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Analysis of the drivers of CO_2 emissions and ecological footprint growth in Australia

Hasan Rüstemoğlu [ORCID]

Abstract This paper investigates the determinants of environmental degradation in Australia from 1990 to 2017, using ecological footprint analysis and the well-established logarithmic mean Divisia index (LMDI) decomposition method. Additionally, decoupling factor analysis was performed to examine the link between environment related variables (CO_2 emissions and ecological footprint) and their determinants such as real income and population. The decomposition analysis considered the impact of five different factors on CO_2 emissions: income effect, population, energy intensity, energy structure, and carbon intensity. For decoupling factor analysis, the link between ecological footprint and its two determinants, real income and population, was examined. Furthermore, the possible decoupling between CO_2 emissions and these determinants was also analyzed, because CO_2 emissions are the main cause of the country's increasing ecological footprint. The present study has a more comprehensive approach because it analyzes the factors affecting environmental degradation in Australia by assigning two proxies (CO_2 emissions and ecological footprint) as dependent variables. The results confirmed that Australia's ecological reserve substantially declined over the past three decades due to deforestation and energy industries. The LMDI results demonstrated that income effect, population, and carbon intensity were the main factors that raised Australia's CO_2 emissions, whereas the energy intensity factor substantially curbed them. The reducing impact of energy structure on CO_2 emissions was minimal; thus, Australia was not able to prevent an upward trend in CO_2 emissions. Lastly, an analysis of Australia's CO_2 emissions according to economic activities was conducted for the period between 1990 and 2017 in order to understand other factors that may have affected environmental sustainability.

Keywords CO_2 emissions · GHG · Energy · LMDI · Decomposition analysis · Decoupling factor · Sustainability

Introduction

It is a necessity for countries to realize their economic growth successfully in order to increase their living standards. However, as Işık et al. (2020) stated, energy consumption is a critical aspect in achieving strong economic growth. In this context, the keyfactor is the type of energy that is used. Since the industrial revolution, the global economy has been using fossil fuels as an energy source due to their abundance and relative cost-effectiveness. However, these widely-used fossil fuels have also brought certain problems.

H. Rüstemoğlu (✉)
Faculty of Economics and Administrative Sciences,
Cyprus International University, via Mersin 10,
99280 Nicosia, Turkey
e-mail: hrustemoglu@ciu.edu.tr

As Marques et al. (2019) highlighted in their study, the extensive use of fossil fuels raised the global CO_2 emissions substantially. According to International Energy Agency (IEA) data, CO_2 emissions around the world increased from 20.5 gigatons (GT) to 32.8 GT over the period 1990–2017. Accordingly, the per capita CO_2 emissions rose from 3.4 to 4.4 tons in the same period (IEA, 2020). It is widely accepted that greenhouse gas (GHG) emissions and specifically carbon dioxide (CO_2) emissions are the main cause of climate change and global warming. The carbon dioxide (CO_2) emissions account for the largest proportion of GHG emissions.

Australia is one of the countries with the highest CO_2 emissions. In 2017, its CO_2 emissions were 1.5 times higher than the level recorded in 1990. Moreover, between 1990 and 2017, the country's per capita CO_2 emissions increased from 16.3 to 17 tons, and these values were four times greater than the global per capita emissions (IEA, 2020). Additionally, the country's economy is heavily dependent on energy. Australia is a net coal exporter in the region, and almost all economic activities are dependent on oil, natural gas, and coal. Therefore, in this context, Australia bears similarities with the USA rather than with Germany, Denmark, and Spain among developed nations. In general, the energy and environment-related dynamics of the country are parallel to developing nations rather than developed ones.

Australia has also recently faced inconsistent weather conditions caused by global warming. One certain result of such climate imbalances was the devastating bushfires that impacted the country before the emergence of the COVID 19 pandemic. In addition to bushfires, the country is dealing with other environmental issues such as illegal deforestation, which is reducing its biodiversity and increasing the ecological degradation. Therefore, understanding Australia's situation in terms of climate justice and sustainability has become important.

This study aims to analyze Australia's environmental conditions from a multi-dimensional perspective. Two different approaches, namely, decoupling factor analysis and logarithmic mean Divisia index (LMDI) analysis, are utilized to accomplish this goal. The intended contributions to the literature are as follows:

(1) In the published literature, scholars have mainly investigated the link between CO_2 emissions and real income (Freitas & Kaneko, 2011). However, in this study, the possible decoupling between CO_2 emissions and other components (such as population) will be also computed. Therefore, a more detailed decoupling factor analysis can be performed to understand the trends in Australia's CO_2 emissions over time.

(2) The present study uses the decoupling factor, which was adapted by Zhang (2000) and adopted by the OECD (2002), to examine the link not only between CO_2 emissions and its determinants but also between ecological footprint and its two determinants. Although CO_2 emissions are the primary determinants of ecological footprint, a decoupling factor analysis was also performed to analyze the link between ecological footprint and its two determinants (i.e., real income and population). By conducting this kind of analysis, the researcher aims to determine whether income and population drive the country towards an ecological deficit. Ecological footprint is also used as a proxy variable in this study because it is a more comprehensive environmental variable than CO_2 emissions.

(3) In this study, the temporal changes in Australia's CO_2 emissions are elucidated by utilizing the LMDI technique. The LMDI method is based on the Kaya identity and considers the impact of four factors on CO_2 emissions: capita real income, energy intensity, carbon intensity, and population. In the current analysis, however, one more variable is added, namely, the energy structure, to determine the influence of more factors on CO_2 emissions. Hence, the aim is to perform a more detailed decomposition analysis on changes in CO_2 emissions.

(4) Rüstemoğlu (2019) also examined ecological footprint and CO_2 emissions in his paper; however, he evaluated only the per capita ecological balances in Germany by subtracting the per capita ecological footprint from the per capita bio-capacity. The present study aims to build on Rüstemoğlu's research by conducting decoupling factor analysis not only for CO_2 emissions but also for ecological footprint. CO_2 emissions have the greatest effect on the ecological footprint of Australia, but other factors affect the ecological balances. Thus, a decoupling factor analysis for ecological footprint could be more helpful in

identifying the trends in Australia's ecological degradation.

(5) By conducting an LMDI decomposition analysis, Rüstemoğlu (2019) demonstrated that Germany is an impressive example for reducing the CO_2 emissions. He conducted a decomposition analysis for Germany, for the time period between 1990 and 2015, focusing on four factors—namely, per capita income, population, energy intensity, and carbon intensity. In the present study, a similar approach has been followed. However, the impact of a fifth factor on CO_2 emissions (i.e., the energy structure) was also examined. Inspired by Rüstemoğlu (2019), the present study will compare the LMDI results between Australia and Germany in the conclusion section of the present paper.

The remainder of this paper is organized as follows. "2" reviews the published decomposition analysis studies, mainly about Australia but also for some other countries. "4" summarizes the energy market of the country. "5" provides an ecological footprint analysis for the country. "6" explains the research methodologies that are applied in this paper. "10" presents the empirical findings. "13" discusses the findings, and "14" concludes the paper.

Literature review

Some of the studies compared the changes in Australia's CO_2 emissions with other countries (Malla, 2009; Madaleno et al., 2018). Madaleno et al. (2018) also involved financial indicators in the research equation while analyzing the factors that affected CO_2 emissions.

For decomposition of changes in energy-related CO_2 or GHG emissions, two major groups of decomposition approaches are used. The first group comprises structural decomposition analysis (SDA), while the second group includes index decomposition analysis (IDA) studies. However, the IDA methods are used more frequently than the SDA methods in the decomposition analysis literature.

A specific SDA study was conducted for Australia. Wood and Lenzen (2009) combined structural decomposition analysis and structural path analysis

to develop a new technique called structural path decomposition. As a case study, the researchers tested their new method for Australia for the period between 1995 and 2005.

Zhou et al. (2019) analyzed the factors that affected waste generation in Australia for the period between 2007 and 2014. Using structural decomposition analysis (SDA), the researchers found that households' economic activity was responsible for the increase in waste generation. They also reported that the changes in the production mix of final demand reduced waste generation during the studied period. Zhou et al. (2019) concluded that the manufacturing sector has the highest waste generation intensity and requires special attention in terms of waste reduction.

The electricity and heat production sectors are among the leading sectors that produce a high amount of CO_2 emissions. Therefore, these sectors have gained the attention of researchers. One of the studies that analyzed CO_2 emissions generated by these economic activities was conducted by Malla (2009) for seven Asia–Pacific and North American countries including Australia, Canada, China, India, Japan, Korea, and USA for the period over 1990–2005. Adopting the LMDI method, the researcher focused on the impacts of three contributing factors, namely, the production effect, energy structure effect, and intensity effect. The analysis revealed that the production effect was the leading determinant in the increase in CO_2 emissions. The researcher also concluded that the energy structure effect increased the CO_2 emissions in the selected countries, albeit by a smaller rate. The findings of this study also demonstrated that the intensity effect had a minor reducing impact on CO_2 emissions in the electricity sector in the studied period.

The IDA methods were not only used for the examination of determinants that change CO_2, but also for the identification of factors that affect energy efficiency. Adopting the LMDI approach, Shahiduzzaman and Alam (2013) decomposed the energy intensity in Australia over the period 1978–2009. The impacts of three identifiers on energy intensity were considered, namely, energy efficiency, fuel mix, and structure effect, in accordance with the sector-level and sub-sector level. The authors reported that energy efficiency and the structure effect were the two factors that reduced Australia's energy intensity in the reviewed period.

Shahiduzzaman et al. (2015) provided a decomposition analysis for Australia's total and per capita CO_2 emissions for the period 1978–2010 by adopting the LMDI method. Their findings indicated that the energy efficiency and structural changes in the country's economy lead to a modest decline in Australia's total emissions. The authors also reported that Australia's efforts to mitigate emissions should be remarkably higher in 2010–2020 period as compared to the 2005–2010 period.

Some case studies have analyzed the factors that lead to changes in GHG emissions rather than CO_2 emissions. For example, Shahiduzzaman and Layton (2015) provided a decomposition analysis of GHG emissions in Australia for the period between 1990 and 2013. Utilizing the LMDI method, the researchers focused on the impacts of five determinants in GHG emissions: GHG intensity, energy intensity, structural change, wealth, and population. The authors concluded that Australia's 2030 target of reducing the GHG emissions by 26–28% below the 2005 level would be very difficult to achieve if the mitigation efforts applied in the period between 2002 and 2013 continued until 2030. They also reported that if the reducing impacts of GHG intensity, energy intensity, and structural change factors for the period 2006–2013 could be continued until 2030, the mitigation target would be less difficult to achieve.

Madaleno et al. (2018) focused on the factors affecting CO_2 emissions in 23 countries, including Australia, for the period between 1985 and 2011. Adopting the LMDI method, the researchers focused on the impact of six factors on CO_2 emissions — namely, carbon trade intensity, the trade of fossil fuels effect, fossil fuels intensity, renewable sources productivity, the electricity financial power effect, and the financial development effect. The researchers concluded that the productivity of renewable sources and the financial development effect in renewable electricity production per GDP were the two leading determinants of CO_2 emissions. In addition, they reported that the fossil fuel energy consumption effect increased CO_2 emissions in the research countries.

Marques et al. (2019) provided another environmental analysis for Australia's GHG emissions over the period 1990–2015. The researchers combined LMDI decomposition analysis with Tapio's (2005) decoupling method in their study. Their findings revealed that two of Australia's economic structures,

agriculture and commercial services, exhibited strong decoupling, whereas the remaining sectors showed weak decoupling. Regarding the decomposition analysis, the researchers evaluated the impacts of five factors on GHGs, namely, economic activity, economic share, energy emissions, energy intensity, and GHG intensity. Marques et al. (2019) concluded that Australia successfully reduced the level of GHG emissions. They also highlighted that construction and agriculture sectors were the most and least efficient sectors in terms of the efficiency of economic activities, respectively.

In addition to Australia, there are some other countries that were investigated to find the factors that increased or decreased their emissions in the relevant literature. For instance, Yu et al. (2021) provided a decoupling factor analysis and decomposition analysis for CO_2 emissions resulting from China's residential buildings utilizing Tapio's approach for the decoupling factor analysis and the LMDI approach for the decomposition analysis. Yu et al. (2021) focused on four different factors, including residential building CO_2 emissions, per capita CO_2 emissions, residential carbon intensity, and per capita GDP across 30 provinces of China over the period 2000–2015. The results of the study confirmed that the decoupling trend between per capita GDP and carbon intensity transformed from weak decoupling to strong decoupling in 30 Chinese provinces during the study period.

Similar to China, Turkey is also widely studied in the decomposition analysis literature. Recently, Rüstemoğlu (2021) conducted a decomposition analysis for Turkish CO_2 emissions at aggregated and sector levels for the period between 1990 and 2017. Although Turkey-related decomposition analysis studies mainly used the LMDI method, Rüstemoğlu (2021) performed the analysis by utilizing the Shapley method. The analysis focused on the effects of five factors in changes of CO_2 emissions, such as scale effect, migration effect, population, energy intensity, and carbon intensity, at the aggregated level. Regarding the sector-level analysis, the electricity and heat production sectors were considered, and the effects of four factors on emissions (income effect, electricity intensity, fuel structure, and pollution coefficient) were computed. Empirical results of the study showed that Turkey's total emissions decreased only due to the energy intensity factor. For electricity and

heat production activities, it was reported that the pollution coefficient was the only factor that reduced Turkey's sectoral CO_2 emissions.

Lastly, Alajmi (2021) analyzed the factors that led to changes in greenhouse gas (GHG) emissions in Saudi Arabia over the period between 1990 and 2016. The author adopted the LMDI method and examined the effects of three factors (energy effect, activity effect, and population effect) on Saudi Arabia's GHG emissions. The empirical findings demonstrated that all three factors increased GHG emissions in Saudi Arabia, with the highest increasing effect being the energy effect. Table 1 briefly summarizes the studies focused on Australia and some other countries in the relevant literature.

Recent developments regarding decoupling factor methods

Studies on decoupling factor methods have become relatively popular in the extant literature. Some researchers established new methods for decoupling, whereas others directly used Tapio's decoupling factor. For instance, based on the LMDI approach, Song and Zhang (2017) developed a new decoupling method to examine the link between energy-deriving factors and energy-saving factors. The researchers used China's energy use as a case study to test the new method. Zhang et al. (2017) also analyzed China as a case study; however, they tested the possible decoupling between CO_2 emissions and GDP instead of the decoupling between energy use and GDP. The researchers reported that China's dependence on coal for primary energy consumption reduced its potential to have a strong decoupling between CO_2 emissions and GDP. Recent studies have focused on economic sectors, such as residential buildings and transport (Zhang and Bai, 2018; Song et al., 2019). Zhang and Bai (2018) used Tapio's decoupling factor to examine the decoupling state of residential energy use in Shandong province, China, for the period between 1995 and 2013. On the other hand, Song et al. (2019) focused on China's transport sector and reported that related CO_2 emissions have some mitigation potential. Song et al. (2019) reached this conclusion using the LMDI approach and the decoupling factor. Another interesting study combined gravity movement and Tapio's decoupling for the analysis of global-level energy-related CO_2 emissions (Zhang and Song,

2019). The researchers concluded that strong decoupling was rarely observed in developing nations over the 2010–2015 period. Finally, Zhang et al. (2020) proposed a new two-dimensional decoupling model to evaluate the decoupling state of the energy footprint of 39 countries for the period between 1995 and 2014. The results of the study demonstrated that 57% of the countries exhibited weak decoupling between energy footprint and GDP, whereas the proportion of countries with a strong decoupling stage was 36%.

Overview of energy market in Australia

Energy is a fundamental component of continuous economic growth in any country. In Australia, total energy consumption increased by 44.5% from 56,651 ktoe (kilotons of oil equivalent) to 81,843 ktoe between 1990 and 2017 (IEA, 2020). However, the country's energy production increased by 47.5% from 86,139 to 127,032 ktoe in the same period (IEA, 2020). Therefore, Australia is one of the few members in the OECD that is an energy exporter (EIA, 2020). In 2015, the country was the leading coal exporter and second-largest liquefied natural gas (LNG) exporter in the world (EIA, 2020).

Oil was the dominant source of Australia's energy consumption during the studied period. According to the IEA (2020) database, oil consumption in Australia increased from 28,994 to 43,644 ktoe between 1990 and 2017. Hence, the share of oil in total energy consumption was calculated as 51.2% and 53.3% for the years 1990 and 2017, respectively. As stated by the EIA (2020), Australia's oil production has drastically declined since 2000. Resultantly, the country's oil import dependence has increased. Australia mainly imports oil products from Singapore and South Korea, whereas other supplies include Japan, China, and India (EIA, 2020).

Electricity made the second largest contribution to total energy consumption in Australia during the reviewed period. The share of electricity in total energy consumption was equal to 19.6% (in 1990), and it increased to 22.1% (in 2017) as indicated by IEA (2020) data. The country's total electricity production increased by 63.1% from 11,110 to 18,115 GWh between 1990 and 2017 (IEA, 2020). Electricity is a type of secondary energy, and it is produced

Table.1 Brief summary of the published studies in the relevant literature

| Author(s)	Name of the study	Method	Case country	Factors analyzed
Wood and Lenzen (2009)	Structural path decomposition	Structural decomposition analysis + Structural path analysis	Australia (1995–2005)	SPA (structural path analysis) and SPD (structural path decomposition) of wood products in country's different sectors are calculated
Malla (2009)	CO_2 emissions from electricity generation in seven Asia–Pacific and North American countries: A decomposition analysis	LMDI	Australia, Canada, China, India, Japan, Korea, USA (1990–2005)	Production effect, energy structure, intensity effect
Shahiduzzaman and Alam (2013)	Changes in energy efficiency in Australia: A decomposition of aggregate energy intensity using logarithmic mean Divisia approach	LMDI	Australia (1978–2009)	Energy efficiency, fuel mix, structure effect
Shahiduzzaman et al. (2015)	Decomposition of energy-related CO_2 emissions in Australia: Challenges and policy implications	LMDI	Australia (1978–2010)	**Decomposed variables:** CO_2 emissions and per capita emissions **Analyzed factors:** energy efficiency, structural changes
Shahiduzzaman and Layton (2015)	Decomposition analysis to examine Australia's 2030 GHGs emissions target: How hard will it be to achieve?	LMDI	Australia (1990–2013)	GHG intensity, energy intensity, structural change, wealth, population
Madaleno et al. (2018)	Factors affecting CO_2 emissions in top countries on renewable energies: A LMDI decomposition application	LMDI	23 countries (including Australia) (1985–2011)	Carbon trade intensity, the trade of fossil fuels effect, fossil fuels intensity, renewable sources productivity, the electricity financial power effect
Marques et al. (2019)	Decoupling economic growth from GHG emissions: Decomposition analysis by sectoral factors for Australia	LMDI + Tapio's decoupling factor	Australia (1990–2015)	Economic activity, economic share, energy emissions, energy intensity, GHG intensity
Zhou et al. (2019)	Changes of waste generation in Australia: Insights from structural decomposition analysis	Structural decomposition analysis	Australia (2007–2014)	Economic activity, production mix

Table.1 (continued)

Author(s)	Name of the study	Method	Case country	Factors analyzed
Yu et al. (2021)	Decoupling and decomposition analysis of residential building carbon emissions from residential income: Evidence from the provincial level in China	LMDI + Tapio's decoupling factor	Residential sector in China (2000–2015)	Residential building CO_2 emissions, per capita CO_2 emissions, residential carbon intensity, per capita GDP
Rüstemoğlu (2021)	Environmental analysis of Turkey's aggregated and sector-level CO_2 emissions	Shapley decomposition method	Total CO_2 emissions and electricity and heat production CO_2 emissions of Turkey (1990–2017)	Scale effect, migration effect, energy intensity, carbon intensity, population for the analysis of total emissions Income effect, electricity intensity, fuel structure, pollution coefficient for the analysis of the emissions from electricity and heat production sector
Alajmi (2021)	Factors that impact greenhouse gas emissions in Saudi Arabia: Decomposition analysis using LMDI	LMDI	GHG emissions in Saudi Arabia (1990–2016)	Energy effect, activity effect, population effect

by using both renewable and nonrenewable energy sources. Therefore, it is necessary to analyze electricity generation based on the type of the sources that are used in production. A report by the EIA (2020) showed that coal was the leading source in Australia's electricity production sector. The share of coal was 62.7% in 2017 (IEA, 2020). Natural gas followed coal in this respect. According to IEA (2020) data, the share of natural gas in electricity generation reached 19.6%, in 2017. Australia began to use solar and wind in its electricity production in 1993 and 1994, respectively. As a result, the total share of these two renewable sources reached 8% in power production at the end of the studied period. Lastly, the shares of hydro, oil, and biofuels in electricity generation were 6.3%, 2%, and 1.4% in 2017, respectively (IEA, 2020). The share of renewable energies in Australia's total electricity output was 15.7% at the end of the studied period due to the substantial efforts made to increase the consumption of renewable energy sources. Figure 1 shows the electricity production of Australia from 1990 to 2017 according to the fuel types utilized.

Natural gas had the third largest share of Australia's total energy consumption in the studied period. As a result of new projects, the country's natural gas production substantially increased in recent decades (EIA, 2020). Australia's natural gas consumption increased from 8655 to 12,936 ktoe between 1990 and 2017 (IEA, 2020), which represents an increase of 49.5%. Australia's dry natural gas production increased faster than consumption over the past three decades. According to an EIA (2020) report, Australia became the leading LNG exporting country in the Asia–Pacific region. Japan, China, and South Korea were the largest consumers of Australia's LNG, and they accounted for 51%, 28%, and 11% of LNG exports in 2016, respectively (EIA, 2020). The country's LNG exports are expected to be higher in the following years because of the anticipated increase in the production of natural gas and new LNG capacities.

The share of biofuels and waste in total energy consumption followed oil, electricity, and natural gas. According to IEA (2020) data, between 1990 and 2017, the consumption of biofuels and waste rose from 3253 to 4237 ktoe. The increase in biofuels and waste consumption was calculated to be 30.2% for this period. Although coal is the main source of

Fig. 1 Australia's electricity production based on the fuel types over 1990–2017
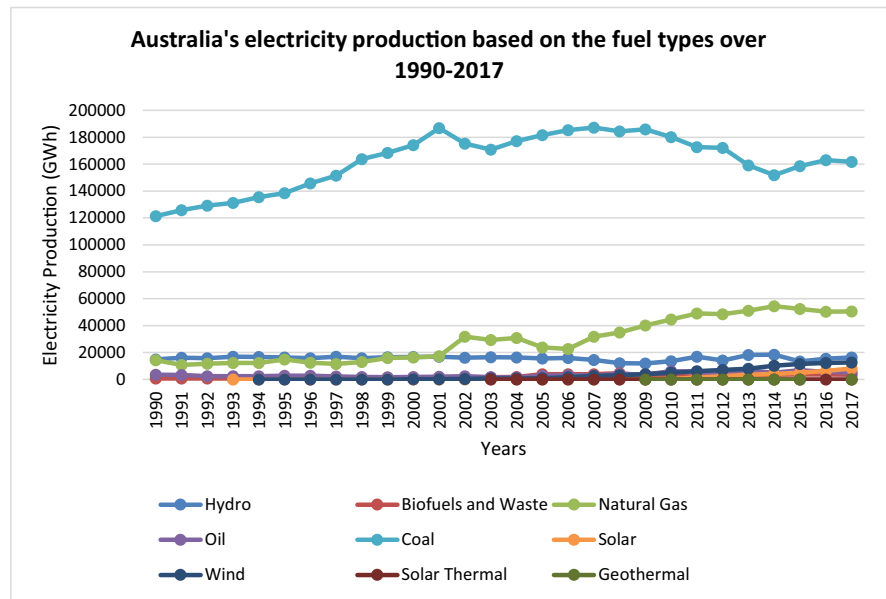
Australia's electricity generation, its share of the total energy consumption is less than oil, natural gas, and biofuels and waste. Australia's coal production increased, whereas its consumption decreased during the reviewed period. Hence, the country became the world's largest coal exporter and the share of coal revenues in total GDP was significantly high (EIA, 2020). Coal consumption in total energy consumption declined by 44.7% from 4558 to 2521 ktoe over the period 1990–2017 (IEA, 2020). The importers of Australian coal include Japan, China, South Korea, India, and Taiwan. According to an EIA (2020) report, these nations accounted for 33%, 19%, 13%, 12%, and 9% of Australia's coal exports in 2016, respectively.

In terms of the total energy consumption, the shares of wind and solar increased rapidly in the studied period. From 1990 to 2017, the total wind and solar energy consumption increased from 81 to 375 ktoe, as revealed by IEA (2020) data, which represents an increase of 363%. Figure 2 presents the energy consumption in Australia for the researched period based on the fuel types used.

Consequently, it is possible to conclude that Australia is a significant player in the world energy market. Additionally, the country is an attractive place for foreign direct investment thanks to its political stability, transparency of its regulatory structure, important energy production capacity, and geographical proximity to Asian markets including Japan, China, South Korea, and India (EIA, 2020).

Evaluation of ecological balance in Australia

Demand and supply analysis should be carried out in order to calculate the ecological balance of a natural area. On the one hand, there is the demand side of the analysis that includes the ecological footprint. The concept of the ecological footprint was originally defined by Wackernagel and Rees in (1996), and it has been used as an appropriate proxy for recent studies involving environmental analysis (Destek et al., 2018). On the other hand, there is the supply side of the analysis that includes the biocapacity. If the biocapacity is higher than the ecological footprint, then the region experiences an ecological reserve, as described by the GFN (2020). Conversely, if a region's footprint is higher than the biocapacity, an ecological deficit will be observed (GFN, 2020). The ecological balance is the difference between the biocapacity and ecological footprint. If the resultant number is positive, it indicates an ecological reserve, whereas it depicts an ecological deficit if it is negative (Table 6).

Australia is one of the countries that have an ecological reserve, which means that the biocapacity is higher than the ecological footprint. However, the country's biocapacity declined rapidly in the studied

Fig. 2 Australia's total energy consumption based on the fuel types over 1990–2017
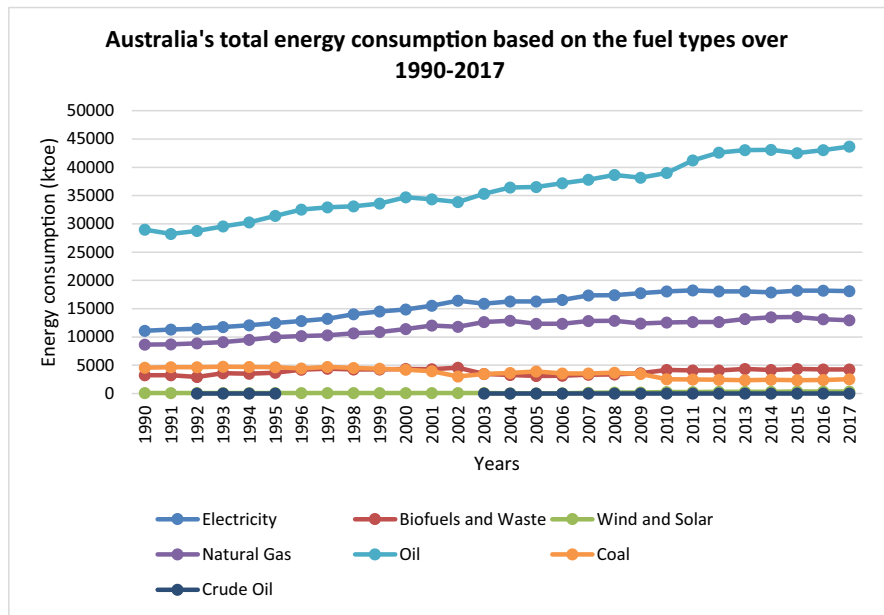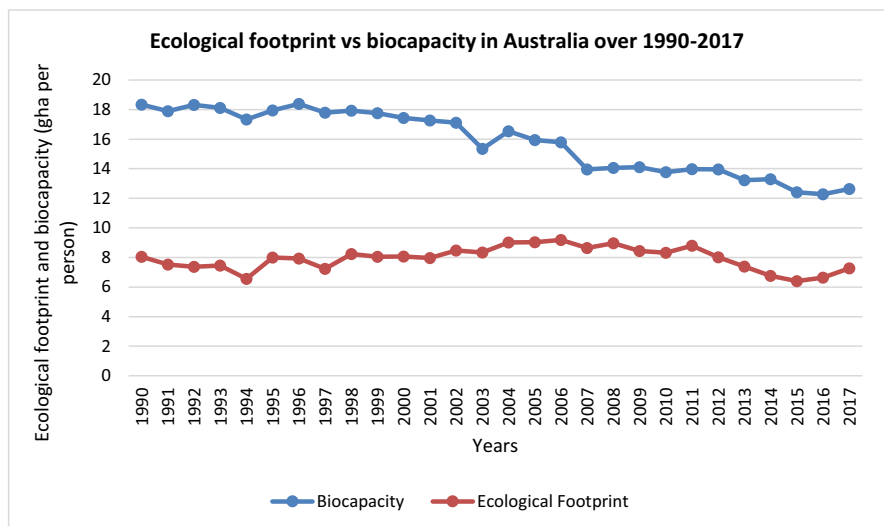

Fig. 3 The biocapacity and ecological footprint per person in Australia over 1990–2017

period, while the ecological footprint largely followed a constant trend. Per person biocapacity and ecological footprint in Australia for the study period can be seen in Fig. 3.

The biocapacity per person was 18.3 gha[1] in 1990, but decreased to 17.4 gha, 13.8 gha, and 12.6 gha in 2000, 2010, and 2017, respectively (GFN, 2020).

Additionally, the ecological footprint per person was 8 gha in 1990, and 8 gha, 8.3 gha, and 7.3 gha in the years 2000, 2010, and 2017, respectively (GFN, 2020). The ecological reserve per person was calculated as 10.3 gha for the year 1990. However, as the biocapacity in Australia declined and the ecological footprint increased, per person ecological reserve was therefore calculated as 9.4 gha, 5.5 gha, and 5.3 gha for the years 2000, 2010, and 2017, respectively.

The main reason for the declining biocapacity in Australia was the deforestation. The country is under

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[1] The symbol gha represents a global hectare, the accounting unit for the ecological footprint and biocapacity accounts.

Table.2 Share of carbon footprint in ecological footprint of Australia

	1990	2000	2010	2017
Carbon footprint (gha)	73,898,291.71	93,204,060.1	121,594,174.06	109,454,148.38
Ecological footprint (gha)	136,688,324.68	152,982,541.25	181,824,032.12	177,820,594.01
Share (%)	54.1	60.9	66.9	61.6

Carbon footprint, with its general definition, is the calculation of the amount of greenhouse gas that is directly or indirectly generated as a result of human activities, with the equivalent of carbon dioxide (CO2) and in tons.

the risk of desertification. Forest areas equivalent to 1000 rugby fields have been destroyed on a daily basis, especially in the state of Queensland (Taner, 2020).[2] Australian farmers aim to open pasture fields for cattle and the acquisition of agricultural land. However, some farmers conduct these activities in an illegal way. Thus, the existence of Australia's national forests continues to decline.

CO_2 emissions were the primary factor increasing Australia's ecological footprint during the studied period. As Table 2 illustrates, the effect of CO_2 emissions on the ecological footprint became more dominant between 1990 and 2017. More than 60% of the ecological footprint resulted from the increase in CO_2 emissions, after 2000. Other factors affecting the ecological footprint were buildup land, cropland, forest products, grazing land, and fishing grounds (GFN, 2020).

Methodology

Decoupling factor

The decoupling formula suggested by Zhang (2000) and adopted by the OECD (2002) is used in environmental studies to describe the link between real income and CO_2 emissions. First, the decoupling ratio should be calculated with the following expression:

$$\text{Decoupling Ratio1} = \frac{\left(\frac{CO_2}{GDP}\right)_t}{\left(\frac{CO_2}{GDP}\right)_{t-1}} \tag{1}$$

In the second step, the decoupling factor is computed by reducing the decoupling ratio from 1.

$$\text{Decoupling Factor1} = 1 - \frac{\left(\frac{CO_2}{GDP}\right)_t}{\left(\frac{CO_2}{GDP}\right)_{t-1}} \tag{2}$$

If the resultant decoupling factor is greater than 0, then this shows a decoupling among real income and CO_2 emissions. Otherwise, there is a re-coupling between the aforementioned variables if the decoupling factor is calculated as negative.

Decoupling could be categorized as either absolute decoupling or relative decoupling. In the first case, CO_2 emissions decrease, while the real income increases (Freitas & Kaneko, 2011). In the second case, both CO_2 emissions and real income increase, but the growth rate of CO_2 emissions is considerably smaller than real income. As Rüstemoğlu (2019) demonstrated in a case study, Germany is an example of a country that achieved an absolute decoupling between CO_2 emissions and real income, and this is an impressive result for sustainability targets.

In the published studies, the decoupling factor has been used to examine the relationship between CO_2 emissions and real income. This kind of analysis provides information about the continuous economic growth and sustainable environment dilemma for the countries. In addition to the real income, there is one more main factor that contributes to CO_2 emissions, namely, population. Therefore, in this study, the existence of decoupling between population and CO_2 emissions will be also investigated.

The second decoupling ratio characterizes the link between CO_2 emissions and population. It has the following form:

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[2] One rugby field is equal to 7000 m^2; therefore, 1000 rugby fields will be equal to 7 million m^2. Because 1 m^2 is equal to 0.0001 ha, then 7 million m^2 will be equal to 700 ha.

$$\text{Decoupling Ratio2} = \frac{\left(\frac{CO_2}{POP}\right)_t}{\left(\frac{CO_2}{POP}\right)_{t-1}} \tag{3}$$

Similar to the first decoupling ratio, the second one is subtracted from 1.

$$\text{Decoupling Factor2} = 1 - \frac{\left(\frac{CO_2}{POP}\right)_t}{\left(\frac{CO_2}{POP}\right)_{t-1}} \tag{4}$$

Hence, results those are greater than 0 indicate the occurrence of decoupling between CO_2 emissions and population. Otherwise, there is no decoupling between the variables mentioned above.

The decoupling factor is also calculated for the ecological footprint and its two determinants, real income and population, in this study. For the examination of the link between ecological footprint and real income, the variable CO_2 is just replaced by ecological footprint (EF) in Eq. 2. Hence;

$$\text{DecouplingFactor3} = 1 - \frac{\left(\frac{EF}{GDP}\right)_t}{\left(\frac{EF}{GDP}\right)_{t-1}} \tag{5}$$

Similarly, for investigating the link between ecological footprint and population, the variable CO_2 is just replaced by ecological footprint (EF) in Eq. 4. Thus;

$$\text{Decoupling Factor4} = 1 - \frac{\left(\frac{EF}{POP}\right)_t}{\left(\frac{EF}{POP}\right)_{t-1}} \tag{6}$$

If it is found to be positive, then the existence of decoupling between ecological footprint and population can be verified. Otherwise, the results will highlight the existence of re-coupling among the same variables.

Recently, a new discussion has emerged regarding the decoupling between real income and environmental degradation. Ward et al. (2016) argued that decoupling GDP from the environmental impact is not possible because GDP is highly dependent on the consumption of energy and resources. Thus, they suggested that it will be disadvantageous to develop some sustainability projects because decoupling will be expected between GDP and environmental degradation. They also suggested that because GDP has been recently deemed a poor proxy of society's wellbeing, it would be better to focus on defining a new and more comprehensive variable to measure the economic growth.

LMDI decomposition method

The decomposition analysis methods are classified into two categories in the literature. The first category comprises structural decomposition analysis (SDA) methods that utilize input–output tables. On the other hand, the second category includes index decomposition analysis (IDA) methods that utilize aggregated data at either the sector-level or aggregate-level.

Several IDA approaches are used in the literature such as the generalized Fisher index (GFI) method, refined Laspeyres index (RLI) method, logarithmic mean Divisia index (LMDI) method, and Shapley decomposition method. Among these mentioned decomposition techniques, the LMDI approach was recommended by Ang (2004) over other techniques due to its advantages. These advantages can be listed as time independence, ability to handle zero values, and consistency in aggregation (Malla, 2009).

The LMDI method is based on the well-established Kaya identity that decomposes the energy-related CO_2 emissions into four factors: per capita income, energy intensity per unit of GDP, carbon intensity (emissions per unit of energy consumption), and population (Kaya, 1989). The Kaya identity can be expressed as

$$CO_2 = \left(\frac{GDP}{\text{Population}}\right) * \left(\frac{EC}{GDP}\right) * \left(\frac{CO_2}{EC}\right) * (\text{Population}) \tag{7}$$

In Eq. 7, EC denotes the total energy consumption.

In this study, we seek to extend the well-established Kaya identity by adding the energy structure effect. Resultantly, Eq. 7 has the following form:

$$CO_2 = \left(\frac{GDP}{\text{Population}}\right) * \left(\frac{EC}{GDP}\right) * \left(\frac{FEC}{EC}\right) * \left(\frac{CO_2}{FEC}\right) * (\text{Population}) \tag{8}$$

In the 8th equation, FEC represents fossil energy consumption; therefore, FEC/EC explains the energy structure effect. For simplicity, the per capita GDP will be referred to as IE, and EC/GDP as EI in this study. In addition, FEC/EC will be represented by ES, and CO_2/FEC by CI. Hence, the changes in CO_2

emissions in Australia can be expressed by the following equation:

$$\Delta CO_2 = CO_2^T - CO_2^0 = \Delta IE_0^T + \Delta POP_0^T + \Delta ES_0^T + \Delta EI_0^T + \Delta CI_0^T \tag{9}$$

where,

$$\Delta IE_0^T = L(C(T), C(0)) \ln\left(\frac{IE(T)}{IE(0)}\right) \tag{10}$$

$$\Delta POP_0^T = L(C(T), C(0)) \ln\left(\frac{POP(T)}{POP(0)}\right) \tag{11}$$

$$\Delta ES_0^T = L(C(T), C(0)) \ln\left(\frac{ES(T)}{ES(0)}\right) \tag{12}$$

$$\Delta EI_0^T = L(C(T), C(0)) \ln\left(\frac{EI(T)}{EI(0)}\right) \tag{13}$$

$$\Delta CI_0^T = L(C(T), C(0)) \ln\left(\frac{CI(T)}{CI(0)}\right) \tag{14}$$

In Eqs. 10 to 14, the function $L(C(T), C(0))$ represents the logarithmic mean of two positive values $C(T)$ and $C(0)$ such that

$$L(C(T), C(0)) = \frac{C(T) - C(0)}{LNC(T) - LNC(0)} \tag{15}$$

$$C(T) \neq C(0)$$

In essence, LMDI formulates the dependent variable, CO_2 emissions, as a summation of independent determinants, including income effect, population, energy structure, energy intensity, and carbon intensity, for this case study (Ang, 2004).

Data collection

In this case study, real income, population, total final energy consumption, CO_2 emissions, and fossil fuel energy consumption data are utilized.

The real income and population data are gathered from the World Bank's World Development Indicators (WDI), whereas CO_2 emissions data is sourced from the United Nations Framework Convention on Climate Change (UNFCCC) database. Lastly, the final energy consumption data and fossil fuel energy consumption data are retrieved from the International

Energy Agency (IEA) database. The research period covers the years from 1990 to 2017, and the annual data are consistent with international standards.

Empirical results

Decoupling factor analysis results

For the period 1990–2017, Australia's real income increased by 125.2%, whereas its CO_2 emissions increased by 49.8% (World Bank, 2020) (UNFCCC, 2020). The yearly changes in Australia's real income and CO_2 emissions are shown in Fig. 4.

By utilizing the decoupling formula, the decoupling factor for each year has been calculated. The results of the decoupling factor analysis for Australia's CO_2 emissions and real income are presented in Table 3.

The results confirmed that Australia experienced decoupling between CO_2 emissions and real income in 22 of 27 periods. Only in the periods 1990–1991, 1991–1992, 1994–1995, 2000–2001, and 2014–2015, did re-coupling of CO_2 emissions and real income occur in the country. Australia's real income increased annually, by an average of 3.1% between 1990 and 2017. In addition, the annual average increase in its emissions was calculated as 1.5% for the same period. Therefore, a relative decoupling was observed between the country's CO_2 and real income in the studied period. In the periods where re-coupling was experienced, the economic growth rate was smaller than that of emissions. The decoupling factor results between Australia's CO_2 emissions and real income are presented in Fig. 5.[3]

The second decoupling factor analysis is conducted to test the link between CO_2 emissions and population. The yearly changes in Australia's population and CO_2 emissions are depicted in the Fig. 6.

Australia's population increased by 44.2% and CO_2 emissions increased by 49.8% in the studied period (World Bank, 2020; UNFCCC, 2020). The findings of the decoupling factor analysis are presented in the third column of Table 3. In 10 of 27 periods, Australia experienced decoupling between its population

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[3] The dotted lines that are used in Figs. 5, 7, 9, and 11 represent the trend in the data over the period 1990–2017.

Fig. 4 Australia's real income and CO_2 emissions over 1990–2017
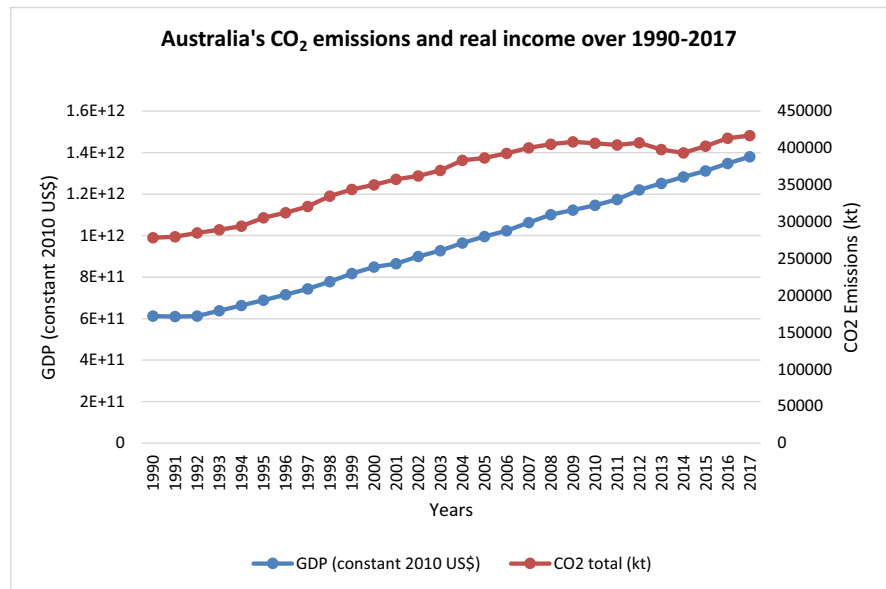
and CO_2 emissions. Hence, in the remaining 17 periods, re-coupling was observed between the country's population and CO_2 emissions. From 1991 to 2004, a consecutive re-coupling was found between the abovementioned variables. On the other hand, a consecutive decoupling was also observed among Australia's population and emissions over the period 2007–2014. The annual average growth rates for Australia's population and CO_2 emissions were 1.4% and 1.5%, respectively. UNFCCC (2020) data indicates that per capita CO_2 emissions in the country increased from 16.3 to 17 tons. The relative decoupling between CO_2 and population could be considered as modest for Australia for the analyzed period. The decoupling factor results between Australia's CO_2 emissions and population are presented in Fig. 7.

From 1990 to 2017, Australia's ecological footprint and real income increased by 30.1% and 125.2%, respectively (GFN, 2020; World Bank, 2020). The annual changes in Australia's ecological footprint and real income are presented in Fig. 8.

Another decoupling factor analysis was conducted between Australia's ecological footprint and real income. In 18 of 27 periods between 1990 and 2017, a decoupling was observed between the country's real income and ecological footprint. From 1990 to 1994, 1998 to 2001, and 2011 to 2015, consecutive decoupling occurred between the aforementioned variables. In 9 of 27 periods, however, re-coupling

was observed between ecological footprint and real income. The decoupling between ecological footprint and real income was more modest than the decoupling between CO_2 emissions and real income. Figure 9 presents the decoupling factor results between ecological footprint and real income for Australia, from 1990 to 2017.

The annual average growth rates in population and ecological footprint were 1.4% and 1.2%, respectively. Figure 10 shows the changes in Australia's ecological footprint and population between 1990 and 2017.

A final decoupling factor analysis was conducted, testing the link between Australia's ecological footprint and population. Decoupling was observed in 15 of 27 periods between the country's ecological footprint and population. In the remaining 12 periods, however, these variables exhibited re-coupling. Figure 11 presents the decoupling factor results between Australia's ecological footprint and population, from 1990 to 2017.

In comparing the frequency of decoupling between CO_2 emissions and ecological footprint from real income, we can conclude that CO_2 emissions decouple from real income more often. In 22 of 27 periods, Australia's CO_2 emissions decoupled from real income, whereas ecological footprint decoupled from real income only 18 times. Together with this, when the graphed trends are compared, an upward trend is observed in CO_2 emissions and real income

Table.3 Decoupling factor results of Australia over 1990–2017

Period	Decoupling factor between CO_2 and real income	Decoupling factor between CO_2 and population	Decoupling factor between ecological footprint and real income	Decoupling factor between ecological footprint and population
1990–1991	− 0.009	**0.008**	**0.05**	**0.06**
1991–1992	− 0.014	− 0.006	**0.02**	**0.02**
1992–1993	**0.024**	− 0.005	**0.01**	− 0.02
1993–1994	**0.022**	− 0.006	**0.14**	**0.11**
1994–1995	− 0.0004	− 0.026	− 0.18	− 0.21
1995–1996	**0.015**	− 0.009	**0.04**	**0.02**
1996–1997	**0.012**	− 0.016	**0.11**	**0.08**
1997–1998	**0.002**	− 0.032	− 0.10	− 0.13
1998–1999	**0.022**	− 0.016	**0.06**	**0.02**
1999–2000	**0.021**	− 0.006	**0.02**	− 0.003
2000–2001	− 0.002	− 0.008	**0.02**	**0.01**
2001–2002	**0.026**	− 0.0004	− 0.03	− 0.06
2002–2003	**0.009**	− 0.008	**0.03**	**0.02**
2003–2004	**0.004**	− 0.025	− 0.04	− 0.07
2004–2005	**0.023**	**0.005**	**0.01**	− 0.01
2005–2006	**0.012**	− 0.001	-0.005	− 0.02
2006–2007	**0.018**	− 0.013	**0.07**	**0.04**
2007–2008	**0.024**	**0.008**	− 0.02	− 0.03
2008–2009	**0.011**	**0.012**	**0.06**	**0.06**
2009–2010	**0.025**	**0.020**	**0.02**	**0.01**
2010–2011	**0.029**	**0.019**	− 0.05	− 0.06
2011–2012	**0.031**	**0.011**	**0.11**	**0.09**
2012–2013	**0.047**	**0.039**	**0.09**	**0.08**
2013–2014	**0.036**	**0.027**	**0.10**	**0.09**
2014–2015	− 0.002	− 0.009	**0.06**	**0.05**
2015–2016	**0.001**	− 0.010	− 0.01	− 0.02
2016–2017	**0.014**	**0.007**	− 0.12	− 0.13
Decoupling Frequency	**22 periods**	**10 periods**	**18 periods**	**15 periods**
Decoupling factor average	**0.014**	**− 0.002**	**0.020**	**0.001**
Decoupling trend	**Upward**	**Upward**	**Constant**	**Constant**

The "bold" entries represent the years where decoupling occurred among the variables.

decoupling, which is a desirable result. Figure 9 illustrates a constant trend in ecological footprint and real income decoupling. Overall, we can conclude that real income was a more dominant influence on ecological footprint.

Regarding the decoupling of two environmental proxies (i.e., CO_2 and ecological footprint) from population, the decoupling factor analysis results are quite revealing. Decoupling was more frequent between ecological footprint and population than between CO_2 and population. On the other hand, Fig. 7 illustrates an upward trend in the decoupling factor values between Australia's CO_2 emissions and population. However, the decoupling factor values followed a relatively constant trend between the country's ecological footprint and population. The decoupling factor results of ecological footprint and its two determinants are also showed in Table 3.
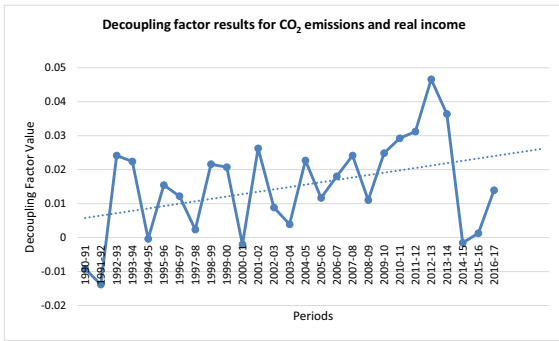
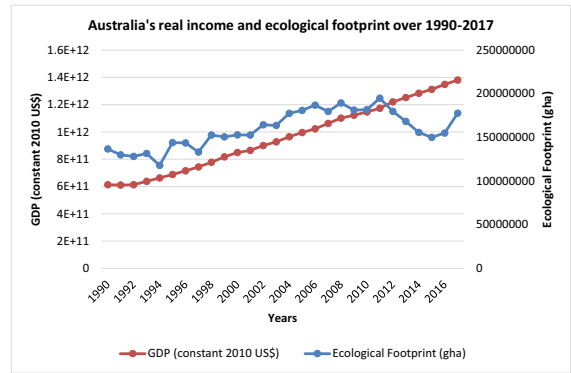**Fig. 5** Decoupling factor results of Australia's CO_2 and real income over 1990–2017

Fig. 6 Australia's CO_2 emissions and population over 1990–2017

Fig. 7 Decoupling factor results for Australia's CO_2 emissions and population over 1990–2017

LMDI decomposition results

The impacts of five different factors on changes in Australia's CO_2 emissions are summarized in Fig. 12.

Fig. 8 Australia's real income and ecological footprint over 1990–2017
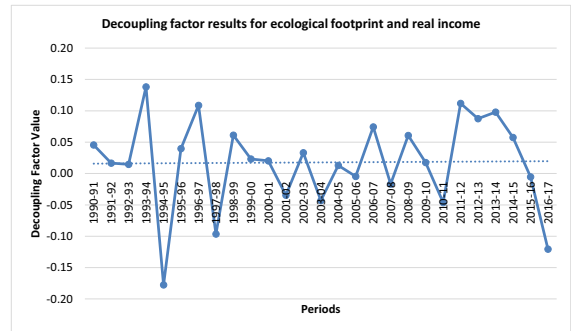
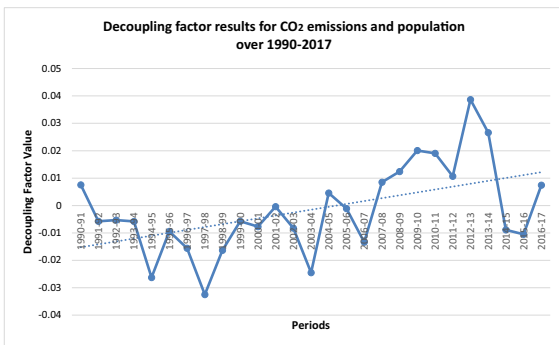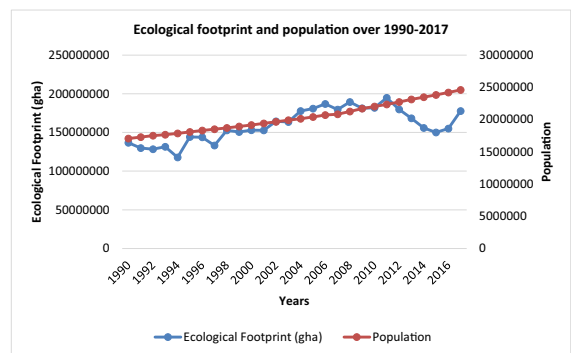**Fig. 9** Decoupling factor results for Australia's ecological footprint and real income over 1990–2017

Fig. 10 Ecological footprint and population of Australia over 1990–2017

Looking at the aggregated impacts of these factors, it is possible to conclude that the trend of CO_2 emissions increased at a rate of 5134 ktons (kilotons) CO_2
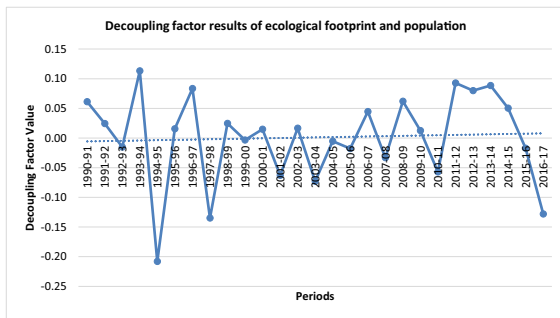
Fig. 11 Decoupling factor results of Australia's ecological footprint and population over 1990–2017

per year, on average. It is clear that one of the main key drivers of the changes in CO_2 emissions was the real income effect in the reviewed period.

The real income effect increased CO_2 emissions in 24 of 27 periods in Australia. A dominant real income effect that yields an increase in CO_2 emissions is consistent with the literature (Kumbaroğlu, 2011; Lise, 2006; Rüstemoğlu and Uğural, 2017; Akbostanci et al., 2018). The real income effect only reduced the emissions in the periods 1990–1991, 1991–1992, and 2008–2009. Australia's real income increased by 125.2%, from 612.8 billion US$ to 1.38 trillion US$, during the period of review (World Bank, 2020). Hence, the per capita income in the country increased by 56.2% from 35,912.2 to 56,095.2 US$ between 1990 and 2017 (World Bank, 2020). Therefore, the LMDI computations indicate that the real income growth in Australia caused an additional 5883.4 ktons of CO_2 emissions per year on average. The cumulative impact of real income on Australia's emissions was calculated as 158,851.4 ktons for 2017 by using the LMDI method. The cumulative share of this factor in total emissions was equal to 114.6% at the end of the studied period.[4]

The impact of population on CO_2 emissions was also consistently positive. Between 1990 and 2017, Australia's population increased from 17.1 to 24.6 million (World Bank, 2020). Therefore, in all years of

the research period, the population effect raised Australia's CO_2 emissions. From 1990 to 2017, the population effect increased country's CO_2 emissions by an average of 4974.1 ktons each year. Among the three factors that raised the CO_2 emissions in Australia, the population effect was the second largest and its share in the total emissions was calculated as 96.9% for 2017.

The energy intensity effect was the leading reducing factor in Australia's CO_2 emissions in the studied period. In 25 of 27 periods, the energy intensity factor reduced the emissions and this was a highly desirable outcome in terms of environmental sustainability. There were only two periods where the energy intensity increased the emissions, namely, 1991–1992 and 2010–2011. Australia's total energy consumption increased by 44.5%, from 56,651 to 81,843 ktoe between 1990 and 2017 (IEA, 2020). The impact of energy intensity on CO_2 emissions was generally negative in the studied period. This result implies that the country used more energy efficient technologies and/or switched to less energy intensive industries year after year. Based on the findings of this study, one can conclude that the energy intensity effect was responsible for reducing an average of 6117.2 ktons of CO_2 emissions in Australia, each year between 1990 and 2017. The cumulative share of the energy intensity factor was calculated as -119.2% for 2017. The cumulative increasing impact of real income effect was calculated as 158,851.4 ktons, whereas the reducing impact of energy intensity effect was computed as $-165,163$ ktons. Thus, it is possible to conclude that Australia's energy intensity factor successfully compensated for the harmful impact of real income during the reviewed period.

From the analysis, one can see that carbon intensity effect was another factor responsible for increasing CO_2 emissions in Australia. In 15 of 27 periods, the carbon intensity raised the CO_2 emissions in the country. The periods where the carbon intensity reduced the CO_2 emissions were found to be 1992–1993, 1993–1994, 1995–1996, 1999–2000, 2002–2003, 2006–2007, 2007–2008, 2009–2010, 2010–2011, 2011–2012, 2012–2013, and 2013–2014. Australia's CO_2 emissions increased by 49.8% from 278,424.4 to 417,041.3 ktons between 1990 and 2017 (UNFCCC, 2020). Over the same period, the non-renewable energy consumption increased by 42.5% (IEA, 2020). Therefore, the carbon intensity effect

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[4] The fact that the cumulative effect of the real income factor is greater than 100% may mislead for the reader. This is because the cumulative effects of other factors on CO_2 emissions are negative. When the sum of all factors is considered, the sum of the effect is 100%.

Fig. 12 LMDI decomposition analysis results of Australia over 1990–2017
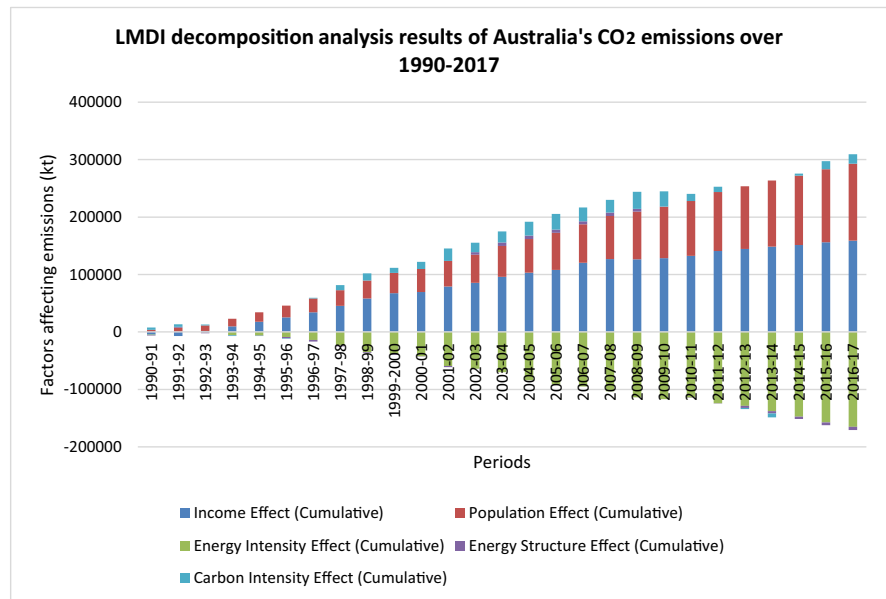
increased Australia's CO_2 emissions by an average of 603.6 ktons on annual basis according to LMDI computations. The cumulative impact of the carbon intensity effect on the country's CO_2 emissions was calculated as 16,295.9 ktons for 2017. In the same year, the cumulative share of the carbon intensity effect was found to be 11.8% using the LMDI approach.

Lastly, the energy structure had a minor impact on CO_2 emissions between 1990 and 2017. Decomposition analysis revealed that in 15 of 27 periods, this factor reduced the CO_2 emissions in the country. On the other hand, in the remaining 12 periods, the energy structure effect increased the amount of harmful emissions. On average, the energy structure effect reduced CO_2 emissions in the country by 209.9 ktons. The cumulative impact of the energy structure was computed as -5668.1 ktons for 2017. Resultantly, the share of energy structure in CO_2 emissions was calculated as -4.1% for the same year. It is possible to conclude that there was randomness in the effect of energy structure on emissions during the period of review. The share of renewable energy rose from 7.9 to 9.1%, while the share of nonrenewable energy decreased from 92.1 to 90.9% over the 1990–2017 period (IEA, 2020). This slight increase in renewable energy consumption indicates why the energy structure effect did not reduce the emissions in Australia. The slow transformation from fossil fuels to renewable energy sources created randomness regarding the

impact of energy structure effect on CO_2 emissions. Figure 13 presents the decomposition analysis results of Australia over 1990–2017 also by including the actual trends reflecting the changes in CO_2 emissions.

Discussion

In this section of the paper, the aim is to perform a critical analysis on the findings of the LMDI decomposition analysis. The Australian economy performed well during the past three decades; therefore, the real income effect was the dominating factor in Australia's CO_2 emission changes. Australia's economic growth continued even during the Asian crisis (in late 1990s) and 2008–2009 financial crises. Therefore, the real income effect continued to increase the country's CO_2 emissions. As highlighted in the empirical findings section, the energy intensity factor offset the increasing impact of real income on CO_2 emissions. Further achievements are possible if the energy intensity of each economic sector could be further reduced. Thus, a sector level evaluation of CO_2 emissions in Australia became essential for the identification of highly energy intensive and CO_2 intensive sectors. In Australia, electricity and heat production were the sectors that emitted the highest amount of emissions during the studied period. Between 1990 and 2017, the CO_2 emissions resulting from electricity

Fig. 13 LMDI decomposition results of Australia's CO_2 emissions over 1990–2017
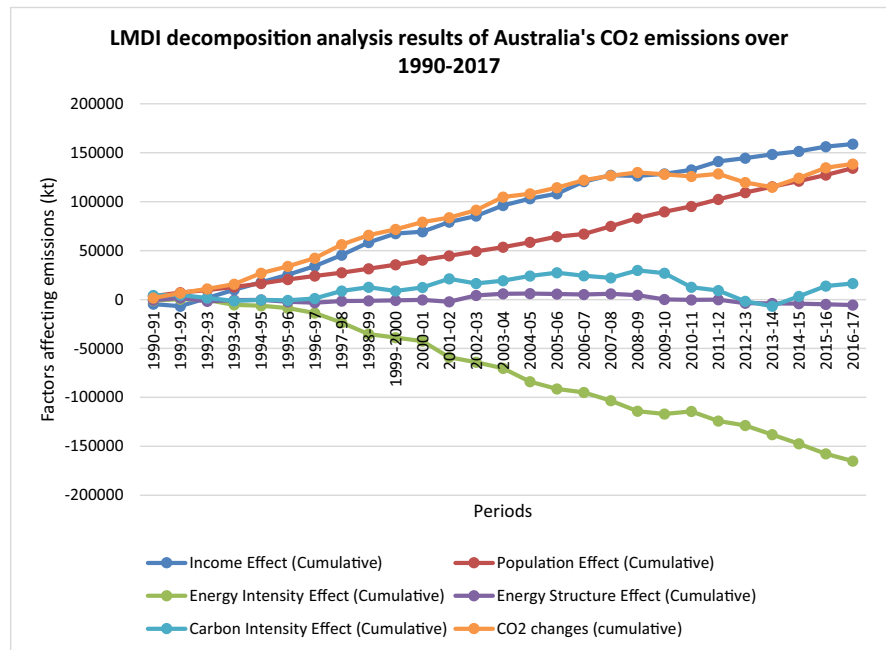
and heat production activities rose from 129 to 191 MT in Australia (IEA, 2020). Since the CO_2 emissions predominantly result from the combustion of fuel for electricity and heat production in Australia, the reduction of those emissions will not hamper the economic growth of the country. Australia's economy relies more on the service sector. In 2017, as indicated by World Bank (2020) data, the services sector comprised 67% of the total economy.

Following the electricity and heat production sectors, there are three other sectors that emit high rates of CO_2 emissions: transport, industry, and other energy industries. Transportation was the second largest CO_2 emitting sector in Australia, and from 1990 to 2017, the CO_2 emissions related to this sector increased from 62 to 98 MT (IEA, 2020). Additionally, transportation was the leading sector in terms of energy consumption in the country between 1990 and 2017. As IEA (2020) data revealed, energy consumption in the transport sector in Australia rose by 58% from 21,111 to 33,352 ktoe over the studied period. Industry followed transportation in this respect and was the third major determining sector in Australia's CO_2 emissions. The emissions that resulted from industrial activities decreased slowly from 43 to 38 MT over the period 1990–2017 (IEA, 2020). In addition, the sector was the second highest energy

intensive sector in Australia, immediately after transportation. The energy consumption of the industry sector increased by 16.4% from 19,320 to 22,476 ktoe in the reviewed period (IEA, 2020).

During the studied period, other energy industries represented the fourth major CO_2 emitting sector in Australia. The emissions resulting from these activities increased from 14 to 35 MT from 1990 to 2017 as indicated by IEA (2020) data. On the other hand, the increase in residential sector emissions was negligible. Between 1990 and 2017, the emissions of this sector increased slightly from 6 to 9 MT (IEA, 2020). However, residential buildings accounted for the third largest share in the country's energy consumption. As IEA (2020) data revealed, the energy consumption of this sector increased from 7490 to 10,540 ktoe, between 1990 and 2017. Clearly, the empirical results of this study show that improvements in energy intensity in Australia were highly commendable during the studied period. The energy intensity in the country decreased from 0.092 to 0.059, and this was a successful outcome for the sustainability targets. However, further achievements are possible if particular attention is paid to sectors that are highly energy intensive such as transportation, industry, and residential buildings in Australia. The country should

Table.4 Sector level distribution of Australia's CO_2 emissions

Sector	in 1990	in 2017	% change
Electricity and heat production	129 MT	191 MT	48.1
Transportation	62 MT	98 MT	58.1
Industry	43 MT	38MT	− 11.6
Other energy industries	14 MT	35 MT	150.0
Residential buildings	6 MT	9 MT	50.0
Commercial and public services	3 MT	6 MT	100.0
Agriculture	3 MT	7 MT	133.3

invest more in energy saving technologies, especially in the transportation and industry sectors.

Although the CO_2 emissions declined as a result of energy intensity, the randomness in emissions due to changes in energy structure could be considered as unnecessary. This result reflects the poor management of the energy sector in the country. Australia's energy sector is heavily dependent on fossil fuels, and therefore, no impressive reduction in emissions was observed due to the energy structure. The countries have two different categorizations about the transition to a non-polluting environment (Madaleno et al., 2018). In the first category, there are the pioneers of the utilization of renewable energy (such as Germany, Denmark, and Spain), whereas in the second category, there are other countries that are relatively distant from the renewable energy transition. Clearly, Australia belongs to the second category in this classification. This type of classification is also confirmed by the decomposition analysis results of the present study. Table 4 presents the sector level distribution of Australia's CO_2 emissions between 1990 and 2017.

Table.5 Brief summary of the LMDI decomposition analysis results

	Impact of the factor on CO_2 emissions (ktons)	Impact of the factor on CO_2 emissions (%)
Per capita income	158,851.4	114.6
Population	134,301.1	96.9
Energy intensity	− 165,163	− 119.2
Carbon intensity	16,295.9	11.8
Energy structure	− 5668.1	− 4.1
Total	138,616.9	100

Population growth rate in Australia was high in the reviewed period. The country had an open immigration policy which made it difficult to reduce the emissions growth rate. Population was one of the significant factors that raised CO_2 emissions in the country according to the LMDI decomposition results. As a result, population policies should be re-evaluated in Australia if the aim is to achieve a green economy.

Conclusion

This study provided an environmental analysis for Australia for the time period covering 1990–2017. To achieve this goal, the study has been prepared in three layers. Initially, the per capita ecological balance of the country was evaluated. In the second step, the decoupling factor analysis for CO_2 emissions was performed, not only to investigate their possible decoupling from real income, but also their decoupling from population. The decoupling factor analysis for ecological footprint was also conducted to examine its possible decoupling from real income and population. Then, the decoupling results of ecological footprint were compared with the results of CO_2 emissions. The decoupling factor analysis results revealed that population and real income were more dominant factors in changes of ecological footprint as compared to CO_2 emissions. In the third and last step, by using the LMDI approach, a decomposition analysis was performed to identify the determinants that change the CO_2 emissions in Australia. The well-known Kaya equation was expanded by including one additional factor, namely, the energy structure. A brief summary of the decomposition analysis results for Australia's CO_2 emissions is presented in Table 5.

According to the LMDI decomposition approach, an increase in CO_2 emissions from a per capita income effect and a population effect are not unexpected. However, if a country targets CO_2 reduction and environmental sustainability, other factors such as energy intensity, carbon intensity, and fuel structure should have decreasing effects on CO_2 emissions. In the present study, however, the researcher has proven that only the energy intensity contributed significantly to Australia's CO_2 reduction goals. As shown in Table 5, the energy intensity curbed the CO_2 emissions of Australia cumulatively by 165,163 ktons. The carbon intensity accelerated the country's CO_2

emissions and energy structure reduced them only by a minimal amount. Empirical findings revealed that Australia should decrease oil and coal use in total energy consumption. Additionally, it should increase the renewable energy share, especially in electricity generation.

Rüstemoğlu (2019) analyzed the factors that led to changes in CO_2 emissions in Germany from 1990 to 2015. He concluded that Germany's CO_2 emissions declined mainly because of energy intensity and carbon intensity. He also noted that a relatively small population growth rate also helped the country to reduce the rate of CO_2 emissions. In the present study, however, the impacts of five factors on Australia's CO_2 emissions were analyzed (an additional factor was the energy structure), concluding that only energy intensity substantially reduced the amount of emissions during the studied period. Contrasting with Germany's results, carbon intensity had a minor accelerating impact on Australia's CO_2 emissions. Furthermore, due to the very slow transformation of Australia's energy matrix from non-renewable to renewable, the energy structure had only a minor impact on the country's CO_2 emissions. Australia's population growth was relatively higher than Germany's; thus, the population effect significantly increased emissions in Australia.

To reduce CO_2 emissions in Australia, the reductive impact of energy intensity should be supported by the two other factors—namely, carbon intensity and energy structure. Currently, as our research demonstrated, the minor impacts of carbon intensity and energy structure will not help to achieve any sustainability targets in Australia. The country should reduce its overreliance on fossil fuels, especially coal, and invest more in modern renewable energy sources. Because Australia is a developed nation, the investments in modern renewables (e.g., wind and solar) would not hamper the citizens' welfare. Germany reduced its carbon emissions by rapidly building modern renewable power plants. The performance of Australia regarding renewable energies is relatively poor as compared to other developed nations. In 2017, renewable energy accounted for 9.1% of Australia's final energy consumption (IEA, 2020). However, this value was 15.3% in Germany (the country that is 3.4 times more populous than Australia), 15.6% in Spain, 36.5% in Denmark, and 44.4% in Finland (IEA, 2020). Australia should follow Germany, Spain,

and Denmark in this respect. Furthermore, the public awareness about green infrastructure should also be increased. Educational programs can improve the public support towards urban greening and cultivating climate justice goal could be achieved. The Australian society could also generate wider socioeconomic benefits by reducing the CO_2 emissions. It can reduce the air pollution and related health issues. As a last note, Australia aims to reduce GHGs by around 27% by 2030 compared to the 2005 level. However, if major policy innovations are not implemented, this will be a very challenging target to achieve. Therefore, Australia should reduce its dependence on coal

Table.6 Ecological balance in Australia over 1990–2017

Year	Biocapacity per person (gha)	Ecological footprint per person (gha)	Ecological Balance per person (gha) = Biocapacity per person (gha) – Ecological footprint per person (gha)
1990	18.3	8.0	10.3
1991	17.9	7.5	10.4
1992	18.3	7.4	11.0
1993	18.1	7.5	10.7
1994	17.3	6.6	10.8
1995	17.9	8.0	9.9
1996	18.4	7.9	10.5
1997	17.8	7.2	10.6
1998	17.9	8.2	9.7
1999	17.8	8.1	9.7
2000	17.4	8.1	9.4
2001	17.3	8.0	9.3
2002	17.1	8.5	8.6
2003	15.4	8.3	7.0
2004	16.5	9.0	7.5
2005	15.9	9.0	6.9
2006	15.8	9.2	6.6
2007	14.0	8.7	5.3
2008	14.1	9.0	5.1
2009	14.1	8.4	5.7
2010	13.8	8.3	5.5
2011	14.0	8.8	5.2
2012	14.0	8.0	5.9
2013	13.2	7.4	5.8
2014	13.3	6.8	6.5
2015	12.4	6.4	6.0
2016	12.3	6.6	5.6
2017	12.6	7.3	5.3

(especially in electricity generation), while increasing its renewable capacity and should particularly focus on the transportation sector, which has the highest level of energy consumption.

Declarations

Conflict of interest   The authors declare no competing interests.

Appendix

Based on the calculation, the results of the ecological balance in Australia for the period between 1990 and 2017 are presented in Table 6.

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