon emission or carbon emission intensity using the Leontief I-O framework (Leontief 1967). Those include studies on the embodied emission in household consumption (Das and Paul 2014; Kurniawan et al. 2018; Su et al. 2017; Wang et al. 2019a), investment (Guan et al. 2008; Markaki et al. 2020), international trade (Weber et al. 2008; M. Xu et al. 2011), final demand structure (Fan et al. 2019; Su et al. 2017), power generator (Wang et al. 2019b), sectoral energy consumption (Cansino et al. 2016; Nie et al. 2016), or combination of those factors.

Even though it has been extensively reported in many countries, there were only limited studies reporting decomposition studies using the Indonesian case. Adopting Logarithmic Mean Divisia Index (LMDI) approach, Lee and Oh (2006) decomposed energy-related CO_2 emission in multi-country, including Indonesia. Meanwhile, Kurniawan et al. (2018) decomposed embodied emission in household consumption. Sitompul and Owen (2006) disintegrated emission in sectoral level between 1980 and 2000, utilizing aggregate sectoral gross value (not with the I-O framework). Even though it was not a decomposition study, Imansyah et al. (2017) and Putranti and Imansyah et al. (2017) identified vital sectors producing emissions, both in terms of quantity and sensitivity toward income changes in all sectors. They later focused on the manufacturing sector.

Based on previous studies, SDA using the Leontief I-O framework in Indonesia has not been performed. This study aims to complement the existing literature by decomposing embodied emission changes using structural decomposition analysis with six factors, i.e., energy intensity, carbonization factor, technology, demand structure, demand allocation, and scale effect (final demand). It used I-O data and framework from 1990 to 2015. The present study also utilized the changes in emission aggregate values (quantity indicator) for the decomposition analysis. The quantity indicator is generally easier to interpret and handle mathematically (Wang et al. 2017). The additive decomposition technique is applied as a standard method for quantity indicator decomposition (Su and Ang 2017).

The decomposition analysis will be classified into two-time intervals, years 1990–1995 and 2010–2015, applying the two types of energy policies (policies without any environmental impact targets and vice versa). These two time intervals were chosen to analyze changes in emissions that occurred in the presence of two different policy situations so that a comparative analysis could be carried out. Besides, there was no significant event that could affect energy consumption and emissions in these two-time intervals (for example, in 1998, when there was a financial crisis), resulting in minimizing the error. As the basis data, official Indonesia I-O Tables are not available annually. The tables were constructed with 5 years interval by Central Bureau of Statistics (*Badan Pusat Statistik,* BPS). Considering the data availability, we decomposed I-O Table between years 1990 and 1995 as well as between 2010 and 2015. The study also updated energy input data and modified I-O Table constructed by the BPS and Ministry of Public Works and Public Housing of the Republic of Indonesia (Ministry of PWPH).

This paper proposes some contribution to the literature as follows: (1) the first application of SDA using I-O framework in Indonesia, (2) applying SDA analysis which allows assessment on the effects of changes in energy intensity, carbonization factor (energy source choice), final demand factors, and also enable the analysis of the indirect impacts of demand in the economy from spillover effect captured by Leontief Inverse Matrix (Miller and Blair 2009), (3) obtaining comparative decomposition analysis before and after environmental aspects considered in national energy policy, (4) deriving decomposition equalities in 48 sectors with 20 manufacturing sectors (to obtain a specific sectoral recommendation). In the present paper, "Literature reviews" reviews the Indonesia energy policy as well as existing literature. "Materials and methods" describes the methodology employed in this study and the sources of data. "Results and discussion" presents the empirical results and discussion. "Conclusions" delivers the conclusion of the study.

Literature reviews

Overview of energy policy between 1990 and 2015

The first discussion on designing energy policies in Indonesia was in 1976. The policy aimed to maximize the use of abundant Indonesian energy resources. The government then formed the National Energy Coordinating Board (*Badan Koordinasi Energi Nasional*, BAKOREN) responsible for formulating energy policies and coordinating the implementation of these policies. BAKOREN, for the first time, issued the General Policy on Energy (*Kebijaksanaan Umum Bidang Energi*, KUBE) in 1981. The 1981 KUBE, subsequently revised in 1987 and 1991, focused on intensification, diversification, and energy conservation. Intensification was implemented through an increasing exploration of energy resource activities to determine economic potential. Diversification was an effort to diversify the use of non-petroleum energy by reducing the use of oil and establishing coal as the primary fuel for power generation and the cement industry. Conservation was carried out through the use of more efficient generating equipment and energy user equipment (Bappenas 2012).

Along with that industrialization process, there were lots of environmental damages. The environmental aspect was considered, and energy policies began to be directed toward using renewable energy that was environmentally friendlier. In 1998, BAKOREN arranged a new KUBE which aimed to create a climate supporting the implementation of the energy sector development strategy. Subsequently, the KUBE energy policy was changed to the National Energy Policy (*Kebijakan Energi Nasional*, KEN) and the Policy for the Development of Renewable Energy and Energy Conservation (Green Energy) in 2003.

Although the energy policy-making process has experienced improvements from time to time, there were still many contradictions in material policies. The energy development strategy, both short and long terms, has not been structured. The existing policies still appear as partial policies without strategic flow to their long-term programs (Bappenas 2012). Therefore, a long-term National Energy Management Blueprint was compiled through Presidential Regulation No. 5 of 2006 concerning KEN as a guideline in national energy management. Based on the Presidential Decree No. 5 of 2006, several national energy policy targets were implemented, such as achieving energy elasticity of less than one and the target of diversifying the energy mix by increasing the percentage of renewable energy, gas, and coal in replacing oil energy in 2025. Afterward, the government has issued Law No.30 of 2007 concerning energy expected to answer problems in the energy sector. Due to this law, the national energy policy shifted not only to securing energy supplies as in the 2006 Presidential Decree, but also covering energy utilization policies to consider the environmental effect and strive for efficiency. The targeted plan was designed to be implemented in 2010–2025.

Structural decomposition analysis

Decomposition is similar to the growth of the accounting method aiming to determine the effects of determinant changes on the output variable (indicator) when other variables do not change from the base year (Das and Paul 2014). The decomposition method is split into three broad categories, i.e., IDA, SDA, and production theoretical decomposition approach (PDA). The main difference between these three decomposition methods lies in the data used. The IDA uses aggregate data, and the changes are then analyzed through algebraic equation manipulation. PDA uses production-related factors such as combination of input which built upon production theory framework (Wang and Zhou 2018; Wang and Feng 2018). SDA uses I-O Table data processed by manipulating equations in the I-O analysis framework.

Utilizing the requisite I-O data, the SDA method has been commonly used to identify driving factors of carbon emission or carbon emission intensity. There were three types of indicators widely used, absolute, intensity, and elasticity (Hoekstra et al. 1994). Representative studies consider two main types of drivers to explain the emission changes, i.e., technological factor and demand factor. The technical factor is commonly described as efficiency in emission intensity, energy intensity, selection of energy mix factor, and efficiency in production used to be described in Leontief inverse matrix (see Cansino et al. 2016; Nie et al. 2016). Meanwhile, some studies related the demand factor to changes in structural economics, population (see Guan et al. 2008), and gross domestic product (GDP) or GDP per capita (see Cansino et al. 2016; Guan et al. 2008). Some other studies were focusing on the effects of changes in each demand category (see Kim et al. 2014; Lim et al. 2009) or impact of international trade (see Lin and Sun 2010; Xu et al. 2011).

The SDA could analyze emission changes in multi regions (Brizga et al. 2014; Liu et al. 2019; Pan et al. 2018; H. Wang et al. 2017), but mostly in single region studies due to the data limitation. Several single-region studies on emission were done in Asian countries, predominantly in China and Korea. Guan et al. (2008) applied the SDA to identify driving factors of emission in the past and future using historical data and scenario projects from 1980 to 2030. The main findings of this study relied on efficiency and technology based on scenarios that might not be sufficient to counter the consumption force toward emission growth in the future. Including energy variables into driving factors, Nie et al. (2016) decomposed energy-related emission changes in China from 1997 to 2010. Similar to the finding of Guan et al. (2008), Nie et al. (2016) revealed that the main driver of China's carbon emission was the changes in final demand, while efficiency in energy was the only factor negatively contributing to the emission changes. Other studies focused on a specific city or area, such as Chongqing (Hu et al. 2017) and Beijing (Wei and Liu 2017). In South Korea, Lim et al. (2009), followed by Kim et al. (2015), found that the growth rate of industrial CO_2 emissions had dropped dramatically since the 1998 financial crisis in Korea. Similar to China, economic growth was the highest contributor to emission in South Korea. This study also found that energy intensity and domestic final demand had significant role in reducing emission, especially between 1995 and 2000.

Although emission has been a popular theme in academic literature, only a few studies are analyzing energy-related emission in Indonesia with different goals and approach: estimating aggregate emission in energy consumption by Priambodo and Kumar (2001), identifying the underlying emission sources by applying decomposition analysis (Lee and Oh 2006; Sitompul and Owen 2006), and sensitivity analysis (Imansyah et al. 2017; Putranti and Imansyah 2017). Priambodo and Kumar (2001) were the first calculating the aggregate amount of energy-related CO_2 emission in Indonesia. They identified energy usage and carbon emission in small- and medium-scale industries (SMI) across 27 Indonesian provinces by employing database statistics of SMI in Indonesia. They found that the textile and fabricated metal industry were the highest contributors to CO_2 emission. They also found that the contribution of liquid fuels in the SMI sector to CO_2 emission was significant.

Using LMDI approach, Lee and Oh (2006) decomposed energy-related CO_2 emission of multi-countries in Asia Pacific Economic Cooperation (APEC) countries, including Indonesia in 1980–1998. For Indonesia, they found that growth in GDP per capita and population were two dominant contributors to rising CO_2 emission. Besides, energy efficiency and renewable energy mix were found to be the most possible and promising field to be improved by APEC member countries. On the one hand, Kurniawan et al. (2018) tried to identify critical factors of CO_2 emission from household consumption. They found that the population led to an increase in energy emission both directly and indirectly, while the energy intensity was the opposite. However, the LMDI approach does not identify sectoral analysis critical to designing a specific policy for each sector.

Sitompul and Owen (2006) are the first to study the decomposition of energy-related emissions in Indonesia at the sectoral level. They decomposed carbon emission from large and medium manufacturing industries in 1980–2000 into four indicators, i.e., carbon factor, energy intensity, structural effect, and output using aggregate sector outputs. Similar to Lee and Oh (2006), they found that economic growth was the primary source of the increase in the Indonesian carbon emission. They also found that carbon factor positively increased the emission due to the increasing trend of coal consumption in paper and non-metal sectors but negatively contributed (i.e., reduce emission) to primary metal and chemical. However, the spillover effect from the I-O framework was missed in this study. Additionally, it decomposed changes in emission in the manufacturing sector before 2000.

In 2017, Imansyah and Putranti (in collaboration with BPS) were the first to produce the Energy Input Table years 1990, 1995, and 2010. The Energy Input Table consisted of the final consumption of 17 types of energy from 48 sectors used for combustion. Utilizing these data, Imansyah et al. (2017) and Putranti and Imansyah et al. (2017) conducted a study to identify the key sectors producing emission, both on quantity and sensitivity toward income changes in all industries, later focusing on manufacture sector. Using the sensitivity method proposed by Alcantara and Padilla (2006), they found that the chemical industry, heavy metal manufacture, and cement manufacture had the highest income elasticity. In the second study, they found that other fabricated metal products, cement, iron, and steel were within the manufacturing industry with the highest flexibility of CO_2 emission due to income changes. Imansyah and Putranti studies only identified the effect of changes in income. At the same time, emission production might also be caused by different types of energy used, change in technology, or other economic variables, such as a change in economic structure. Also, this study did not explain how to calculate emissions from the existing Energy Input Table.

Materials and methods

This section discusses the method used in this study: first, estimating the amount of CO_2 emission released from energy consumption in each sector; second, internalizing the emission variable using input-output analysis (IOA) to construct the fundamental equation of energy-related emission; and finally, mathematically manipulating the equation to decompose changes in energy-related emission into six driving factors.

Embodied emission in economics

This study calculates the amount of emission in each sector as a CO_2 emission measurement variable. Referring to Lim et al.

(2009), Embodied emission in energy consumption can be calculated in the following equation:

$$e = E.C \quad (1)$$

where e is the $(m \times n)$ matrix of CO_2 emission for each sector, E is the $(m \times n)$ matrix of energy consumption for each sector, and C is the vector of constants showing realized emission for each type of energy (carbonization factor). This study uses the value of carbonization factors, referring to BPS (Table 1). This equation generates the emission value (in tons) in each sector from each energy type.

I-O analysis: Non-competitive import assumption

The emission variable is internalized in the IOA framework so that it can be analyzed as the basic equation for the structural decomposition model. There are two IOA approaches available, depending on the type of I-O table used. The first is the I-O table with the assumption of non-competitive imports. This assumption treats imported products outside the domestic products. The second is the assumption of competitive imports. This assumption accumulates imported products in inter-sector transactions.

The I-O available as the database in this study applies the non-competitive import assumption. This assumption assumes that the technology used in domestic and imported products are not the same. United Nations (1993) advocate uses non-competitive import assumptions in environmental IOA (Su and Ang 2013). Using non-competitive import assumption, the basic equation linking the total output to the final demand in the production sector activities can be expressed in the following equation (Miller and Blair 2009; Su and Ang 2013)

$$x = Ax + y_d = Ax + (y_f + y_x) \quad (2)$$

where x is the vector $(n \times 1)$ containing the total output of each sector, A is the $(n \times n)$ matrix which includes the technology coefficient, showing the input needed for each industry to produce one output in the corresponding sector, and y is the $(n \times 1)$ vector representing the final domestic demand (y_f) plus final demand from export (y_x). From this point forward, the final demand that has been added to the export value will be expressed by y_d or demand produced domestically. Thus, eq. 2 can be modified as follows:

$$x = (1{-}A)^{-1} \times y_d \quad (3)$$

where 1 is the identity matrix as $(1-A)^{-1}$ is the Leontief inverse matrix (usually abbreviated as "l") and showing the requirements (inputs) for production in each sector. This model is commonly called the basic framework of IOA (Miller and Blair 2009). By inserting the emission intensity variable or emissions per unit in eq. 3, the total emissions in the economy can also be expressed as follows:

$$e = \widehat{K} \times l \times y_d \quad (4)$$

where e is the $(n \times 1)$ vector that represents total CO_2 emissions per unit of each sector. $\widehat{K}$ is a diagonal matrix $(n \times n)$ that represents the intensity of emissions in each sector of the economy. This equation links between emissions, technology, and final demand.

Table 1 Carbonization factors

Energy types		Unit	Carbonization factor
Coal	Coal	M/T	0.690
	Coke	M/T	0.795
	Coal briquette	M/T	0.547
Oil	Crude petroleum	KL	0.777
	Gasoline (benzene)	KL	0.629
	Kerosene	KL	0.672
	Diesel oil	KL	0.697
	Fuel oil (FO)	KL	0.761
	Naphtha	KL	0.623
Gas	Other petroleum products	KL	0.724
	Natural gas	000 M^3	0.609
	Liquefied petroleum gas	M/T	0.870
	Town gas	M3	0.030
Geothermal	Geothermal	G.cal	0.000
Others	Electricity	MWH	0.000
	Vegetable fuels	M/T	0.669
	Industrial waste	M/T	0.000

Source: Central Bureau of Statistic (2017)

Structural decomposition analysis

This study follows an extended Kaya Identity to construct an equation model for SDA. Kaya Identity states that CO_2 emission is influenced by population, energy intensity, GDP per population, and carbonization factor (emission/energy). Referring to Cansino et al. (2016) and Nie et al. (2016), this study combines Kaya Identity and IOA to link Kaya Identity to sectoral analysis as well as incorporate structural changes and efficiency in productions (indicated by Leontief matrix) into the model. This analysis solves the drawback of the Kaya Identity equation, which only assesses the direct effect of emission on the environment. Therefore, this study uses six driving factors, as described in Table 2.

Carbonization and energy intensity effects are chosen to identify changes in energy consumption, either the energy consumption emits more emission or not. Both are widely used in decomposition literature (see Freitas and Kaneko 2011; X. Y. Xu and Ang 2014). The Leontief factor, depicting

Table 2 Descriptions of emission driving factors

	Factors	Variable	Description
Energy Consumption factor	Energy intensity	E	Energy consumption per unit output
	Carbonization	C	CO_2 emission per unit energy
Leontief factor	Technology	l	Efficiency in production (derivative of Leontief effect)
Final demand factor	Demand structure	S	Sector structure in each final demand category
	Demand allocation	D	The proportion of each final demand category (household consumption, government expenditure, fixed capital formation, change in stock, export-import) to total final demand
	Scale effect/total final demand	F	Total final demand

efficiency in production per output (usually called technology factor), allows a more productive analysis. It was also used by Cansino et al. (2016) and Brizga et al. (2014). Also, because of the limitation of the model framework and data sources, analysis of the final demand variables (demand structure and demand allocation) usually abstains from IDA analysis (Estiri et al. 2013). Meanwhile, scale effect, or change in final demand, is mostly used in emission decomposition analysis as it depicts affluence in well-known IPAT equation and Kaya Identity.

These six driving factors are the extension form of eq. 5. Following the approach used by Cansino et al. (2016), $\widehat{K}$ is decomposed into $\widehat{C}.\ \widehat{E}$, where $\widehat{C}$ is a diagonal matrix of emission per energy in each sector, and $\widehat{E}$ the diagonal matrix of energy intensity per sector. The final demand (y_d) is disaggregated into $S.\widehat{D}.F$ in which S is $(n \times d)$ matrix, indicating structural demand effect; $\widehat{D}$ is $(d \times d)$ matrix, indicating demand allocation effect; and F is the $(d \times 1)$ unitary vector of total final demand. Thus, emission embodied can also be expressed as follows

$$e = \widehat{C}.\widehat{E}.l.S.\widehat{D}.F \tag{5}$$

Equation 6 is then derived from creating an equation that shows the relationship between changes in each driving factor and changes in emission indicators. The derivative result is as follows:

$$\Delta e = e^1 - e^0 = \Delta e_C + \Delta e_E + \Delta e_l + \Delta e_S + \Delta e_D + \Delta e_F \tag{6}$$

where Δe indicates the emission changes between periods 1 and 0, corresponding to the superscript letters, and the subscript letter denotes the source of the effect. Equation 7 is the fundamental equation of decomposition using an additive approach.

There were several methods to be used in decomposing changes in emissions between two periods. One of them is by taking the average of two polar decompositions (Miller and Blair 2009). This method has no residue and is easy to calculate and estimate results close to decomposition with the average of full set decomposition (Dietzenbacher and Los 1998). The same method was commonly applied in many decomposition studies (Llop 2017; Nie et al. 2016; Supasa et al. 2016). This study applies two polar decompositions to break down the emission changes between 1990–1995 and 2010–2015. Having used this method, the emission changes resulting from each driving factor can be expressed as follows[1]:

$$\begin{aligned}
\Delta e_C &= \frac{1}{2}\left(\Delta\widehat{C}.\widehat{E}^0.l^0.S^0.\widehat{D}^0.F^0 + \Delta\widehat{C}.\widehat{E}^1.l^1.S^1.\widehat{D}^1.F^1\right)\\
\Delta e_E &= \frac{1}{2}\left(\widehat{C}^1.\Delta\widehat{E}.l^0.S^0.\widehat{D}^0.F^0 + \widehat{C}^0.\Delta\widehat{E}.l^1.S^1.\widehat{D}^1.F^1\right)\\
\Delta e_l &= \frac{1}{2}\left(\widehat{C}^1.\widehat{E}^1.\Delta l.S^0.\widehat{D}^0.F^0 + \widehat{C}^0.\widehat{E}^0.\Delta l.S^1.\widehat{D}^1.F^1\right)\\
\Delta e_S &= \frac{1}{2}\left(\widehat{C}^1.\widehat{E}^1.l^1.\Delta S.\widehat{D}^0.F^0 + \widehat{C}^0.\widehat{E}^0.l^0.\Delta S.\widehat{D}^1.F^1\right)\\
\Delta e_D &= \frac{1}{2}\left(\widehat{C}^1.\widehat{E}^1.l^1.S^1.\Delta\widehat{D}.F^0 + \widehat{C}^0.\widehat{E}^0.l^0.S^0.\Delta\widehat{D}.F^1\right)\\
\Delta e_C &= \frac{1}{2}\left(\widehat{C}^1.\widehat{E}^1.l^1.S^1.\widehat{D}^1.\Delta F + \widehat{C}^0.\widehat{E}^0.l^0.S^0.\widehat{D}^0.\Delta F\right)
\end{aligned} \tag{7}$$

where Δe denotes the emission changes between periods 1 and 0, while the superscript letters indicate the drivers, period 0 refers to 1990, while period 1 in the medium-term analysis refers to 1995 and 2010 in the long term.

Data sources

This study uses the energy input data for each sector constructed by BPS with some modifications. The updated energy input data consisted of 48 industries from 17 types of energy

[1] Detailed calculation of two polar decompositions can be found in Nie et al. (2016)

from 1990, 1995, 2010, and 2015. BPS have also constructed I-O Table year 1971, 1980, 1985, 1990, 1995, 2000, 2005, and 2010. This study then used the I-O Table years 1990, 1995, 2010, published by BPS and I-O Table year 2015 constructed by the Ministry of PWPH with modification to adjust with available energy input data by sectors. The I-O and SAM data have been widely used by some researchers such as Thorbecke (1992), Clements et al. (2007), and Hartono and Resosudarmo (2008), to demonstrate the validity and reliability of the data published by BPS. Table I-O is deflated to a constant value with the 1993 base year to analyze changes in variables over time.

Results and discussion

The results consisted of two sub-sections: the descriptive analysis of energy and emission patterns between 1990 and 2015 and the result of a decomposition analysis from each sector cluster and factors.

Energy and emission between 1990 and 2015

Indonesia is a highly emerging market with a rapid economic growth rate. Indonesia's GDP growth (with nominal price) from 1990 to 2015 reached 8.9%, which was higher than those of Malaysia (6.4%), Thailand (6.2%), Philippines (6.1%), and India (6.5%) (World Bank 2018). Along with the rapid growth, Indonesia needs to maintain the energy supply to support economic expansion continuously. Based on the calculation of the consumption of 17 types of energy, Indonesia's energy consumption has increased from 33 million TCal (Terra Calorie) to 179 million TCal in 25 years. In the same period, the electrification ratio also increased dramatically, from 25 to 88.3% in 2015 (MEMR 2018).

Assessing the relationship between energy use and energy growth, the calculation of total energy consumption for the production of each output at a constant price is an excellent indicator to be used (Isaksen 2011). This calculation is commonly referred to as energy intensity. In terms of energy intensity, the production of a Billion GDP required at least 1.71 TCal energy in 1990, while in 2015, the intensity increased to 3.92 TCal per billion GDP with a constant value (Fig. 1). The increase in energy intensity was also found in the studies of Hartono and Resosudarmo (2008), Kartiasih et al. (2012), and Rustandi (2017). According to Lapillonne (2006), increasing energy intensity over time was commonly observed in developing countries. The economy of a country needs more energy intensity due to the industrialization process, growth in vehicle ownership, increased welfare, and so on. In contrast, energy consumption grows faster than the GDP (Kartiasih et al. 2012).

In line with energy consumption, a quite similar rate is also applied to emission intensity. CO_2 emissions grew rapidly from 33.7 million tons in 1990 to nearly double within 5 years and almost five times within 25 years. The intensity rose from 140 ton emission per billion GDP to 330 tons of emission per billion GDP. It is important to note that the rise was apparent in 2010–2015 compared with 1990–1995, even though the GDP rose at a similar rate. This figure showed that there was a growth difference between the level of emissions and the level of GDP. This may imply that other factors were influencing the change in energy and emission intensity outside of the growth of final demand.

Showing the change in the primary energy mix, Fig. 2 depicts that in 1990, 73% of Indonesian activities use oil-based energy as a primary source of energy, including crude oil and several types of oil fuel such as gasoline. This number is followed by gas, coal, and other energy. By the time the share of fuel energy decreased continuously to 73%, 61%, 54%, and 51% in 2015, the highest drop was taking place in 1990–1995 as oil fuel converted to gas and coal due to diversification policy implemented since 1990.

Structural decomposition analysis

Table 3 shows the aggregate results of structural decomposition analysis on the emission changes in 1990–1995 and

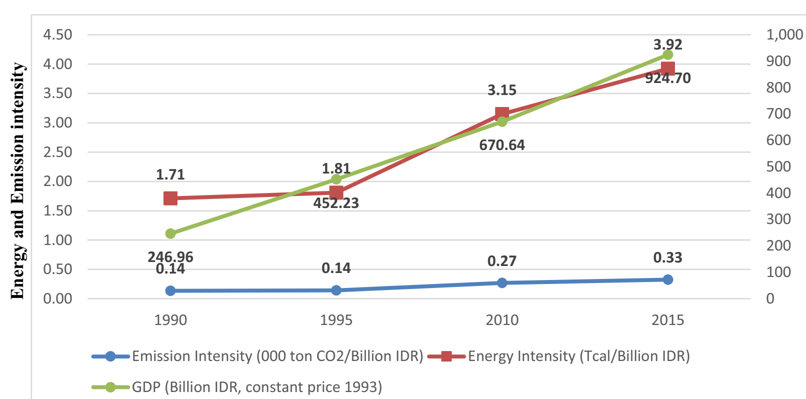

Fig. 1 Energy intensity, emission intensity, and GDP. Source: BPS with Author's Calculation (2020)

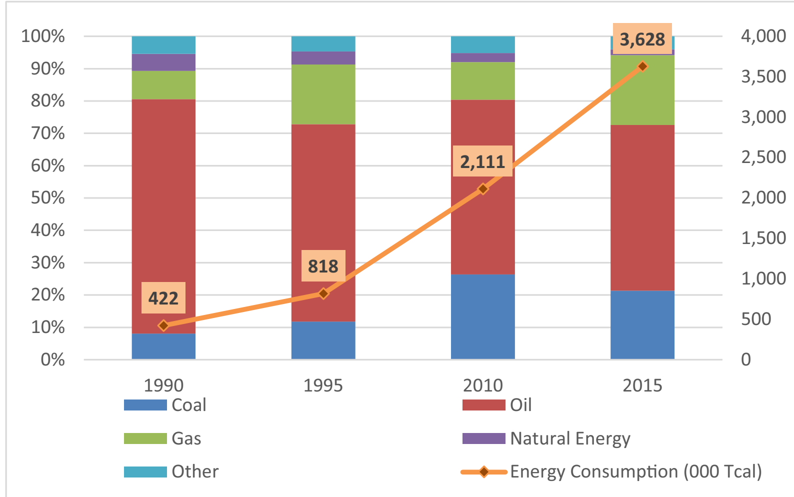

Fig. 2 Primary energy mix and total energy consumption. Source: BPS with Author's Calculation (2020)

2010–2015. Between the initial period, the amount of CO_2 emissions increased by 31.3 million tons, while it rose to 121.4 million tons within the same year range between 2010 and 2015. In both periods, the accretion of final demand was the main driver of the emission increase. This result was commonly found in other countries (Hu et al. 2017; Kim et al. 2015; Nie et al. 2016; Wei et al. 2017). However, it is interesting to note that the contribution of the final demand/scale effect was low in 2010–2015 compared with 1990–1995. This result implied that other factors contribute to the high rise of emission in 2010–2015, especially energy intensity factor, which contributed to around 66 Million tons of emission (54.3%).

Figs. 3 and 4 depict the embodied emission for each cluster sectors. This study classified 48 sectors into 8 clusters, namely, agriculture, mining, manufacture (non-oil and gas), manufacture (oil and gas), utilities, construction, transportation and communication, and trade and services. In 1990–1995, the highest embodied emission was found in manufactures (non-oil and gas), such as chemical, cement, and pulp and paper sectors, followed by utilities (such as electricity), mining, construction, and transportation communication. All mentioned clusters consisted of energy-intensive sectors. Thus, it is logical that these sectors are the highest contributor to energy-related emissions. Scale effect/total final demand factor was the primary contributor to the emission in all industries.

Meanwhile, there was a change in the rank of the emission contributors in 2010–2015. Mining is the first contributor to emissions. Interestingly, this is not caused by an increase in final demand factors. The change in energy intensity plays a significant role. A substantial contribution to energy intensity is also found in the manufacture sector (non-oil and gas) and the oil and gas manufacture, indicating that there were sectors that might experience a decrease in energy efficiency. However, this result could be due to an increase in energy consumption or a significant rise in demand growth (Isaksen 2011). On the other hand, declining energy intensity was seen in the utilities, construction, and transportation and communication sectors. Yet, this decline was outdrawn by the effect of increasing efficiency (technology) in production due to the changes in the Leontief factor.

Table 3 Driving factors of CO_2 emission changes

000 tons							
,	Carbonization factor	Energy intensity factor	Technology factor	Demand structure factor	Demand allocation factor	Final demand (scale effect)	Total change in emission
	(Δe_C)	(Δe_E)	(Δe_I)	(Δe_S)	(Δe_D)	(Δe_F)	(Δe)
1990–1995	717	441	1200	914	− 534	28,544	31,283
in %	2.3%	1.4%	3.8%	2.9%	− 1.7%	91.2%	100.0%
2010–2015	500	65,985	10,755	− 24,162	− 1082	69,438	121,433
in %	0.4%	54.3%	8.9%	− 19.9%	− 0.9%	57.2%	100.0%

Source: Author's Calculation (2020)

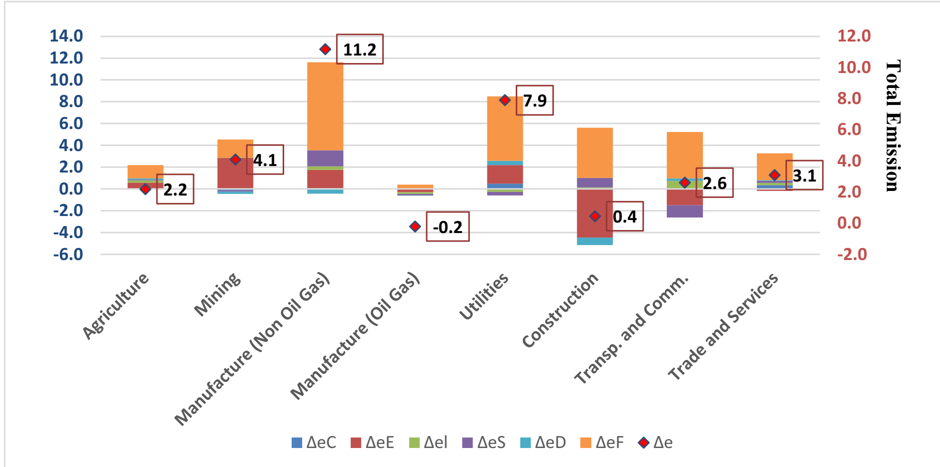

Fig. 3 Embodied emission between 1990 and 1995 in Sector Cluster. Source: Author's Calculation (2020)

From the decomposition analysis of each sector, it was found that all clusters, except trade and service and agriculture, had a significant emission contribution. There were three types of factors that determined the emission changes: elements from the difference in the structure of energy consumption, factors from change production efficiency (Leontief), and external factors from the change in final demand. The following discussion will be looking at the contribution of CO_2 emissions to changes from mining, manufacture (non-oil and gas), manufacture (oil and gas), utilities, construction, transportation, and communication clusters, especially calculated at the contribution of energy consumption factor and Leontief factor. Meanwhile, the contribution of structural demand factor, demand allocation factor, and scale effect were grouped into one indicator, namely, embodied emissions due to changes in final demand (Δe_{yd}).

In 1990–1995, the contributions of the mining and manufacture sectors for oil and gas products were not precisely determined the total emission level. In this time interval, energy policy was initially aimed at diversifying primary energy consumption from oil-based to coal and metal ores. Thus, there was a decrease in demand for oil fuels reducing emissions, and yet, the effect was less than an increase in emissions due to the rise of coal mining (embodied high emission value). Besides, coal tends to have the lowest energy conversion rate (Rustandi 2017). Thus energy-related emission was worse in the mining sector, even though it did not significantly change the total emission level.

On the other hand, the total emissions embodied in these two cluster sectors were the highest among all the sectors between 2010 and 2015. Refinery products, coal, and metal ores mining, as well as oil and natural gas, emitted 17.1, 15.5, and 12.5 million tons of CO_2, respectively (see Table 4). Leontief effect was higher in mining sectors, leading to a drop in emission, especially for coal and metal ores mining. Yet, the emission due to a rise in energy intensity outdraws the adverse effect. Additionally, the carbonization factor did not affect energy-related emissions in 1990–1995 but contributed to 3.8 million tons between 2010 and 2015. A significant increase in crude oil energy consumption was reported as the leading cause of high emission.

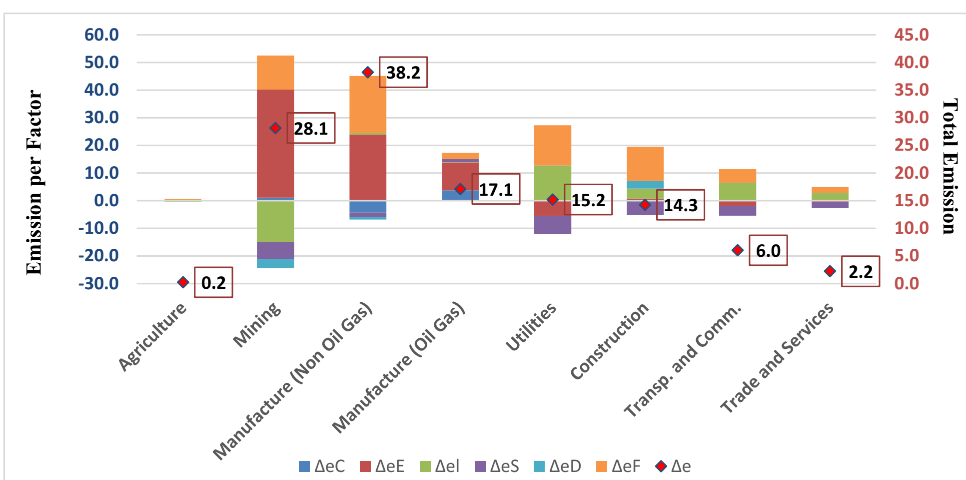

Fig. 4 Embodied emission between 2010 and 2015 in Sector Cluster. Source: Author's Calculation (2020)

Table 4 Driving factors of CO_2 emission changes in mining and manufacture (oil and gas)

	1990–1995 (in a million tons)					2010–2015 (in a million tons)				
	Δe_C	Δe_E	Δe_l	Δe_{yd}	Δe	Δe_C	Δe_E	Δe_l	Δe_{yd}	Δe
Mining										
Coal and Met. Ores Min.	0.0	0.7	0.1	1.1	1.8	0.0	24.9	− 14.3	1.8	12.5
Oil and natural gas	− 0.1	1.8	− 0.1	− 0.1	1.5	1.1	14.6	− 0.7	0.5	15.5
Non-metallic ores Min.	0.0	0.4	0.1	0.3	0.8	0.0	− 0.4	0.0	0.5	0.2
Manufacture (oil and gas)										
Refinery Prod.	0.0	− 0.3	− 0.2	0.2	− 0.2	3.8	10.0	0.1	3.2	17.1

Source: Author's Calculation (2020)

Similar results were also found in manufacturing industries for non-oil and gas products (Table 5). There was not a significant change in emissions between 1990 and 1995. The highest contribution was found in the non-metallic mineral product, mainly due to an increase in final demand factors. In that period, the 5-year development policy (Pelita), stages V and VI, was implemented. These stages were aimed out by accelerating the transfer of high technology and strengthening the existence of strategic industries previously built. Also, the implementation of government regulation No. 20 in 1994, which permits foreign equity investment, encourages manufacturing growth (Sitompul and Owen 2006). Therefore, this may be related to an increase in demand for manufactured products such as the food industry, textiles, iron, and steel products, as well as non-metallic products indirectly leading to a slight rise in emissions.

On the other hand, between 2010 and 2015, energy intensity factors in the chemical industry played a significant role in rising energy-related emissions. Energy intensity does not necessarily tell how efficient energy is used in a given sector. The energy intensity of a country depends, at least on the structure of the economy, climate, and landscape (Isaksen

Table 5 Driving factors of CO_2 emission changes in manufacture (non-oil and gas)

	1990–1995 (in million tons)					2010–2015 (in million tons)				
	Δe_C	Δe_E	Δe_l	Δe_{yd}	Δe	Δe_C	Δe_E	Δe_l	Δe_{yd}	Δe
Manufacture (non-oil and gas)										
Food Ind.	− 0.1	0.9	0.1	1.1	2.0	0.0	0.1	− 0.1	0.4	0.4
Beverages Ind.	0.0	0.0	0.0	0.1	0.1	0.0	0.0	0.0	0.0	0.0
Tobacco	0.0	0.0	0.0	0.1	0.1	0.0	− 0.2	− 0.1	0.5	0.2
Textile Ind.	0.0	0.4	0.0	0.9	1.3	0.0	− 0.1	− 0.2	0.6	0.3
Leather Prod.	0.0	0.0	0.0	0.1	0.1	0.0	0.0	0.0	0.0	0.0
Timb. and wood Prod.	− 0.1	− 0.2	0.1	1.3	1.1	0.2	− 0.2	− 1.0	1.2	0.2
Furniture Ind.	− 0.3	− 1.1	0.0	1.5	0.1	0.5	− 0.8	− 0.3	0.9	0.2
Pulp and paper Prod.	0.0	0.2	0.1	0.6	1.0	0.0	− 0.7	0.5	0.2	0.1
Print. and Publ.	0.0	0.0	0.0	0.0	0.0	0.0	1.5	− 1.1	− 0.3	0.0
Chemical Ind.	0.0	0.1	0.0	0.3	0.5	− 5.1	27.6	− 1.6	6.2	27.1
Rubber Ind.	0.0	0.0	0.0	0.1	0.2	0.0	0.9	− 0.7	0.1	0.3
Plastic Ind.	0.0	0.0	0.0	0.1	0.1	0.0	0.6	− 0.6	0.8	0.8
Non-metallic Min. Prod.	0.3	0.7	0.1	1.7	2.7	0.0	− 6.9	5.2	5.7	4.1
Basic iron and steel Ind.	0.0	− 0.1	− 0.2	0.3	0.0	0.0	− 0.5	0.9	0.4	0.8
Iron and steel Ind.	0.0	0.6	0.1	0.5	1.2	0.0	− 1.0	1.6	0.7	1.3
Non-ferrous Met. Prod.	0.0	− 0.1	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0
Other Fab. metal Prod.	0.0	0.1	− 0.1	0.2	0.2	0.0	3.7	− 1.4	0.1	2.4
Elect. Mach. and Equip	0.0	0.1	0.0	0.2	0.4	0.0	0.0	− 0.3	0.6	0.3
Oth. Man. Prod.	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Source: Author's Calculation (2020)

2011). As there was no environmental aspect change between 2010 and 2015, the economic structure might be the underlying reason for changes in energy intensity. Comparing energy consumption and economic growth in the chemical industry sector, the GDP growth from the chemical industry was only 0.4%, while energy consumption grew by 2.7%. Those values showed that the increase in demand for the chemical industry was not as fast as the increase in energy consumption. One possible reason was that since 2013, premature deindustrialization was indicated to strike, one of which was shown in the chemical industry. The GDP growth from these sectors dropped continuously in 2013. As the sector was an energy-intensive sector, the sector might need a longer time to adapt its energy-related technology with a continuous decline in demand.

Additionally, the study by Irawan et al. (2010) showed that there was no change in technology used in the industrial sector. Thus, the use of technology relatively unchanged indicates a waste of energy. The increase in embodied emission from energy intensity changes was also found in other energy-intensive sectors such as the rubber industry, plastic industry, and other fabricated metal products.

At the same time, efficiency in production from the Leontief factor contributed either negatively or idled to the emission in most manufacturing sectors. Yet, the effect was less than the impact of demand change and energy intensity factor. Meanwhile, the carbonization factor only slightly contributed to the embodied energy emission in several sectors, implying that energy consumption composition was unchanged in most manufacturing sectors.

Table 6 shows the decomposition results from three sector clusters, i.e., construction, utilities, and transportation, and telecommunication. Between 1990 and 1995, a significant contribution to the rise in emission came from the electricity sector with 7.1 million tons of emission. Energy policy in that period focused on increasing energy supply, which was still at a low level to support economic growth. Therefore, the increase in final demand encouraged a rise in emissions from the electricity sector. Moreover, the primary energy sources of the electricity sector were fuel oil and coal. Thus, electricity was the most significant contributor to emissions in 1990–1995.

In 2010–2015, three sectors were reported to have high increments in embodied emissions, namely, the construction sector, electricity, and road transportation. For the construction sector, the final demand factor was the main contributor, followed by the Leontief factor, and the energy intensity factor. During President Jokowi Widodo’s administration, which began in 2014, infrastructure development to increase the country’s competitive value was one of the top priorities. The infrastructure budget for 2015 reached IDR 280.3 Trillion (USD 19.0 Billion), almost tripled that of 2010 (Ministry of Finance 2018). With the increasing demand for the construction sector, the energy needed to move supplies and other necessary materials to construction sites and transport dirt stone and waste rose, leading to an incline in energy-related emission. The increase in final demand also contributed to encouraging embodied emission in the electricity sector.

Additionally, inefficiency production marked by the increased contribution of the Leontief factor in the electricity sector encouraged increased emissions. Even though there was a decrease in energy intensity, the increase from final demand factors and the Leontief factor outdrew the adverse effect. Meanwhile, road transportation also contributed to the emission of 3.2 million tons, mainly due to the Leontief factor and final demand factor. In 2010–2015, there was a significant reduction in gasoline subsidies. Rustandi (2017) found that energy efficiency conditions in the industrial sectors and

Table 6 Driving factors of CO_2 emission changes in construction, utilities, and transportation and telecommunication

	1990–1995 (in million tons)					2010–2015 (in million tons)				
	Δe_C	Δe_E	Δe_l	Δe_{yd}	Δe	Δe_C	Δe_E	Δe_l	Δe_{yd}	Δe
Construction	0.0	− 4.4	0.1	4.8	0.4	0.0	0.7	3.7	9.8	14.3
Utilities										
Electricity	0.1	1.6	− 0.3	5.7	7.1	0.0	− 4.3	12.4	7.1	15.2
Gas and water	0.3	0.1	0.1	0.3	0.8	0.0	− 1.2	0.1	1.1	0.0
Transportation and telecommunication										
Railway Trans.	0.0	0.1	0.0	0.1	0.2	0.0	− 0.1	0.1	0.0	0.0
Road Trans.	0.0	− 1.0	0.4	1.4	0.8	0.0	− 0.1	3.1	0.2	3.2
Water Trans.	0.0	− 0.3	0.1	0.6	0.4	0.0	1.2	0.0	− 0.4	0.8
Air Trans.	0.0	− 0.1	0.1	0.9	0.9	0.0	− 3.0	3.2	1.6	1.8
Trans. related Serv.	0.0	− 0.2	0.1	0.3	0.2	0.0	0.0	0.1	0.0	0.0
Post. and Telecomm. Serv.	0.0	0.0	0.0	0.1	0.1	0.0	0.0	0.0	0.0	0.0

Source: Author’s Calculation (2020)

households were firmly related to the energy selling prices. That might be the cause of the negative effect of embodied emission from the energy intensity factor, even though the impact was relatively small.

Focusing on the demand factor, Fig. 5 shows the decomposition only from the demand factor, including changes in structural demand, final demand allocation, and scale effect (total final demand) from the economy. It showed that the impact of fundamental demand and scale (final demand) was more apparent in 2010–2015 compared with 1990–1995. In 1990–1995, the contribution of the final demand factors only occurred due to an increase in overall economic growth (scale effect) without any impact from changes in the structure of demand on the economy or changes in users of final demand. However, in 2010–2015, the demand for energy-intensive sectors such as electricity and coal and metal ores mining structurally declined compared with other sectors, thus contributing negatively to emissions. Even so, the overall increase in economic growth was quite significant so that in aggregate terms, factors from the final demand side still contributed positively to emissions.

Conclusions

This study attempted to decompose energy-related emissions in 1990–1995 and 2010–2015 into six driving factors: energy intensity, carbonization, technology, demand structure, consumption allocation patterns, and final demand. These six factors were developed from Kaya Identity as a basic equation that has been widely used by academics in examining changes in emissions.

The aggregate results showed that the growth of energy-related emissions in Indonesia was primarily due to the increase in economic activities (scale effect) both in 1990–1995 and 2010–2015. In 1990–1995, manufacture from non-oil and gas products (particularly the food industry, non-metallic mineral products, textile, and iron and steel industry), electricity, and construction were having the highest

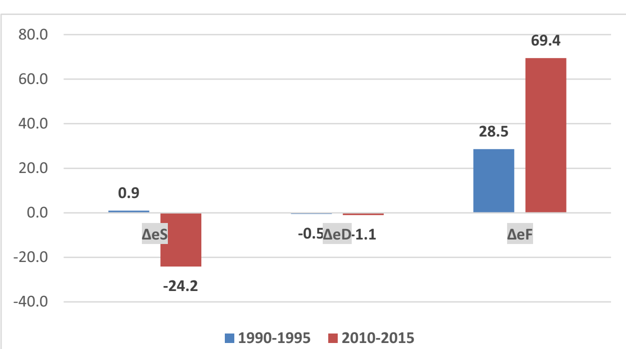

Fig. 5 Embodied emission between 2010 and 2015 in final demand factor (million tons CO_2). Source: Author's Calculation (2020)

embodied emission. About 91% of the changes in embodied emission were due to an increase in scale effect, while other factors were relatively unaffected. The implementation of policy programs for strengthening the manufacturing sector and allowing foreign direct investment may have a role in the increment of the manufacturing sector and the entire sector in general.

Meanwhile, the CO_2 emissions increased by 4-folds in 2010–2015 (in the same interval period). Even so, the role of the scale effect decreased to 57.2% and replaced with the contribution of other factors: the energy intensity factor, technology (Leontief) factor, and the demand structure factor. The embodied emission of the change in chemical industry energy intensity increased significantly. A similar condition also occurred in several other energy-intensive sectors such as mining, rubber industry, plastic industry, and other fabricated metal products. Deindustrialization is suspected to be the reason for the decline in demand in the manufacturing sector. In contrast, the energy-intensive sector (energy-related technology adaptation process) is not fast enough, causing an increase in energy intensity. On the other hand, there was a decrease in embodied emissions due to a drop in energy intensity factor in the electricity sector and almost all modes of transportation. It is suspected that the withdrawal of energy subsidies could be one of the reasons for energy efficiency in several sectors. Also, there was a decrease in structural demand for energy-intensive sectors such as mining and electricity, thus contributing negatively to emission growth. However, inefficiency in production, as well as encouragement from the final demand (scale effect), outdraws the adverse impact. Meanwhile, the carbonization factor has relatively no effect.

Two types of energy policies were implemented in each interval. In 1990–1995, the energy policy aimed to utilize energy sources without considering environmental aspects, while in 2010–2015, energy efficiency and renewable energy shared targets were implemented. Yet, comparing 2010 and 2015, energy intensity in several sectors increased instead, and there was no change in the primary energy mix. This study suggests that the government evaluates energy efficiency policies, especially for the chemical industry, mining, and rubber and plastic industries. Besides, increasing the composition of gas and renewable energy in all sectors needs to be intensified to reduce embodied emissions. Sectors experiencing inefficiency production such as electricity, road and air transportation, and non-metallic mineral production need more attention because they may indirectly contribute to emission. Although the research conducted in this study has led to an important identification of emission driving factors, this study used absolute indicator of emission which does not consider the size of GDP of a country. Therefore, we recommend further research focusing on emission intensity in Indonesia.

Authors' contributions All authors contributed to the study conception and design. Sasmita Hastri H. concepted the paper, processed the data, interpreted and analyzed the result, wrote original draft and editing; Djoni Hartono concepted the paper, interpreted and analyzed the result, reviewed the paper, supervising; Titi Muswati Putranti prepared the data; Muhammad Handry Imansyah prepared the data.

Data availability The datasets generated and/or analyzed during the current study are not publicly available but are available from the corresponding author on reasonable request.

Compliance with ethical standards

Ethics approval The authors commit to uphold integrity of the scientific record by complying with ethical standards.

Contest to participate Not applicable.

Consent for publication Not applicable.

Conflict of interest The authors declare that they have no conflict of interest.

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