Energy Consumption Trends and Decoupling Effects between Carbon Dioxide and Gross Domestic Product in South Africa

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ABSTRACT

This study evaluates the occurrence of decoupling of CO_2 emissions from Gross Domestic Product (GDP) in South Africa (SA) for the period of 1990 to 2012 by using the Organization for Economic Cooperation and Development (OECD) and Tapio methods, and identifies the primary CO_2 emissions driving forces by the Kaya identity. The results showed a strong decoupling during the period of 2010–2012, which is considered as the best development situation. In 1994–2010 SA had a weak decoupling; while during the period 1990–1994, the development in SA presented an expansive negative decoupling state. The comparison of the OECD and Tapio's methods showed well-correlated results but differed in their applications; however, the OECD method appeared as the simpler one. The results of Kaya identity demonstrated that the increase in population, GDP per capita and deteriorating energy efficiency were the main primary driving forces for the increase of CO_2 emissions. It is suggested that SA can expand the share of renewable energy and promote green energy technology in addition to better strategies of the demand side management (DSM) to raise the efficiency of energy consumption as well as CO_2 emission reductions. The methods used in this research can be applied to other countries with similar situations to evaluate the trends of energy consumption and CO_2 emissions and an aid to decision-making tool for better sustainable development.

Keywords: Carbon emissions; Fuel usage; OECD decoupling method; Tapio's method; Kaya identity.

INTRODUCTION

South Africa's economy has grown rapidly since the end of the apartheid era in 1994, and the country is now one of the most developed nations in Africa. South Africa has the second largest economy in Africa (behind Nigeria since 2014), in terms of gross domestic product (GDP), and it has the highest energy consumption on the continent, accounting for about 30% of total primary energy consumption in Africa in 2012, according to the British Petroleum (BP) Statistical Review of World Energy (2013). South Africa's energy sector is critical to its economy, as the country relies heavily on its large-scale, energy-intensive coal mining industry. Since its economy is heavily dependent on its energy sector that accounts for 15% of the country's GDP with coal being the dominant energy source; this makes the SA case study very important and interesting (Department of Energy and Minerals, South Africa, 2008). SA has limited proved reserves of oil and natural gas and uses its

large coal deposits to meet most of its energy needs. The SA primary energy supply structure which has been dominated by coal for decades is revealed in Fig. 1. The supply of hydro and geothermal/solar/wind power represents less than 0.3% of the total supply. The biofuels being used are primary solid biofuels, and the wastes correspond to municipal and industrial wastes (IEA, 2014).

In 2013, 72% of South Africa's total primary energy supply (TPES) came from coal, followed by oil (22%), natural gas (3%), nuclear (3%), and renewables (less than 1%, primarily from hydropower), according to BP Statistical Review of Energy (2014). South Africa's dependence on coal has led the country to become the leading carbon dioxide emitter in Africa and the 13th largest in the world, according to the latest U.S. Energy Information Administration report (EIA, 2015). Coal dominates the South African energy system, accounting for an annual average of 27.96% of total primary energy consumption and 64.50% of CO_2 emissions from 1990 to 2012 (Fig. 2). The same figure shows that the CO_2 emissions from natural gas (for 2010–2012) are very low because it was directly tied to liquefaction plants until 2009 according to the International Energy Agency (IEA, 2014). Moreover, this high dependence on coal makes the country also very high carbon-intensive and one of the highest emitters of CO_2 emissions when compared to many
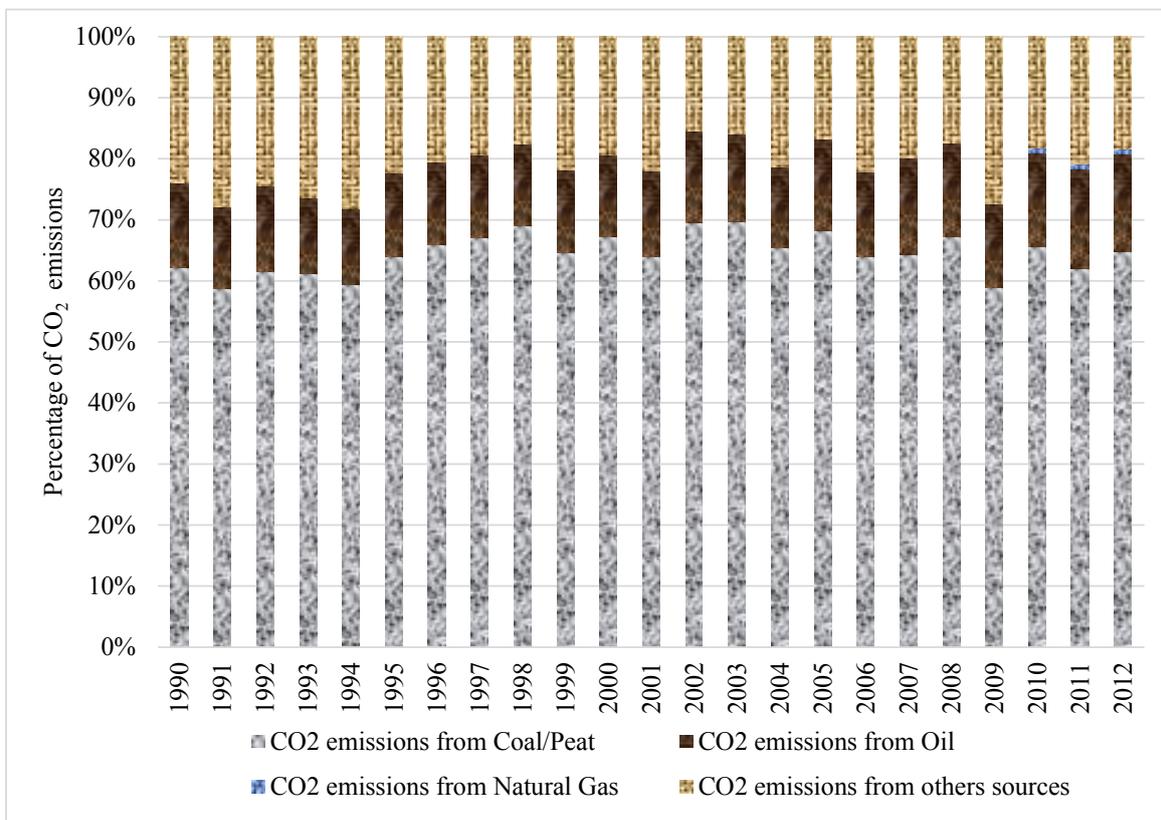
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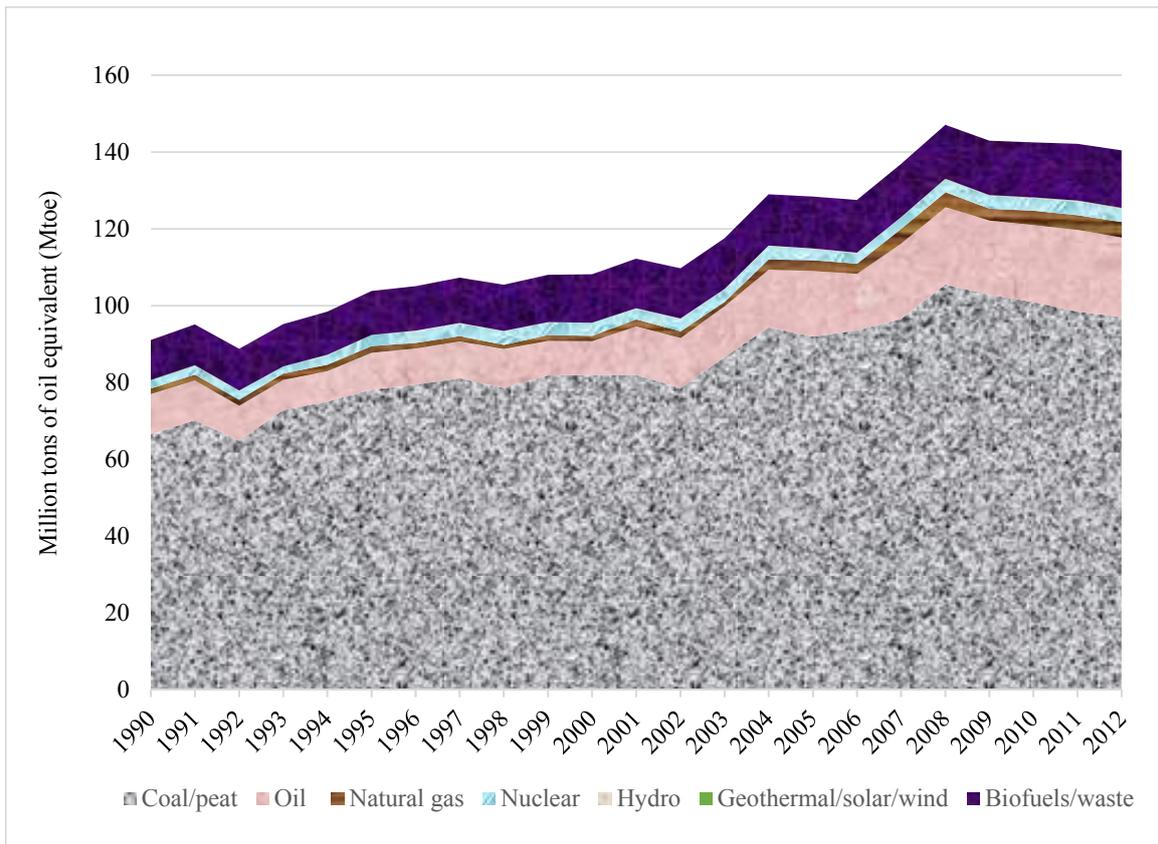
Fig. 1. Total primary energy supply of South Africa by fuel types.

Fig. 2. Share of total CO_2 emissions from fossil fuels burned and others energy sources in South Africa.

developed and developing countries, whether this is measured in emissions per person or per unit of GDP or per unit of TPES (IEA, 2014 statistic report) (Table 1). This emissions profile poses a significant challenge in developing the energy sector, providing more affordable access to energy services, while contributing to climate change mitigation.

In South Africa's Long-Term Mitigation Scenarios (LTMS), in the absence of radical energy choice changes, emissions would quadruple between 2003 and 2050, dominated by energy-related emissions (notably from the electricity, industrial and transport sectors) (IEA 2013 statistic report). One of the major climate change mitigation issues facing South Africa is the need to reduce emissions from the power sector, primarily by reducing reliance on coal. South Africa is already taking steps to expand the use of both renewable and nuclear energy, to explore the use of carbon capture and storage (CCS) technologies, to explore options for shale gas development, and to reduce energy demand through a nationwide energy efficiency program (IEA, 2013). Using CCS technologies and applications may become imperative in the upcoming years to preserve the atmosphere from high CO_2 concentration if the world continues to rely on fossil fuels to produce energy. This could address the challenge of climate change mitigation. In that order, several studies have been recently conducted by scholars as Chiu and Ku (2012), Reich *et al.* (2014) and Chen *et al.* (2014). According to the IEA 2013 statistic report, SA submitted a pledge, under the Copenhagen Accord, to reduce emissions by 34% by 2020 and by 42% by 2025, compared to a current emission baseline. There was also a plan to promote renewable and clean energy, where the Government had set a 10-year target to increase the share of renewable energy in total energy consumption from 9–14% by 2012 (Department of Energy and Minerals, South Africa, 2002); However, this target has not been met according to Eberhard *et al.* (2014). Sebitosi and Pillay (2008a) pointed out that policy-makers consider the reduction of greenhouse gases (GHGs) emissions as a kind gesture of human beings and not as a serious means to solve the environmental challenges with which SA is dealing. Several studies related to the linkage between energy consumption and economic growth of South Africa included Menyah and Wolde-Rufael (2010), Ziramba (2009), Odhiambo (2009), Wolde-Rufael (2009). The main purpose of this paper is to analyze the linkage effect among energy consumption, CO_2 emissions and economics of SA by using OECD (2002) and Tapio

(2005) decoupling index. Also the Kaya identity method is used to explore the primary factors related to CO_2 emissions.

The causal relationship between energy consumption and an aggregated output, introduced at the end of the 1970 by Kraft and Kraft (1978), has generated much research interest. Different methods such as correlation analysis, simple regression, divaricate causality, and unit root testing as well as the multivariate co-integration, panel co-integration, and variance decomposition have been tested to determine the strength of the causal link between energy consumption/CO_2 emission and the economic growth (Climent and Pardo, 2007). Ang (2007) and Soytas *et al.* (2007) analysed both sets of relationships in the same multivariate framework in order to examine the dynamic links between economic growth, energy consumption and environmental pollutants. Budzianowski (2012) also analyzed CO_2 emissions from the fossil fuel combustion and provided tools for estimating the target for national carbon intensity of energy by 2050. Liu *et al.* (2013) constructed an integrated environmental and operational model by data envelopment analysis (DEA) to investigate seven thermal power plants operating in Taiwan during 2001–2008. Recently, Liou *et al.* (2015) modified the conventional two-stage DEA model to construct an analytical model for energy-related efficiency with undesirable outputs. The proposed model is applied to measure the energy use efficiency and the economic efficiency of 28 OECD countries during 2005 to 2007.

The term "decoupling" was first adapted to environmental studies at the beginning of the 2000s by Zhang (2000), and it was later adopted as an indicator by the OECD (2002). Thus, the notion of decoupling has achieved global recognition as a significant conceptualization of successful economy–environment integration. Vehmas *et al.* (2003) constructed a comprehensive framework of the different aspects of decoupling. According to the framework, eight logical possibilities were presented by Tapio (2005) to distinguish the decoupling state. Today, the decoupling analysis is widely used in a variety of studies. For example, Climent and Pardo (2007) investigated the relationship between GDP and energy consumption in Spanish by taking into account several decoupling factors. Diakoulaki and Mandaraka (2007) evaluated the progress made in 14 EU countries in decoupling CO_2 emissions from the industrial growth. The occurrence of a decoupling between the growth rates in economic activity and CO_2 emissions from energy consumption in Brazil from 2004 to 2009 was examined by

Table 1. Energy sector carbon dioxide emissions intensity and per capita in 2012.

	CO_2 emissions/Population (tonnes CO_2/capita)	CO_2 emissions/GDP (kilogrammes CO_2/US dollar using 2005 prices)	CO_2 emissions/TPES (tonnes CO_2/terajoule)
World	4.51	0.58	56.7
SA	*7.20*	*1.22*	*64.2*
Africa	0.95	0.78	33.7
OECD	9.68	0.31	55.3
Non OECD	3.20	1.23	56.9
OECD Europe	6.67	0.24	50.9

Source: IEA 2014 statistic report.

Freitas and Kaneko (2011). Lu *et al.* (2007) combined the decoupling index with the Divisia index method to investigate CO_2 emissions from highway transportation in Taiwan, Germany, Japan and South Korea during 1990–2003. Liu (2011) used the environmental Kuznets curve (EKC) to coin the term "environmental poverty" to refer to the lack of a healthy environment needed for a society's survival and development as a direct result of the human-induced environmental degradation. Luken and Piras (2011) studied the decoupling of energy use and industrial output in the Asian region. Lin *et al.* (2012) concentrated on the modeling of economic-based linkage effects of CO_2 emissions from the electricity industry in Taiwan by using input-output analysis. Liu *et al.* (2012) used Input-Output Life Cycle Assessment (I-O LCA) to assess the environmental impact of Taiwan's electricity sector during 2001–2006. Ren *et al.* (2012) calculated the trend of decoupling effects in nonferrous metals industry in China by presenting a theoretical framework for decoupling. Recently, Muangthai *et al.* (2014) used decoupling to evaluate the relationships between energy consumption and the CO_2 emissions from Thailand's thermal power generation that were caused by economic developments during 2000–2011. Many different concepts have been used to express the different aspects of decoupling. Up to now, among the methods used for measuring the decoupling effect, there is no uniformity as to which method provides the best decoupling indicator (Zhong *et al.*, 2010).

As far as we know, there have been limited studies devoted to analyzing decoupling of the energy-related CO_2 emission from the economic growth in South Africa. This research serves as a preliminary study of applying the decoupling index presented by Tapio (2005) and OECD (2002) to examine the occurrence of a decoupling between the growth in economic activity and the CO_2 emission resulting from energy consumption in South Africa from 1990 to 2012. A comparison of the results by these two methods is presented. However, decoupling is assumed as the unlinking of the environmental pressure variable from the economic performance variable, while the study of the driving forces behind CO_2 emissions levels and their evolution has therefore comprehensibly been of considerable interest to researchers and policymakers. Many factors influence these emissions, such as economic and demographic developments, technological change, energy structure, institutional frameworks and lifestyles. One of the analytical tools that is conventionally used for evaluating the main driving forces behind this pollutant behavior is the Kaya (1989) identity illustrated by Yamaji *et al.* (1991).

Many studies in the past decade as well as recent ones have been done using the Kaya identity. For examples Albrecht *et al.* (2002) analyzed the carbon emissions over the period 1960–1996 by using the Shapley decomposition technique where an extended Kaya identity with nine components was the starting point of their analysis. The Shapley decomposition is a decomposition method which iterates the cumulative approach for every possible permutation of variables. Duro and Padilla (2006) provided a methodology for decomposing international inequalities in per capita CO_2 emissions into Kaya (multiplicative)

factors and two interaction terms. They used the Theil index of inequality and show that this decomposition methodology can be extended to analyzing between- and within-group inequality components, whereas Jung *et al.* (2012) undertook the LMDI (logarithmic mean Divisia index) analysis based on the Kaya identity to identify the factors driving energy-related CO_2 emissions in five regions of South Korea, where substantial eco-industrial parks (EIPs) are operational. CO_2 emissions were decomposed into five effects: production, population, energy intensity, emission, and fuel mix. Very recently, Mahony (2013) used the extended Kaya identity to analyze the driving forces of Ireland's carbon emissions from 1990 to 2010 and Ren *et al.* (2014) adopted the Log Mean Divisia Index (LMDI) method based on the extended Kaya identity to explore the impacts of industry structure, economic output, energy structure, energy intensity, and emission factors on the total carbon dioxide emissions from China's manufacturing industry during the period 1996–2010. In addition, they calculated the trend of decoupling effects in the manufacturing industry in China by presenting a theoretical framework for decoupling. The main purpose of this paper is to show first the similarities in the method and the correlation in the results of both OECD (2002) and Tapio (2005) decoupling index, then apply the Kaya identity factors to discuss the primary CO_2 emissions drivers and, finally, to support the results from decoupling. This paper also examined the strengths and weaknesses of Tapio and OECD decoupling methods using the collected CO_2 emission and GDP data of South Africa from 1990 to 2012, with 1990 as the base year. This gives us a sufficiently large database for revealing the trend and pattern of variations over that period of time.

METHODS

OECD Method

According to the Organization for Economic Co-operation and Development (OECD, 2002), the term "decoupling" means a process of breaking the relationship between environmental damages and economic benefits or between environmental pressures and economic performances. Decoupling indicators are determined by the following equations (OECD, 2002):

$$Decoupling\ index = \frac{(EP/DF)_T}{(EP/DF)_{T_o}} \tag{1}$$

$$Decoupling\ factor = 1 - Decoupling\ index \tag{2}$$

where EP is the environmental pressure, DF is the driving force, T is the end of period, and T_o is the start of period.

If the decoupling index is < 1, it means that decoupling has occurred during the period, although it does not indicate whether decoupling is absolute or relative; the decoupling factor is zero or negative in the absence of decoupling and has a maximum value of 1 when the environmental pressure reaches zero (OECD, 2002). Relative decoupling is meant when the growth rate of the energy used or the carbon dioxide

emission variable is positive but less than the growth rate of economic variable. Absolute decoupling is meant when the growth rate of energy use or the carbon dioxide emission variable is zero or negative and the growth rate of economic value is positive; in this case the pressure on the environment from energy used or carbon dioxide emission is either stable or falling (OECD, 2002). %ΔEP and %ΔDF are the growth rates of environmental pressures and economic factors, respectively, with $\%\Delta EP = (EP_t - EP_{t-1})/EP_{t-1}$ and $\%\Delta DF = (DF_t - DF_{t-1})/DF_{t-1}$ (t represents a year). Mathematically that can be expressed as following:

The decoupling is relative if the decoupling index < 1 or the decoupling factor > 0, and %ΔEP > 0, %ΔDF > 0 (with %ΔDF > %ΔEP). It is absolute when the decoupling index < 1 or the decoupling factor > 0, and %ΔEP ≤ 0, %ΔDF > 0.

Tapio Method

The concept of relative decoupling and absolute decoupling cannot meet all the descriptions of the relationship between environmental pressures and economic growth. Since the environmental pressure may exceed the economic growth, some situations for a decrease in economic growth cannot be avoided. Based on the above reasons, Tapio extended Vehmas' decoupling classification (Vehmas *et al.*, 2003) by dividing it into three major categories: weak, strong and recessive decoupling. Similarly, negative decoupling can be divided in three major categories: weak negative, strong negative and expansive negative decoupling. Previously, relevant cases for all categories have been found in the analysis of CO_2 emissions and the GDPs of 140 countries using data over five-year intervals between 1975 and 2005 (Tapio, 2007). Our study focuses on the relationship between the GDP and CO_2 emission. The decoupling analyses describe the relative growth (or decrease) rates where two components are being related to each other. Based on the definition given by Tapio (2005), the decoupling index (*d*) of CO_2 emission and economic growth can be measured as the ratio of the percentage change of the environmental pressure (EP: CO_2 emission) to the percentage change of the driving force (DF: GDP) in a given time period from a base year 0 to a target year t, as shown in the following equation:

$$d = \%EP/\%DF \tag{3}$$

where *d* means the decoupling elasticity, %ΔEP and %ΔDF represent the change rates of environmental pressures and

economic factors, respectively, with $\%\Delta EP = (EP_t - EP_{t-1})/EP_{t-1}$ and $\%\Delta DF = (DF_t - DF_{t-1})/DF_{t-1}$ (t represents a year). In this study the environmental pressures are the energy consumption and the CO_2 emission (on which we focus the most). The driving force is represented by the GDP.

An elasticity value of 1 means that the CO_2 emission and the GDP grow at a similar rate. In order not to over-interpret very small changes as significant signs of decoupling in the analysis, a ± 20% variation of the elasticity values around 1.0 is regarded as coupling, which leads to coupling being defined as the elasticity value between 0.8 and 1.2 (Tapio, 2005). The rates of change of the variables can be either positive, expressed as an expansive coupling, or negative, expressed as a recessive coupling. The Tapio's decoupling state takes the following eight cases shown in Table 2.

Kaya Identity Method

The Kaya identity is an equation relating factors that determine the level of human impact on climate, in the form of emissions of the GHG carbon dioxide. This identity states that total emission level can be expressed as the product of four inputs: population, GDP per capita, energy use per unit of GDP, carbon emissions per unit of energy consumed (Yamaji *et al.*, 1991). The Kaya identity is a real form of the more general I = PAT equation (Nakicenovic *et al.*, 2000), where I is described as the environmental impact in terms of the factors P = Population, A = Affluence and T = Technology. In the Kaya identity, impact is carbon emissions, while technology is split into energy use per unit of GDP and carbon emissions per unit of energy consumed.

The advantage of Kaya identity in general is that it is simple and facilitates at least some standardization in the comparison and analysis of historical developments and many future scenarios of emissions; it has been widely used to disaggregate and identify the drivers for the variations in carbon emissions; and with its simple mathematical form, it can decompose drivers without residuals; however its policy implications has some limitations (Yuan and Pan, 2013). In this paper, to eliminate those limitations, we focus on the decomposition model of energy-related carbon emission only to get change amount of carbon emission of each decomposition factor and use them to see the consistency with the results in the Tapio and OECD decoupling models. This part presents the decomposition of CO_2 emissions into five driving factors following the Kaya identity, which is generally presented as the Eq. (4):

Table 2. Tapio's decoupling states.

Conditions	Decoupling state
If 0 < d ≤ 0.8, ΔEP > 0, ΔDF > 0	weak decoupling
If 0.8 < d ≤ 1.2, ΔEP > 0, ΔDF > 0	expansive coupling
If d > 1.2, ΔEP > 0, ΔDF > 0	expansive negative decoupling
If d ≤ 0, ΔEP < 0, ΔDF > 0	strong decoupling
If d ≤ 0, ΔEP > 0, ΔDF < 0	strong negative decoupling
If 0 < d ≤ 0.8, ΔEP < 0, ΔDF < 0	weak negative decoupling
If 0.8 < d ≤ 1.2, ΔEP < 0, ΔDF < 0	recessive coupling
If d > 1.2, ΔEP < 0, ΔDF < 0	recessive decoupling

Source: Tapio (2005).

$$CO_2 = (CO_2/TPES) \, (TPES/TFC) \, (TFC/GDP) \, (GDP/P) \, P \tag{4}$$

where $CO_2 = CO_2$ *emissions*; $CO_2/TPES$ = CO_2 emissions per unit Total primary energy supply (TPES) that depends on emission factors and fuel mix; *TPES/TFC* = Total primary energy supply per total final energy consumption (*TFC*) that depends on conversion efficiency and the fuel mix; *TFC/GDP* = Total final energy consumption per GDP that depends on end-use energy intensities; *GDP/P = GDP/ population* that depends on fuel mix, activity and structure of the economy; and P = population. If we consider the CO_2 emissions intensity per unit of GDP (CO_2/GDP) expressed by the following equation:

$$CO_2/GDP = (CO_2/TPES) \, (TPES/TFC) \, (TFC/GDP) \tag{5}$$

The Eq. (5) can be modified as the following:

$$CO_2 = (CO_2/GDP) \, (GDP/P) \, P \tag{6}$$

At any moment in time, the level of energy-related carbon emissions next to emissions that result from changes in land-use can be seen as the product of the five Kaya Identity components. For small to moderate changes in the Kaya components between any two years, the sum of the percent changes in each of the variables closely approximates the percent change in carbon emissions between those two years Albrecht et al (2002) as the following:

$$d(lnCO_2)/dt = d(lnCO_2/TPES)/dt + d(lnTPES/TFC)/dt +$$
$$d(lnTFC/GDP)/dt + d(lnGDP/P)/dt + d(lnP)/dt. \tag{7}$$

By analogy with Eq. (6), Eq. (7) leads to:

$$d(lnCO_2/GPD)/dt = d(lnCO_2/TPES)/dt + d(ln\,TPES/TFC)/$$
$$dt + d(ln\,TFC/GDP)/dt \tag{8}$$

The reference year for the indices of all terms is 1990 = 100.

DATA CONSOLIDATION

he main purpose of this paper is to show first the similarities in the method and the correlation in the results of both OECD (2002) and Tapio (2005) decoupling index, then apply the Kaya identity factors to discuss the primary CO_2 emissions drivers and, finally, to support the results from decoupling. The research period starts in 1990 and ends in 2012. The data has been collected from various sources. The total CO_2 emissions measured in Kilotons, the GDP (constant 2005) is measured in USD and comes from the World Bank website. The total population also comes from the World Bank Website. The total primary energy supply and the total final energy consumption in Million ton of oil equivalent have both been obtained from the International Energy Agency (IEA) website.

RESULTS AND DISCUSSION

The South African energy sector has been largely driven by economic and political forces, which have had a profound impact on energy policies. When considering SA's energy policies, it is best to consider three different periods: The first being the period of the apartheid regime, from 1948 up to 1994; the second being the period following the first democratic elections of 1994, up to 2000; and the third from 2000 on, after the elation of independence had started to recede (Energy Research Centre, 2006). So, to simplify the analysis of the results, the study period was subdivided into five periods (P_1: 1990–1994; P_2: 1994–2000; P_3: 2000–2005; P_4: 2005–2010; P_5: 2010–2012) related to the energy policies history.

Analysis of CO_2 Emissions

South Africa's economic experienced a spectacular economic growth from 1993 to 2008 and 2009 to 2012. Its GDP increased at the annual average rate of about 3.47% between 1993 and 2008 but at a bit lower rate of about 3.07% between 2009 and 2012. This can be justified that since 1994, the government has been firm about getting the macroeconomic balance right in order to attract investors, reduce the budget deficit, and fight inflation through high interest rates. The government set economic objectives to achieve economic growth to create employment, and decrease inequality and poverty. Despite an economy that did not achieve rates of economic growth as high as predicted, the government has met key fiscal and monetary targets, and has been successful in reducing the fiscal deficit, inflation, and interest rates (Energy Research Centre, 2006). During 1990–1993, the economy activity was slow in SA, with the GDP decreased by about −1.92% from 1990 to 1993. In fact, according to Energy Research Centre (2006), from the 1970s until 1993, increased public spending, economic sanctions, and the effects of political instability stifled the economy. Over this period, although the GDP growth rate decreased very fast from 3.62% to −1.52% in 2008–2009 due to the economic crisis in SA and over the world (Table 3 and Fig. 3). Since SA's energy sector is dominated by coal, it is suggested that this is the reason why the trends for total primary energy supply and energy consumption in SA kept approximately the same range for decades (Fig. 3). It means that the energy consumption behavior (dominated by coal and oil) remained the same. This manifests that the CO_2 emission strongly depends on the energy consumption. Accompanying the growth in fossil fuel use, the SA's energy-related CO_2 emission has grown slowly as compared to the economic activity. It is apparent that the CO_2 emission increased at a rapid pace between 2002–2004 and 2005–2009. Specifically, the CO_2 emission in SA increased 59.00% from 1990 to 2012.

Decoupling Analysis

In Fig. 3 we observed the development of the absolute values where the 1990 value was given an index value of 100. From these graphs we can see that there has generally been some decoupling since the GDP has the highest
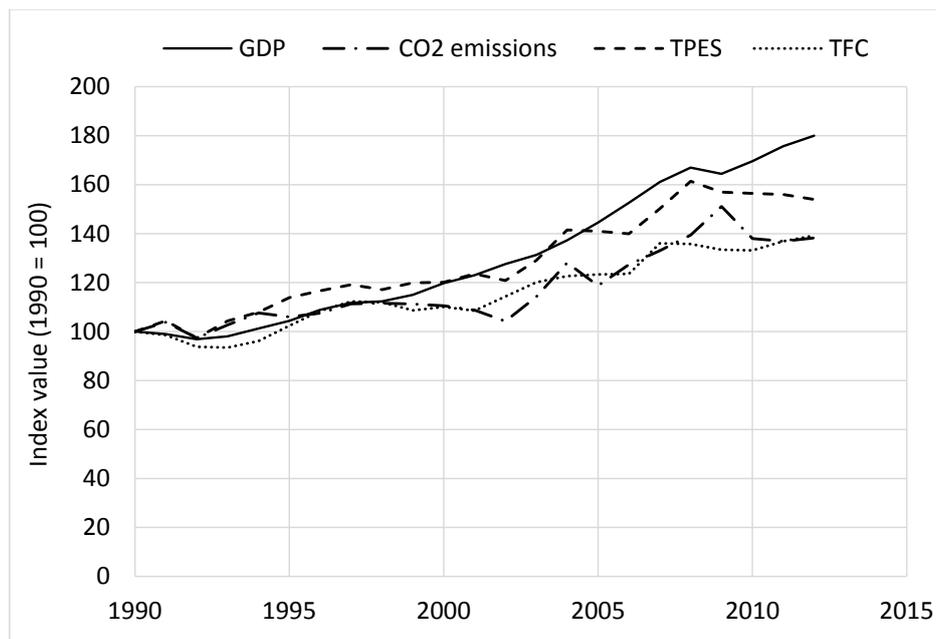
Fig. 3. Trend of GDP, CO_2 emissions, Total Primary Energy Supply and Total Final Energy Consumption of SA.

Table 3. Total primary energy supply, total final energy consumption, total CO_2 emission from fuels combustion and Gross Domestic Product (GDP) of SA.

year	GDP (constant 2005 10^11US$)	CO_2 emissions (Mt)	TPES (Mtoe)	TFC (Mtoe)	ΔGDP (%)	ΔCO_2 (%)	TFC (%)
1990	1.709	333.514	90.956	51.048	–	–	–
1991	1.692	346.337	94.981	50.293	−1.02	3.84	−1.48
1992	1.656	324.852	88.589	47.865	−2.14	−6.20	−4.83
1993	1.676	342.549	94.940	47.703	1.23	5.45	−0.34
1994	1.730	358.930	98.168	49.059	3.23	4.78	2.84
1995	1.784	353.458	103.581	52.286	3.12	−1.52	6.58
1996	1.861	358.640	106.143	55.368	4.31	1.47	5.89
1997	1.910	371.328	108.374	57.318	2.65	3.54	3.52
1998	1.920	372.219	106.517	57.164	0.52	0.24	−0.27
1999	1.965	371.034	109.055	55.455	2.36	−0.32	−2.99
2000	2.047	368.611	109.264	56.195	4.15	−0.65	1.33
2001	2.103	362.743	112.399	55.394	2.74	−1.59	−1.43
2002	2.180	347.687	109.908	58.355	3.67	−4.15	5.35
2003	2.244	380.811	117.374	61.334	2.95	9.53	5.10
2004	2.347	427.132	128.723	62.635	4.55	12.16	2.12
2005	2.471	396.117	128.214	62.963	5.28	−7.26	0.52
2006	2.609	424.844	127.255	63.09	5.60	7.25	0.20
2007	2.754	443.648	136.604	69.432	5.55	4.43	10.05
2008	2.853	465.023	146.768	69.308	3.62	4.82	−0.18
2009	2.81	503.941	142.76	68.111	−1.53	8.37	−1.73
2010	2.898	460.124	142.291	67.975	3.14	−8.69	−0.20
2011	3.002	456.576	141.888	69.861	3.60	−0.77	2.77
2012	3.076	461.095	140.004	71.072	2.47	0.99	1.73

values at the end of the period. GDP, energy consumption and CO_2 emissions has increased during the chosen study period. However GDP increased faster with an annual average growth rate of 2.70% while energy consumption and CO_2 emissions have 2.35% and 1.57% respectively.

According to the methods presented in Section 2, the decoupling of the energy-related CO_2 emission from the economic growth is presented below. The decoupling state is presented in Fig. 4 (by the OECD method) and in Table 4 (by the Tapio method). Based on the OECD method, the results in 1994–2000, 2000–2005 and 2005–2010 showed a state of relative decoupling, while in 1990–1994 and 2010–
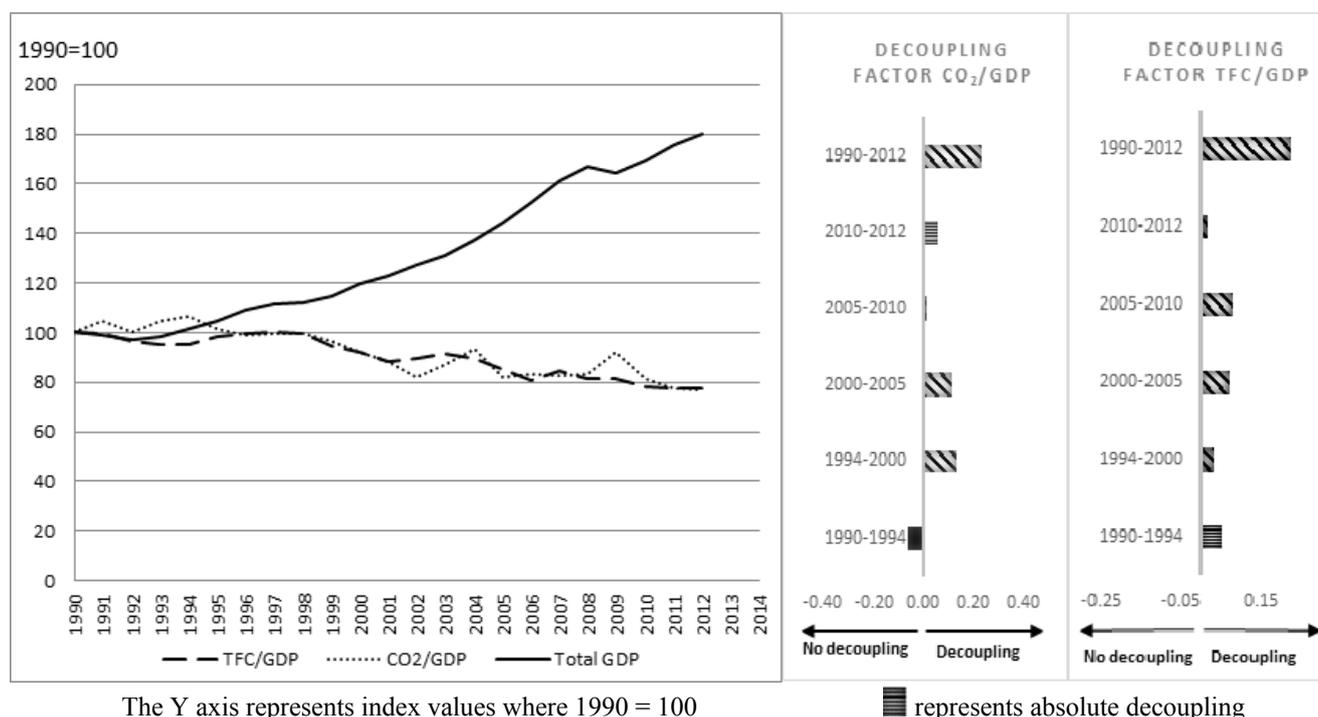
The Y axis represents index values where 1990 = 100   ▤ represents absolute decoupling

Fig. 4. Trend of GDP, CO_2/GDP, TFC/GDP and decoupling factor in South Africa. Decoupling factor is defined as $1 - (EP/DF)_{To}/(EP/DF)_T$ where EP = environmental pressure and DF = driving force. Decoupling occurs when the value of the decoupling factor is between 0 and 1. *Source:* OECD, Eurostat (2002).

Table 4. Tapio decoupling method results of SA.

Period (yrs.)	ΔGDP (%)	ΔCO₂ (%)	d	Decoupling state
1990–1994	0.33	1.97	6.00	Expansive negative decoupling
1994–2000	2.90	1.08	0.37	Weak decoupling
2000–2005	3.89	1.34	0.34	Weak decoupling
2005–2010	3.61	1.48	0.41	Weak decoupling
2010–2012	3.07	−2.83	−0.92	Strong decoupling
1990–2012	2.73	1.62	0.59	Weak decoupling

ΔGDP (%) and $ΔCO_2$ (%) in this case, represent the average change which correspond to the mean value of the annual changes during each period.

2012 they revealed a state of coupling and absolute decoupling respectively. In the whole period of the study, a state of relative decoupling was observed (Fig. 4). Fig. 4 shows as well the decoupling of energy consumption from GDP where the decoupling was absolute in 1990–1994, and relative for the others periods. The reason of this absolute decoupling could be that during that period in SA, due to the energy policies were mostly centered on energy security and significance, the priority was given to the needs of the industrial sector because of its role in economic (Energy Research Centre, 2006). The decoupling is observed when both CO_2 intensity and energy intensity decrease while the GDP increases.

From the Tapio method, the CO_2 emission and the GDP growth in 1994–2000, 2000–2005 and 2005–2010 were weakly decoupled with decoupling factor values of 0.37, 0.07 and 0.41, respectively. It means the rate of growth in CO_2 emissions fell short of that of economic growth. The decoupling factor in 2000–2005 is much lower compared

to others; it means higher resource efficiency and lower dependence on resources. The best development situation occurred during 2010–2012 where we observed a strong decoupling following by the increase of economic growth and the decrease of CO_2 emissions growth. In 2003 the government published a White Paper on Renewable Energy, which sets a 10 TWh renewable energy production target for 2013. So the reason of that strong decoupling could be explained by this mitigation action of CO_2 emissions set by promoting renewable energy. The SA development in 1990–1994 corresponded to an expansive negative decoupling. During that period the decoupling factor was 6.00 much higher than 1.2 (Table 4). It means the increasing rate of CO_2 emissions keeps pace with or is higher than economic growth. In other words, as the economy grows, resource consumption and environmental degradation increase rapidly. However, a weak decoupling was observed over the whole study period with a decoupling factor equal to 0.56 which implied an acceptable development.

Comparison of the Methods

Based on the OECD and Tapio evaluation methods, SA experienced different decoupling states. The two methods showed well-correlated results but differed in their applications. The OECD method seemed to be simpler, in the sense that it offered only two cases of decoupling, i.e., 'relative decoupling' and 'absolute decoupling', which corresponded to 'weak decoupling' and 'strong decoupling', respectively, according to the Tapio's classification. Since the OECD method is a fixed base year method while the Tapio's method is a rolling base year method, there is a difference in the results (see appendix). When subdividing the study period into sub-periods the results showed some correlations. The reason is that the base year of each sub-period is the same for both methods. The coupling cases of the OCDE method correspond to other decoupling states of the Tapio method as shown above. The limitation of the former method is that knowing the decoupling index or factor was not enough to know the decoupling state. It only allowed one to know if there was decoupling or not. A comparison of the calculated growth rates of GDP and CO_2 emission is necessary to find out the decoupling state, as shown in appendix (Tables 6 and 7). The Tapio method is more complicated but provides more details about the decoupling states. The advantage of this method is that it gives a better analysis of the results for a long study period and is good for decomposition purposes. For a quick and simple decoupling study, the OECD method should be more appropriate. Thus, combining these two methods is useful to substantiate the results.

The calculated growth rates of GDP and CO_2 emission are necessary to determine the decoupling state; this suggests a relationship between the two methods. In fact by reconsidering the Eq. (3) in the case of continued driving force growth, namely ΔDF (%) > 0, the Decoupling factor d may imply one of three scenarios as follows:

(1) For $d > 1$, the environmental pressure is higher than the driving force growth. In this case, no decoupling is taking place. In other words, as the driving force grows, resource consumption and environmental degradation increase rapidly. When d equals 1, it is the turning point between absolute coupling and relative decoupling. In the stage of absolute coupling, a higher d value means higher dependence on resources by driving force growth, lower resource efficiency and heavier environmental pressure.

(2) For $0 < d < 1$, the rate of growth of environmental pressure falls short of that of driving force growth. In this case, relative decoupling is taking place. When d ranges from 0 to 1, lower d means higher resource efficiency and lower dependence on resources.

(3) For $d = 0$, the driving force is growing while environmental pressure remains constant. In other words, when the driving force grows continuously, the amount of environmental pressure does not increase. If environmental pressure decreases while the driving force keeps growing, then $d < 0$. Here the relationship between CO_2 emissions and economy can be described as the 'declining stage', namely absolutely decoupling.

So, knowing the value of "d" in the case of continued driving force growth, namely ΔDF (%) > 0, will directly reveal the decoupling state in the OECD (2002) method.

Kaya Factors Analysis

Applying the Kaya identity method allowed the identification of the primary CO_2 emissions driving forces. As presented in Table 5, CO_2 emissions did increase in SA over the period 1990–2012 (32.4%) and the differences are significant. The emissions increased strongly during the period 2005–2010 (15.0%), mildly from 1990–1994 (7.3%) and 2000–2005 (7.2%); it was quite low in 1994–2000 (2.7%). During 2010–2012 the CO_2 emission was insignificant (0.2%). Conversely the CO_2 emissions factor decreased overall during the study period. It increased from 2005 to 2012, perhaps due to the huge consumption of coal which dominates the SA's fuel structure. The energy inefficiency, defined as TPES/TFC, increased by 10.0% during 1990–2012; the large dependence on fossil fuels and the less improved technologies might be the major reasons for this increase. In the same order with the CO_2 emissions factor, the energy intensity decreased during the whole study period; this could have an impact on CO_2 emission mitigation. As well as the CO_2 emissions, SA's population has increased during each period; the same effect can be seen with the GDP per capita which only decreased in 1990–1994. That can be explained by the economic sanctions and probably by the effects of political instability. So, the increases in population, GDP per capita, decrease of energy efficiency and the fuel mix have been the driving forces for the upwards trends in CO_2 emissions, more than offsetting the reduction in energy intensity.

The results from the Kaya identity method are consistent with those from the OECD and Tapio methods. In fact, Table 5 clearly shows that carbon intensity decreased from 1994 to 2012 where decoupling has been observed and increased only during the period 1990–1994 where coupling or negative decoupling occurred. This is clearly revealed in the decoupling results shown above. In fact, the energy consumption continues to be dominated by fossil fuels in SA, particularly coal in the energy mix, and to the slow uptake of low-carbon technologies. Coal is a high-carbon intensity fuel, which releases vast amounts of CO_2 and other greenhouse gases and pollutants during combustion. The major reason for poor energy efficiency in SA is that best quality coal is exported, thereby earning the country its third-largest export revenues after gold and platinum; the use of low quality coal contributes to GHG emissions levels and other environmental problems (Nkomo, 2005). According to the Ward and Walsh (2010), South Africa used more than double the amount of energy as Germany in 2006 to generate the same economic effect. This has been the major source of inefficient energy use of SA, and the value added to the economy per unit of energy is even lower than some other countries.

CONCLUSIONS

This study analyzed the decoupling effects of energy and CO_2 emissions from GDP in SA by using the OECD and

Table 5. Carbon emissions and the Kaya identity components of SA (percentage changes per period).

Period	CO_2 emissions	CO_2/TPES	TPES/TFC	TFC/GDP	CO_2/GDP	GDP/P	P
1990–1994	7.3%	–0.3%	11.6%	–5.2%	6%	–7.2%	8.4%
1994–2000	2.7%	–8.0%	–2.9%	–3.2%	–14%	2.9%	13.9%
2000–2005	7.2%	–8.8%	4.6%	–7.4%	–12%	10.9%	7.9%
2005–2010	15.0%	4.6%	2.8%	–8.3%	–1%	9.4%	6.6%
2010–2012	0.2%	1.8%	–6.1%	–1.5%	–6%	3.3%	2.7%
1990–2012	32.4%	–10.7%	10.0%	–25.7%	–26%	19.2%	39.5%

Tapio methods, and identified the primary CO_2 emissions driving forces by Kaya identity method. The results showed that SA presented an acceptable development situation while the CO_2 emissions still increased noticeably. Based on the OECD and Tapio evaluation methods, SA experienced different decoupling states. The two methods showed well-correlated results but differed in their applications. The OECD method seemed to be simpler. According to the Kaya identity, the increase in population and GDP per capita and the adverse of energy efficiency were the primary driving forces for the CO_2 increase. The energy inefficiency, defined as TPES/TFC, did increase by 10.0% during 1990–2012; the large dependence on fossil fuels was the major reason for the increase of CO_2 emissions. As matter of fact, SA has been highly dependent on coal 72% of the energy supply, which had led the country to become one of the major carbon dioxide emitter in Africa. Also, the Kaya identity results were consistent with those from the OECD and the Tapio methods.

Base on the results of our study, South Africa needs to reduce its emission amount by improving the fuel structure towards lower carbon intensity and enhancing the energy efficiency. Recently, the shortage of energy challenge facing by South Africa is mostly being met by building more coal-powered stations to generate more electricity (Sebitosi and Pillay, 2008b). This will further contribute to more CO_2 emissions. The current energy strategy of South Africa indicates that coal consumption will continue to increase, and this will inevitably exacerbate further environmental degradation unless effective measures are taken to reduce emissions and to increase the portion of environmental friendly sources of energy. To fight against energy shortages and deal with the environmental degradation facing this country, there is a need for South Africa to develop strategies to exploit its clean energy potential and increase their utilization. South Africa is imbued with sufficient sources of renewable energy that can concurrently deal with both the energy needs as well as the concerns of CO_2 emissions. Therefore, it is suggested that SA expand the share of the renewable energy such as more of solar energy, bio and wind power; and promote related green energy technology programs. Considering the demand side management (DSM), the national policy can also apply effective economic strategies to enhance research and investments in promoting energy-saving programs and to raise the energy efficiency by major industries and the residential and commercial sectors to further controlling the CO_2 emissions. The methods used in this research can be applied to other countries with similar situations for evaluation the trend of energy consumption and CO_2 emissions and as a decision-making tool for measuring sustainable development. Also, the Kaya identity can be extended to decompose and to further quantify the major factors which affect the changes of energy consumption and CO_2 emissions, in order to develop strategic policy and effective measures for coping with the increase of CO_2 emissions and related environmental concerns.

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APPENDIX

Tables 6 and 7. Supplementary data associated with this article can be found in the online version at http://www.aaqr.org.

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