Environmental Science and Pollution Research (2021) 28:14329–14342
https://doi.org/10.1007/s11356-020-11531-3

RESEARCH ARTICLE

Driving forces and decoupling indicators for carbon emissions from the industrial sector in Egypt, Morocco, Algeria, and Tunisia

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Received: 8 May 2020 / Accepted: 3 November 2020 / Published online: 18 November 2020

Abstract
North Africa currently accounts for about 40% of Africa's total CO_2 emissions, and the industrial sector is one of the energy-intensive sectors in the region. To this end, special attention should be paid to this region if the African continent's GHG mitigation targets are to be achieved. An extended decomposition approach was combined with the Tapio method to explore the decoupling of CO_2 emissions from industrial growth in North African countries over the period of 1990–2016. The effects of five factors were assessed in the decoupling and the study took into account all fossil fuels used in the industrial sector of this region. Unlike Morocco, Egypt, Tunisia, and Algeria, this study did not consider Libya because of the unavailability of data. Meanwhile, the results showed that: (i) low decoupling was achieved in Tunisia, compared with Morocco and Egypt, where significant decoupling occurred significantly over the study period. (ii) Due to the slowdown in industrial growth, the decoupling analysis did not show satisfactory results in the case of Algeria. (iii) Scale effects contributed to promoting decoupling only in Algeria, while the energy intensity effect played a negative role in decoupling only in Tunisia. (iv) The energy structure effect played an important role in decoupling in Tunisia and Egypt, while the economic structural effect favored decoupling in Tunisia and Morocco alone. An energy policy conducive to the use of more renewable energy is needed to promote decoupling in North African countries.

Keywords North Africa · CO_2 emission · Industry · Decoupling · Energy · Economic growth

Introduction

The current global challenge is to lift one billion people out of absolute poverty and chart the way forward to meet the needs of nine billion people by 2050 (Johnson 2006), while maintaining climate change, biodiversity loss, and threats to health within acceptable limits (IPCC 2014). For the well-being of today and tomorrow, it is necessary to achieve sustainable resource management by dissociating the use of natural resources and the environmental impacts of human well-being. Sustainability requires that resources be used more efficiently, reducing the economic and environmental costs associated with resource depletion and negative environmental impacts. Decoupling analysis has proved to be an indispensable tool for determining the interdependence between economic development and environmental pressures.

Responsible Editor: Eyup Dogan

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According to the IEA, global CO_2 emissions related to the consumption of fossil fuel were estimated at 32.31 $GtCO_2$ in 2016. In this amount of carbon, which increased by 1.5% in 2017, the share of carbon emissions attributed to Africa was estimated at 1.16 $GtCO_2$, and about 40% of these carbon emissions originated from North Africa (IEA 2019). This high level of carbon emissions demonstrates that North Africa deserves particular attention in Africa's GHG mitigation policies. Conscious of the weight of their GHG emissions on a continental scale, significant GHG mitigation measures were taken by North African countries at the Paris Summit in 2015 (UNFCCC 2015).

Algeria is committed to reducing its greenhouse gas emissions by 29% by 2030, but only 7% of this target should be achieved by the country's means. Besides Algeria, Egypt is seeking funding of around US$73 billion to develop a clean economy based on renewable energies by 2030. To reduce its GHG by 32% by 2030, Morocco needs about US$35 billion of the US$73 billion estimated for this project, while US$18 billion is also needed in Tunisia to decrease emissions by 41% by 2030 (UNFCCC 2019). As far as Libya is concerned, no objective has been set so far because of the deplorable security situation in that country.

Speaking of security, it should be noted that the North African region is experiencing a major revolutionary movement known as the Arab Spring since 2010 (Britannica 2013). This movement undermines the economic growth and well-being of the people of this region, while destabilizing any goal related to sustainable development in this region. Based on this security context and given their objectives in terms of environmental pollution, there is no doubt that the countries of North Africa are looking for the ideal solutions to decouple their GHG emissions from economic growth. Therefore, this study aims to explore the decoupling relationship between economic growth and carbon emissions from the industrial sector of North African countries over the period of 1990–2016.

The Tapio and extended LMDI models were used in this study to decompose, analyze, and highlight the main reasons related to decoupling status identified throughout the study period. Meanwhile, while local environmental impacts have diminished in some parts of the world, they however are becoming increasingly important and require an international policy response. For this purpose, the main contribution of this study is that its results provide North African countries with policy benchmarks that will enable them not only to achieve energy-saving and carbon emissions targets but also to promote sustainable economic development in this region. Besides, this study is the first to evaluate the decoupling relationship between economic growth and carbon emissions in this region of Africa.

The rest of this paper is organized as follows. A short review of the literature on decoupling is presented in the "Literature review" section and the research area in the "Study area" section. The methodological approach used to achieve the objectives of this study is represented in the "Methods and data sources" section, while the results are presented and discussed in the "Results and discussions" section. We conclude the study in the "Conclusion and policy implications" section.

Literature review

The current global challenge is to lift one billion people out of absolute poverty and chart the way forward to meet the needs of nine billion people by 2050 (Johnson 2006), while maintaining climate change, biodiversity loss, and threats to health within acceptable limits (IPCC 2014). For the well-being of today and tomorrow, it is necessary to achieve sustainable resource management by dissociating the use of natural resources and the environmental impacts of human well-being. Sustainability requires that resources be used more efficiently, reducing the economic and environmental costs associated with resource depletion and negative environmental impacts. Decoupling analysis has proved to be an indispensable tool for determining the interdependence between economic development and environmental pressures.

The concept of decoupling was first proposed by (Meyer and Rowan 1977) in the 1970s and was recognized as an indicator by the OECD in 2002 (OECD 2010). Although used for the first time in environmental studies in 2000 by (Zhang 2000), the decoupling analysis showed widespread application after Tapio developed the eight logical states of a decoupling status in 2005 (Tapio 2005). However, the main limitation related to the Tapio method is that it only allows us to define the decoupling state, but it is difficult to determine the real reasons that led to these decoupling states. To address this problem, (Zhang and Da 2015) has shown that the log mean Divisia index (LMDI) and Tapio methods can be combined to decompose the decoupling indicators into several factors.

The LMDI approach is part of the index decomposition analysis model proposed by Boyd in 1987 (Boyd et al. 1987). After considerable improvement by many researchers, IDA finally condensed into two classical extension forms: the logarithmic mean Divisia index (LMDI) method and the arithmetic mean Divisia index (AMDI) method (Ang 2005; Ang and Choi 1997; Ang and Zhang 2000). Unlike the AMDI method, which poses huge problems of residual value and zero value (Wang et al. 2018; Zhang and Da 2015), the LMDI method has become the most widely used decomposition method in environmental studies (Salamah et al. 2019), because it leaves no residue and provides a solution to the problem of zero value (Liu and Ang 2007). Meanwhile, faced with the urgency of the global warming problem (Shi et al. 2020), Tapio and LMDI have become the preferred methods for many researchers, not only to explore the underlying drivers of carbon growth but also to determine if economic growth depends on these CO_2 emissions and propose mitigation policies.

For example, Xie et al. (2019) used the Tapio and LMDI models to decompose the decoupling index and to explore the determinants of CO_2 emissions in China's power industry over the period of 1985–2016. They found that the decoupling relationship of this sector evolved from weak decoupling to expansive decoupling and that energy intensity and energy consumption in electricity generation favored decoupling, while the economic scale and electrification were the two main factors that inhibited decoupling. Based on the Tapio and LMDI models, Engo (2019) showed that the decoupling of CO_2 emissions is low in Cameroon's transport sector and that scale effects, followed by energy intensity and energy structure effect, have prevented decoupling, while the economic structure effect favored decoupling over the period of 1990–2016. Wu et al. (2018) studied decoupling trends between CO_2 emissions and economic growth in developed and developing countries using decoupling theories over the period of 1965–2015. They found a strong decoupling in developed countries and a slight increase in their stabilization, while developing countries showed a weak decoupling that fluctuated a lot and lacked regularity. Wang et al. (2019) applied the Tapio and LMDI models to compare the decoupling performance of economic production and CO_2 emissions between Beijing and Shanghai over the period of 2000–2015. They found that there were several similarities between the decoupling statuses of the two cities, but agriculture seemed more strongly decoupled in Beijing than in Shanghai where recessive decoupling appeared, while the industry has shown strong decoupling in Beijing and weak decoupling in Shanghai. Also, scale effects inhibited decoupling, while the effects of energy intensity, industrial share, and energy mix accelerated the decoupling process in both cities. Engo (11) also combined the Tapio and LMDI models to explore the decoupling of CO_2 emissions from economic growth in Cameroon over the period of 1990–2015. He found that CO_2 emissions were slightly dissociated from economic growth and that scale effects and energy intensity prevented decoupling, while the economic structure effect and the emission factor favored decoupling. He finally concluded that the growth of the industrial sector determined the degree of decoupling of CO_2 emissions from Cameroon's economic growth. Like these authors, several other researchers have used the Tapio and LMDI models to provide solutions to the problem of reducing CO_2 emissions around the world. Among these studies, we found those of Akram et al. (2019); Engo (2019); Song et al. (2020); Song et al. (2019); Song and Zhang (2017); Wang et al. (2017); Wang et al. (2014); Zhang et al. (2018); Zhang et al. (2017); Zhang et al. (2015).

However, some remarks can be drawn from the literature presented above. First, previous studies on decoupling and decomposition have been conducted at the national level. Secondly, concerning the question of this research, China, the largest emitter of CO_2 in the world, has been the subject of several case studies conducted by researchers. However, very few analyses of the decoupling of CO_2 emissions from economic growth have been conducted for countries and regions other than China; yet, China alone cannot respond to the threat of current climate change. Finally, as the largest emitter of CO_2 on the African continent, it is very curious to note that there is virtually no literature on the issue of the dependence of CO_2 emissions on the economic growth of North African countries.

Based on the research gaps that this study is attempting to fill, the Tapio and LMDI models were applied in this paper to break down, identify, and analyze the main drivers of decoupling indicators in North African countries over the period of 1990–2016. An extended Kaya identity was used in the LMDI model to decompose the decoupling indicators into six factors, namely, the effect of the total change in CO_2 emissions, the effect of the population change, the effect of economic output, the effect of energy intensity, the effect of energy structure, and the effect of economic structure. Due to the quality of energy consumed and its impact on the economic development of North African countries, the analysis in this study focused only on the industrial sector, taking into account all the fossil fuels used in that sector. Meanwhile, with the threat of climate change requiring a global response, the results provided by this study will contribute to and serve as a basis for the development of a regional mitigation policy that will enable North African countries to meet their GHG targets. However, the methodology used to achieve the objectives of this study is presented in the following section.

Study area

The African continent is divided into five sub-regions namely, North Africa, South Africa, East Africa, West Africa, and Central Africa. Meanwhile, Algeria, Morocco, Libya, Egypt, and Tunisia are the five main countries that make up the North Africa region, as you can see in Fig. 1 (Wikimedia Commons 2020). The southern part of this region crosses the Sahara Desert which separates all the countries of the continent, from these five countries. The population of North Africa is predominantly Muslim, and Arabic is the most widely spoken language in this region (NWE 2018). The area of this African region is estimated at 6,017,435 km^2, with a total population estimated at 193,655,631 million inhabitants. The People's Democratic Republic of Algeria (2,381,740 km^2) is the largest territory in the region, followed by the State of Libya (1,759,540 km^2) and the Arab Republic of Egypt (1,001,450 km^2), while the Republic of Tunisia and the United Kingdom of Morocco represent the smallest territories with an estimated area of 162,155 and 712,550 km^2, respectively (NWE 2018).

Unlike their areas, Egypt (99,413,317 inhabitants) is the most populous country in the region, followed by Algeria (41,657,488 inhabitants), with annual population growth rates estimated at 2.38 and 1.63% in 2018, respectively. Although having an annual population growth rate estimated at 1.45%, Libya is the least populated country in North Africa with a population of 6,754,507 million inhabitants, while Morocco and Tunisia are countries with a population growth rate of less than 1%, but with an average population estimated at 34,314,130 and 11,516,189 million inhabitants, respectively (CIA 2019; WDI 2019).

Since the Arab Spring of 2010, the region of North Africa has recovered strongly in economic terms. The real GDP growth in this region was estimated at 4.9% in 2017, compared with 3.3% in 2016, which represents a growth rate above the average of the continent's GDP (3.6%) (ADBG 2018). The economy of the countries of this region is less agricultural and relies mainly on hydrocarbons and tourism, which explains

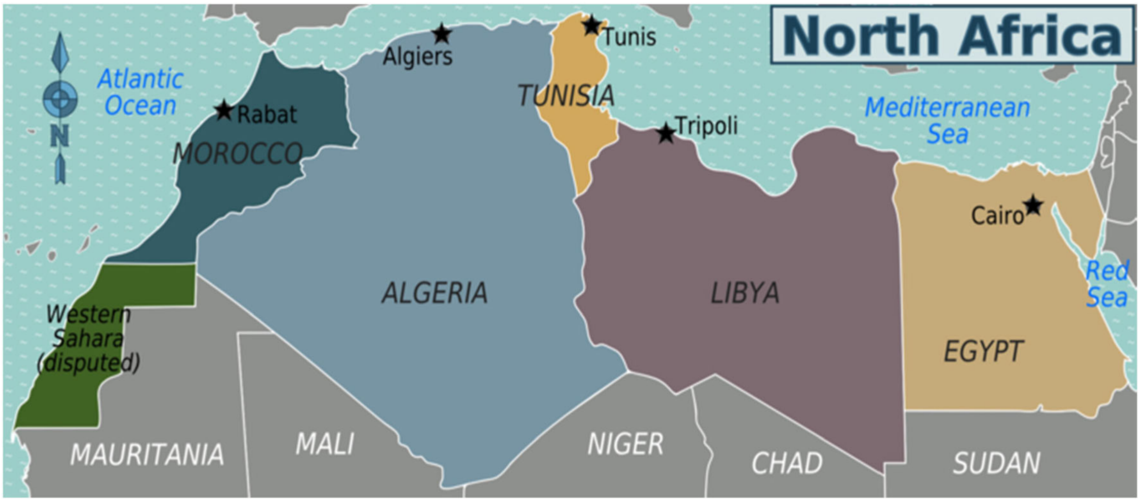

Fig. 1 North Africa region map. Source: Wikimedia Commons (2020)

their strong economic growth. Apart from Egypt, where the average annual economic growth for the period of 1990–2017 was estimated at just over 4%, that of the other four countries was estimated at around 3% (WDI 2019). In Tunisia, during the same period, the share of the average annual GDP of the service sector was higher (52.24%), followed by the industrial (27.44%) and agricultural (10.57%) sectors. Similarly, these shares are estimated at 48.14, 33.25, and 18.6%, respectively, in the Egyptian tertiary, industrial, and agricultural sectors, whereas they were estimated at 49.54, 36.86, and 13.59%, respectively, in these same sectors in Morocco. In contrast to these three countries, the share of GDP in the industrial sector (48.67%) was higher in Algeria, followed by the tertiary (37.54%) and agricultural (13.78%) sectors between 1999 and 2017 (ADBG 2018; WDI 2019). Libya remained the most industrialized country in this region with an average annual share of industrial GDP estimated at 80%.

The population's access rate to electricity is estimated at 99% for each of the North African countries, where oil and natural gas cover more than 95% of the energy needs of the region's economic sectors (Tagliapietra 2019). From 1990 to 2016, the energy indicators of this region show that the total primary energy supply (TPES) rose from 32.25 to 86.17 Mtoe in Egypt, from 22.19 to 53.75 Mtoe in Algeria, from 7.62 to 19.5 Mtoe in Morocco, then from 11.17 to 15.07 Mtoe in Libya, and from 1.95 to 11 Mtoe in Tunisia (IEA 2019). This high-energy consumption, which is largely due to industrial development and population growth, has also led to an increase in this region's carbon emissions. Between 1990 and 2016, total carbon emissions increased from 77.86 to 204.8 $MtCO_2$ in Egypt, from 51.17 to 127.64 $MtCO_2$ in Algeria, from 19.66 to 55.3 $MtCO_2$ in Morocco, from 25.84 to 43.28 $MtCO_2$ in Libya, and finally from 12.2 to 25.17 $MtCO_2$ in Tunisia (IEA 2019).

North Africa's carbon emissions are higher in Egypt, Algeria, and Morocco, which can be explained by the use of coal as a source of energy in the industrial sectors of these countries. Tunisia had stopped using coal since 2003, while Libya has not yet used it. Although heavily dependent on energy imports to support its economic development, an effort to eliminate the use of coal in the industrial sector is observed in Morocco, unlike Egypt and Algeria, where this source of energy continues to occupy an important place in their TPES (IEA 2019). In North Africa, the transport and industry are the two economic sectors that define not only the energy consumption profile but also the emission trends of this region. More than 50% of North Africa's oil supplies are consumed in the transport sector, while all supplies of coal and about 50% of natural gas are consumed in the industrial sector (Tagliapietra 2019; WDI 2019).

Methods and data sources

This research seeks to answer the following question: How can North African countries succeed in separating CO_2 emissions from their economic growth? To answer this question, several methods can be used, namely, simple regressions, variance decomposition, Tapio elasticity analysis, vector error correction modeling, ARDL model, LMDI decomposition, STIRPAT Model analysis, panel cointegration, unit root testing, and many others (Climent and Pardo 2007; Danish et al. 2018; Fan et al. 2006). In this study, the models of Kaya, Tapio, and LMDI were used (Hossain et al. 2020). Carbon intensity, population, energy intensity, and economic activity are responsible for the observed changes in a country's CO_2 emissions. The interconnection of these four factors constitutes the Kaya model on which the LMDI and Tapio models were combined to enable us to meet the objectives of this research. The choice of these models was made not only based on the objectives of our research, but above all, because of their advantages as presented in the literature review and also because they are the most used models of nowadays in case studies like ours.

Data sources

Since this research relies heavily on secondary data, our first task was to collect the data according to the different factors considered in the analysis of this study. This involved collecting data on the population, economic growth, energy, and CO_2 emissions of each country's industrial sector. The total population is estimated in millions of inhabitants. In terms of economic data, GDP per capita and shares of the industry in each country are estimated in billions constant 2010 US$. Energy consumption data is estimated in tons of oil equivalent (toe). These data were collected from the databases of the World Bank and the International Energy Agency (IEA 2019; WDI 2019). In the meantime, we estimated the CO_2 emissions data for each country's industrial sector based on the IPCC National Guidelines on Greenhouse Gas Inventory (IPCC 2006; Engo 2019), using the different fossil fuels (EC) and emissions factor (π) presented in Table 1 and Eq. (1).

$$CO_{2}{}_{i}^{t}=\sum_{j=1}^{n=10}\mathrm{EC}_{ij}^{t}\times\pi_{j} \tag{1}$$

where $CO_2{}_i^t$ represent the total CO_2 emissions of the industrial sector of the country (i) for the year (t); EC_{ij}^t and π_j are the total amount of j-type of fossil fuel used in the industrial sector of the country (i) for the year (t) and the amount of carbon contained in the fossil fuel type (j), respectively. n is the number of fossil fuel used in the industrial sector of North African countries.

Table 1 Emission factor by type of fossil fuel

(j)	Type of fossil fuel (EC)	(π) in kg/GJ
1	Liquefied petroleum gases (LPG)	17.2
2	Crude oil	20
3	Other kerosene	19.6
4	Gas diesel	20.2
5	Fuel oil	21.1
6	Natural gas	17.5
7	Other bituminous coal	25.8
8	Coke oven coke	29.2
9	Blast furnace gas	70.8
10	Gas coke	29.2

Adapted from IPCC (2006)

Empirical model

According to (Tapio 2005), the decoupling indicator of CO_2 emissions from economic growth can be determined using the following equation.

$$\rho_{(C,G)}=\frac{\Delta C/C^0}{\Delta G/G^0} \tag{2}$$

where $\rho_{(C,G)}$, ΔC, ΔG, C^0, and G^0 represent the decoupling indicator, the change in carbon emissions between the base period (0) and a target period (t), the change in GDP between the base period (0) and a target period (t), carbon emissions, and GDP in the base period (0), respectively.

However, according to the Kaya model (Kaya 1990), as illustrated in Eq. (3), CO_2 emissions can be estimated from four main factors: carbon emission per unit of energy consumption ($\frac{CO_2}{E}$), energy consumption per unit of GDP ($\frac{E}{\mathrm{GDP}}$), GDP per capita ($\frac{\mathrm{GDP}}{P}$), and population (P). In this study, the carbon intensity was extended (as indicated in Eqs. (4) and (5)) to obtain the six factors that were used as the basis for the decoupling indicator calculations while applying the additive method of the LMDI model (Ang 2005).

$$\mathrm{C}=\frac{CO_2}{E}\times\frac{E}{\mathrm{GDP}}\times\frac{\mathrm{GDP}}{P}\times P \tag{3}$$

$$C=\frac{C_{ij}}{E_{ij}}\times\frac{E_{ij}}{E_j}\times\frac{E_j}{\mathrm{GDP}_{sj}}\times\frac{\mathrm{GDP}_{sj}}{\mathrm{GDP}_j}\times\frac{\mathrm{GDP}_j}{P}\times P$$
$$=F\times E\times I\times S\times G\times P \tag{4}$$

$$\Delta C_{\mathrm{tot}}=C^t-C^0=\Delta C_F+\Delta C_E+\Delta C_I+\Delta C_S+\Delta C_G+\Delta C_P \tag{5}$$

where C_{ij}, E_{ij}, E_j, GDP_{sj}, and GDP_j represent the amount of carbon emitted by the fossil fuel type (i) in the country (j), the amount of fossil fuel type (i) consumed in the country (j), the total amount of fossil fuel consumed in the industrial sector of the country (j), the total GDP from the industrial sector of the country (j), and the total GDP from the country (j), respectively. F, E, I, S, and G represent the emission factor ($\frac{C_{ij}}{} E_{ij}$), the energy structure ($\frac{E_{ij}}{} E_j$), the energy consumption per unit of GDP ($\frac{E_j}{} \mathrm{GDP}_{sj}$), the economic structure ($\frac{\mathrm{GDP}_{sj}}{} \mathrm{GDP}_j$), and the GDP per capita ($\frac{\mathrm{GDP}_j}{P}$), respectively. Furthermore, ΔC, ΔC_F, ΔC_E, ΔC_I, ΔC_S, ΔC_G, and ΔC_P measure the effect of the total change in CO_2 emissions over the study period, the effect of the emission factor, the effect of the change in energy structure, the effect of the change in energy consumption per unit of GDP, the effect of the change in economic structure, the effect of the change in GDP per capita, and the effect of population change, respectively. At the same time, based on the principles of the LMDI additive method (Ang 2005; Engo 2019), the integration of Eq. (5) into Eq. (2) allowed us not only to determine the decoupling indicators but also to identify possible reasons related to these decoupling statuses. For this purpose, the following equations were used.

$$\rho_{(C,G)} = \frac{G^0}{C^0 \times \Delta G} \times (\Delta C_F + \Delta C_E + \Delta C_I + \Delta C_S + \Delta C_G + \Delta C_P) \quad (6)$$

$$\rho_{(C,G)} = \frac{G^0 \times \Delta C_F}{C^0 \times \Delta G} + \frac{G^0 \times \Delta C_E}{C^0 \times \Delta G} + \frac{G^0 \times \Delta C_I}{C^0 \times \Delta G} + \frac{G^0 \times \Delta C_S}{C^0 \times \Delta G} + \frac{G^0 \times \Delta C_G}{C^0 \times \Delta G} + \frac{G^0 \times \Delta C_P}{C^0 \times \Delta G} \quad (7)$$

$$\rho_{(C,G)} = \rho_F + \rho_E + \rho_I + \rho_S + \rho_G + \rho_P \quad (8)$$

$$\rho_F = \frac{G^0}{C^0 \times \Delta G} \times \left[\sum_{i=1}^{n} B \times \left(\ln(F^t) - \ln(F^0)\right)\right] \quad (9)$$

$$\rho_E = \frac{G^0}{C^0 \times \Delta G} \times \left[\sum_{i=1}^{n} B \times \left(\ln(E^t) - \ln(E^0)\right)\right] \quad (10)$$

$$\rho_I = \frac{G^0}{C^0 \times \Delta G} \times \left[\sum_{i=1}^{n} B \times \left(\ln(I^t) - \ln(I^0)\right)\right] \quad (11)$$

$$\rho_S = \frac{G^0}{C^0 \times \Delta G} \times \left[\sum_{i=1}^{n} B \times \left(\ln(S^t) - \ln(S^0)\right)\right] \quad (12)$$

$$\rho_G = \frac{G^0}{C^0 \times \Delta G} \times \left[\sum_{i=1}^{n} B \times \left(\ln(G^t) - \ln(G^0)\right)\right] \quad (13)$$

$$\rho_P = \frac{G^0}{C^0 \times \Delta G} \times \left[\sum_{i=1}^{n} B \times \left(\ln(P^t) - \ln(P^0)\right)\right] \quad (14)$$

Meanwhile, since the emission factor of the different types of fossil fuels is constant, Eq. (9) will be zero ($\rho_F = 0$). As a result, CO_2 emissions from the industrial sector in North African countries were affected by changes in the energy structure. In the equations above, B is the weight function that we defined as follows.

$$B = \frac{C_i^t - C_i^0}{\ln(C_i^t) - \ln(C_i^0)} \quad (15)$$

$$B_{(a,b)} = \begin{cases} a = b \\ a = b = 0 \\ \frac{a-b}{\ln(a/b)} \text{ with } a \neq b \end{cases} \quad (16)$$

In Eqs. (9), (10), (11), (12), (13), and (14), we evaluated the effect of the decoupling indicator due to the emission factor (ρ_F), the effect of the decoupling indicator due to the energy structure (ρ_E), the effect of the decoupling indicator due to energy consumption per unit of GDP (ρ_I), the effect of the decoupling indicator due to the economic structure (ρ_S), the effect of the decoupling indicator due to GDP per capita (ρ_G), and the effect of the decoupling indicator due to the population (ρ_P). The sum of all these factors, as shown in Eq. (8), allowed us to obtain the total decoupling indicator from which we determined the decoupling statuses using the eight logical indicators presented in Table 2. Equation (16) represents the different cases in which Eq. (15) is applicable; therefore, the logical parameters a and b refer to C_i^t, $c1$, and C_i^0 of Eq. (15), respectively. However, the results of this study are presented and explained in the next section.

Results and discussions

The objective of this section is to present and explain the results obtained in the analysis of this research. To this end, Table 3 represents the decoupling indicators of CO_2 emissions from the industrial sector in North African countries during the study period of this research. The results of the decomposition analysis of CO_2 emissions from the industrial sector for each country are presented in Figs. 2, 3, and 4 and Tables 4 and 5.

The final results of the decoupling analysis of CO_2 emissions from the industrial sector of North African countries

Table 3 shows that four decoupling statuses (WD, SD, WND, and SND) appeared in North African countries during the period of 1990–2016. The weak coupling (WD) dominated the relationship between CO_2 emissions and the economic growth of the industrial sector in Tunisia, followed by Morocco, Egypt, and Algeria. This meant that CO_2 emissions and economic development were moving in the same direction, but the rate of growth of carbon emissions was slower

Table 2 The eight logical criteria for defining the decoupling status

Symbol	Definition	$(\rho_{(C,G)})$	$(\%\Delta C)$	$(\%\Delta G)$
SD	Strong decoupling	$(\rho_{(C,G)} < 0)$	−	+
WD	Weak decoupling	$(0.8 \geq \rho_{(C,G)} > 0)$	+	+
SND	Strong negative decoupling	$(\rho_{(C,G)} < 0)$	+	−
WND	Weak negative decoupling	$(0.8 \geq \rho_{(C,G)} > 0)$	−	−
ED	Expansive decoupling	$(1.2 \geq \rho_{(C,G)} > 0.8)$	+	+
END	Expansive negative decoupling	$(\rho_{(C,G)} > 1.2)$	+	+
RC	Recessive coupling	$(1.2 \geq \rho_{(C,G)} > 0.8)$	−	−
RD	Recessive decoupling	$(\rho_{(C,G)} > 1.2)$	−	−

Adapted from Tapio (2005)

than that of economic growth. Moreover, it suggests that a good harmonization of economic resources has been practiced by the governments of North Africa, which has consequently favored a slowdown of CO_2 emissions in this region.

The strong decoupling (SD) is the second major decoupling statute that has emerged in North Africa over the period of 1990–2016. This indicates that CO_2 emissions and industrial growth have moved in the opposite direction, and the rate of economic growth was greater compared to that of carbon emissions. Table 3 shows that this phenomenon was important in Morocco followed by Egypt, Algeria, and Tunisia. Carbon emissions were strongly decoupled from industrial growth in Morocco and Egypt during the period of 1999–2005, while this status of decoupling appeared in Tunisia during the periods of 1998–1999 and 2010–2011 and in Algeria between 2005–2006 and 2010–2011.

Unlike these two decoupling statuses, a strong negative decoupling (SND) appeared in Algeria, Egypt, and Tunisia, while a weak negative decoupling (WND) occurred only in Algeria, as shown in Table 3. In the first case, it was found that the CO_2 emissions and economic growth evolve negatively in the same direction, but the growth rate of carbon emissions was higher than the economic rate. The scenario was the same in the second case, but the rate of economic growth was higher than that of carbon emissions. Meanwhile, it should be noted that these two decoupling statuses usually appear when a country experiences economic instability. However, to better understand how these decoupling states arose, it is important to take an in-depth look at the results of the decomposition analysis presented in the next paragraph.

The final results of the decomposition analysis of CO_2 emissions from North African countries

Regarding the factors that influenced the decoupling indicators during the period of 1990–2016, Table 4 shows that the total CO_2 emissions (ΔC_{tot}) increased by 0.019, 1.3E−10, and 0.001 tCO_2 in Algeria, Egypt, and Tunisia, whereas they decreased by − 1.6E−12tCO_2 in Morocco. This explains not only why the relationship between CO_2 emissions and industrial growth was dominated by weak decoupling in all countries, but also why strong decoupling was important in Morocco. However, to better understand these results, which are in agreement with those of previous studies, an in-depth analysis by country is necessary.

Table 4 and Fig. 2 shows the effects of economic activity (ΔC_G), demographic changes (ΔC_P), and economic structure (ΔC_S) contributed to increasing CO_2 emissions by 76.61, 65, and 27.07%, respectively. Although experiencing considerable political instability during the period under review, Egyptian's GDP per capita increased by about 44% from 1522 to 2725 constant 2010 US$ between 1990 and 2016, whereas its population also grew from 57,412,215 to 95,688,681 inhabitants during the same period. These growth rates, which also imply an increase in energy needs, suggest that the government should increase its energy efficiency through renewable sources, especially when we know that industrial growth went from 27.4 to 32.45% under the constant consumption of coal, oil, and natural gas.

In contrast to those three factors, our results also indicate that between 1990 and 2016, the effects of energy intensity (ΔC_I) and energy structure (ΔC_E) contributed to reducing CO_2 emissions by − 35.45 and − 32.24%, respectively. These results, which agree with those of previous studies, show both a good adjustment of energy consumption at the structural level and a good improvement of the technology. This can be explained by the significant structural economic reform implemented by the Egyptian government during the period under review (ADBG 2018). These reforms have helped to increase the rate of new technologies in the industrial sector while improving the sector's energy consumption. To this end, the share of renewable energy has increased by about 49% in the country's energy mix over the period of 1990–2016 (IEA 2019). Therefore, structural and energy intensity effects are the two main factors by which the Egyptian government can strive to further promote their positive decoupling impact.

The cumulative effects of energy intensity (ΔC_I) and economic structure (ΔC_S) are − 9.3E−12 and − 9.3E−13 tCO_2 (see

Table 3 Decoupling indicators from the industrial sector of North African countries over the period of 1990–2016

	Egypt				Morocco				Tunisia				Algeria			
	%Δ*G*	%Δ*C*	$\rho_{(C,G)}$	DS	%Δ*G*	%Δ*C*	$\rho_{(C,G)}$	DS	%Δ*G*	%Δ*C*	$\rho_{(C,G)}$	DS	%Δ*G*	%Δ*C*	$\rho_{(C,G)}$	DS
1990–1991	0.185	0.073	6.7E−15	WD	0.01	− 0.07	− 3E−13	SD	0.01	0.039	3.6E−06	WD	-	-	-	-
1991–1992	0.021	0.036	2.9E−14	WD	− 0.007	− 0.08	4.2E−13	WD	0.058	0.104	1.7E−06	WD	-	-	-	-
1992–1993	0.02	0.177	1.4E−13	WD	− 0.003	− 0.09	12E−12	WD	0.008	0.036	4.2E−06	WD	-	-	-	-
1993–1994	0.018	− 0.29	− 2.6E−13	SD	0.05	0.068	5E−14	WD	0.073	0.044	6E−07	WD	-	-	-	-
1994–1995	0.037	− 0.08	− 3.6E−14	SD	− 0.01	− 0.41	7E−13	WD	0.029	0.092	3E−06	WD	-	-	-	-
1995–1996	0.024	0.036	2.3E−14	WD	0.093	0.34	1.3E−13	WD	0.038	0.053	1.3E−06	WD	-	-	-	-
1996–1997	0.036	0.118	4.9E−14	WD	0.049	0.109	7.9E−14	WD	− 0.019	0.016	− 8.7E−07	SND	-	-	-	-
1997–1998	0.042	0.129	4.5E−14	WD	0.009	0.005	1.9E−14	WD	0.019	0.032	1.6E−06	WD	-	-	-	-
1998–1999	0.051	0.272	7.7E−14	WD	0.024	0.124	1.7E−13	WD	0.071	− 0.003	− 4.5E−08	SD	-	-	-	-
1999–2000	0.151	− 0.09	− 9E−15	SD	0.052	0.015	1E−14	WD	0.071	0.133	1.8E−06	WD	0.244	0.045	5.7E−15	WD
2000–2001	0.04	0.769	2.7E−13	WD	0.01	0.016	5.4E−14	WD	0.032	0.038	1E−06	WD	− 0.05	0.017	− 0.004	SND
2001–2002	0.066	− 0.13	− 2.9E−14	SD	0.023	− 0.03	− 5.3E−14	SD	0.015	0.034	2.2E−06	WD	0.036	0.024	0.007	WD
2002–2003	0.07	− 0.06	− 1.3E−14	SD	0.09	− 0.17	− 6.6E−14	SD	− 0.004	0.102	− 2.5E−05	SND	0.107	0.0004	1.5E−15	WD
2003–2004	0.081	− 0.53	− 8.8E−14	SD	0.072	− 0.02	− 1.2E−14	SD	0.071	0.103	1.4E−06	WD	0.073	0.147	6E−14	WD
2004–2005	0.029	2.161	9.7E−13	WD	0.014	− 0.1	− 2.4E−13	SD	0.079	0.039	4.9E−07	WD	0.161	0.052	0.0003	WD
2005–2006	0.131	0.163	1.6E−14	WD	0.034	0.255	2.4E−13	WD	0.056	0.101	1.7E−06	WD	0.044	0.072	4.8E−14	WD
2006–2007	0.036	0.289	1E−13	WD	0.015	0.02	4.4E−14	WD	0.145	0.156	1E−06	WD	0.012	0.106	2.5E−13	WD
2007–2008	0.109	− 0.11	− 1.3E−14	SD	0.149	− 0.12	− 2.6E−14	SD	0.143	0.021	1.4E−07	WD	0.04	0.043	3E−14	WD
2008–2009	0.035	− 0.27	− 9.7E−14	SD	− 0.055	− 0.1	6.1E−14	WD	− 0.09	− 0.113	1.2E−06	WD	0.169	− 0.078	− 0.0002	SD
2009–2010	0.05	0.03	7.2E−15	WD	0.098	0.165	5.1E−14	WD	0.08	0.102	1.2E−06	WD	0.092	0.175	0.0004	WD
2010–2011	0.022	0.079	4.2E−14	WD	0.091	0.105	3.5E−14	WD	0.008	− 0.022	− 2.6E−06	SD	0.011	− 0.0002	− 5.8E−16	SD
2011–2012	0.116	0.038	3.8E−15	WD	0.022	0.176	2.4E−13	WD	0.034	0.121	3.5E−06	WD	− 0.003	− 0.006	0.01	WND
2012–2013	0.038	− 0.01	− 4.9E−15	SD	0.035	− 0.23	− 1.9E−13	SD	− 0.001	− 0.002	1.7E−06	WD	− 0.049	0.019	− 1E−14	SND
2013–2014	0.029	− 0.27	− 1E−13	SD	0.039	0.431	3.2E−13	WD	− 0.037	− 0.035	9.4E−07	WD	− 0.007	0.031	−0.003	SND
2014–2015	− 0.04	0.083	− 2.2E−14	SND	0.029	− 0.16	− 1.6E−13	SD	− 0.061	− 0.07	1E−06	WD	− 0.123	0.053	− 1E−14	SND
2015–2016	− 0.07	0.038	− 5.5E−15	SND	0.007	− 0.1	− 3.7E−13	SD	− 0.027	− 0.014	5.4E−07	WD	0.004	0.023	0.01	WD

DS decoupling status

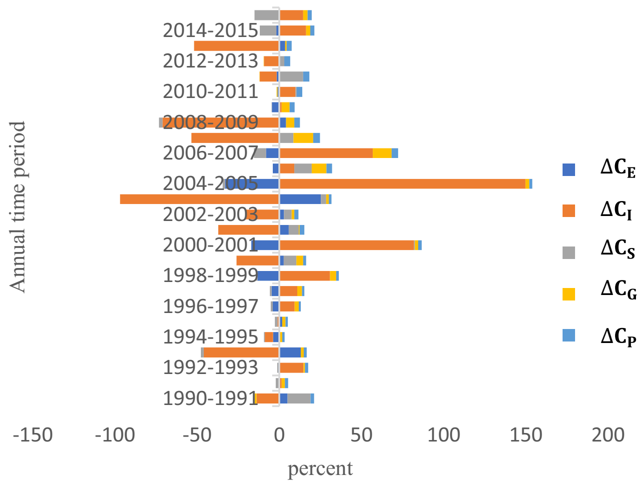

Fig. 2 Final results of the decomposition analysis of CO_2 emissions from the Egyptian industrial sector (1990–2016). Source: Author own production

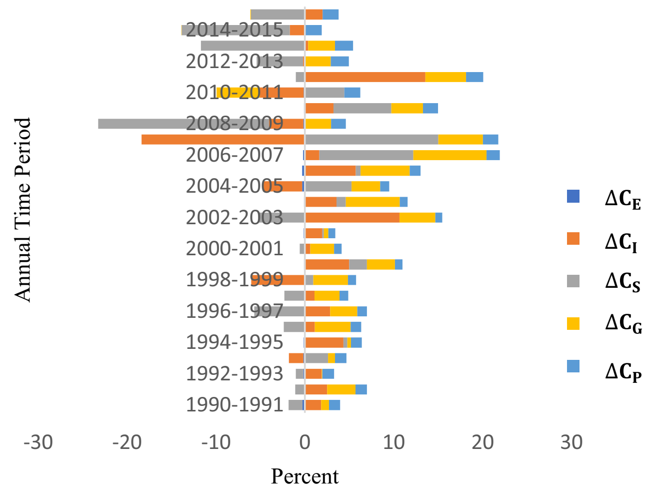

Fig. 4 Final results of the decomposition analysis of CO_2 emissions from the Tunisian industrial sector (1990–2016). Source: Author own production

Table 4), indicating that these factors contributed to reducing CO_2 emissions in Morocco over the study period, as shown in Fig. 3. The data used represented in Fig. 5 shows that energy intensity decreased from 0.0002 to 0.00008 toe over the period of 1990–2016, reflecting an improvement in energy efficiency, with the government having almost removed coal from the industrial sector's energy sources in favor of renewable energies. This improvement in energy intensity is the main cause of the strong decoupling that appeared between the two variables, as presented above. Likewise, we found in this study that the economic growth of the Moroccan industrial sector decreased from 39.94 to 37.69% over the period studied, as shown in Fig. 7. For example, industrial growth fell from 38 to 36% and from 36 to 34%, while its energy intensity

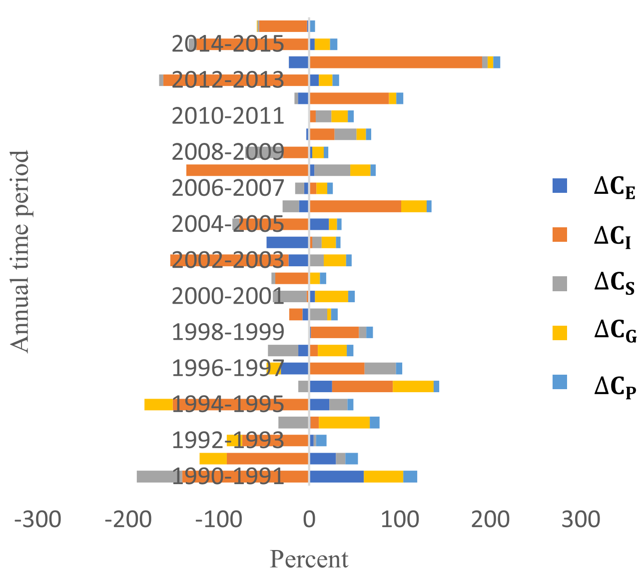

Fig. 3 Final results of the decomposition analysis of CO_2 emissions from the Moroccan industrial sector (1990–2016). Source: Author own production

rose from 0.00011 to 0.00015 toe and from 0.0001 to 0.00011 toe over the periods of 1995–1996 and 2010–2011, respectively. These periods also coincide with those where the economic and environmental indicators have evolved in the same direction as illustrated in Table 4, indicating the existence of a weak decoupling between the two variables.

Meanwhile, the effect of economic activity (ΔC_G) followed by the effect of demographic change (ΔC_P) and the effect of energy structure (ΔC_E) are the three factors that contributed to the increase in CO_2 emissions over the period of 1990–2016. Indeed, the Moroccan population has increased by about 29%, from 24,879,136 to 35,276,786 inhabitants in 1990 and 2016, respectively. To meet the needs of this population, the United Kingdom of Morocco had been forced to increase the consumption of oil and natural gas in 1990, especially in the industrial and transport sectors, while restructuring the energy mix of the country by renewable sources between 1991 and 2016 (see Fig. 6). This had contributed to reducing the effect of the energy structure factor on Morocco's CO_2 emissions while promoting the emergence of weak decoupling. In the meantime, the country's GDP per capita had almost increased by 50% from 1720 to 3204 constant 2010 US$ during the study period. This situation has not only contributed to the increase in air pollution, but above all, it has continued to promote low decoupling and to reduce the quality of the environment.

In Tunisia, we found that the effect of economic activity (ΔC_G), followed by the effect of demographic change (ΔC_P) and energy intensity (ΔC_I), contributed to increased CO_2 emissions by 69.67, 35, and 22.99%, respectively, as shown in Fig. 4. This result is in line with previous studies, especially with those of Engo (2018), where the effect of energy intensity has also contributed to increasing CO_2 emissions while preventing decoupling in Cameroon's industrial sector.

Table 4 The cumulative results of the decomposition of CO_2 emissions from the industrial sector of North African countries over the period of 1999–2016 in tCO_2

	ΔC_E	ΔC_I	ΔC_S	ΔC_G	ΔC_P	ΔC_{tot}
Algeria	0.176	− 0.409	0.849	− 0.435	− 0.199	0.019
Egypt	− 4.4E−11	− 4.9E−11	3.7E−11	1.05E−10	8.8E−11	1.3E−10
Morocco	3.6E−13	− 9.6E−12	− 9.3E−13	5.3E−12	3.1E−12	− 1.6E−12
Tunisia	− 3.7E−05	0.0003	− 0.0003	0.001	0.0005	0.001

Moreover, it should be noted that the Tunisian population has increased from 8,232,797 to 11,403,248 inhabitants, whereas the country's GDP per capita has also increased from 2227 to 4269 constant 2010 US$ in 1990 and 2016, respectively. This strong economic and demographic growth has forced Tunisia to increase its energy intensity, due to the high consumption of natural gas (IEA 2019). The energy intensity of the Tunisian industrial sector increased from 0.0023 to 0.0035 toe during the study period, as shown in Fig. 5, while negatively influencing the decoupling indicators of this country (see Table 4). The effects of these factors were positive and increased throughout the study period. This has helped to increase the decoupling index. As a result, the sustainable development process in Tunisia is experiencing a problem of resource harmonization, which contributes to huge energy and environmental expenditures. Table 4 also shows that the economic structure effect (ΔC_S) and the energy structure effect (ΔC_E) are the two main factors contributing to the reduction of CO_2 emissions. Although energy consumption increased from 1.54 to 3.23 toe between 1990 and 2016 as shown in Fig. 2, we noticed that the consumption of several fuels had significantly decreased in Tunisia, except natural gas. For example, coal consumption fell from 0.0072 to 0 t between 1990 and 2016, while that of fossil fuel rose from 0.069 to 0.019 toe during the same period. These reductions in energy consumption indicate some improvement in energy supplies from renewable energies. It is for this reason that the share of the GDP of the Tunisian industrial sector has dropped systematically, from 29.78 to 23.99% (see Fig. 7), in favor of the tertiary sector.

Table 5 The cumulative results of the decomposition of CO_2 emissions of the Algerian industrial sector over the period of 1999–2016 in tCO_2

	ΔC_E	ΔC_I	ΔC_S	ΔC_G	ΔC_P	ΔC_{tot}
1999–2004	− 0.005	− 0.422	0.856	− 0.439	− 0.203	− 0.215
2004–2009	0.014	0.007	− 0.0036	0.001	0.0009	0.0202
2009–2016	0.167	0.005	− 0.003	0.002	0.003	0.176
1999–2016	0.176	− 0.409	0.849	− 0.435	− 0.199	− 0.019

In this study, the results were less satisfactory in the case of Algeria compared with those of Tunisia, Morocco, and Egypt. We found that the cumulative effects of population (ΔC_P), economic activity (ΔC_G), and energy intensity (ΔC_I) are − 0.199, − 0.435, and − 0.409 tCO_2, respectively, whereas those of energy structure (ΔC_E) and economic structure (ΔC_S) are 0.176 and 0.849 tCO_2 (see Table 4). This shows that the first three factors have helped reduce carbon emissions, while the other two have contributed to the increases in carbon emissions. These results are in line with those of previous studies and reflect the political tensions that the country has been going through for many years. For example, Table 5 shows that during the period of 1999–2004, the effect of economic activity, followed by energy intensity, demographic change, and energy structure, helped to the reduction of CO_2 emissions, whereas the economic structure (ΔC_S) contributed to the increase of CO_2 emissions. This result is both in agreement and in disagreement with those of previous studies. They disagree with previous studies because the effect of population change is a factor that has always contributed to the increase in carbon emissions, whereas they reflect those found in other studies in the case of other factors.

However, it should be noted that over the period of 1999–2004, the growth of the Algerian industrial sector increased from 45 to 52%. Apart from this performance, the country's economic growth slowed in 2001, and in 2003, the population growth rate went from 1.4% in 1999 to 1.3% in 2004, while energy intensity in the industrial sector remained virtually stable (see Figs. 5 and 7). These growth indicators could explain the behavior of the factors presented above on CO_2 emissions and above all the state of decoupling that appeared in Algeria during the period of 1999–2004. This suggests that Algeria's industrial growth has increased, resulting in not only high-energy costs but also considerable environmental damage.

We also found that economic growth declined, while the growth of CO_2 emissions increased between 2000–2001 and 2012–2015, indicating a strong negative decoupling. Due to the instability of the global hydrocarbon market, Algeria is suffering a lot from the drop in oil prices, with oil accounting for about 90% of exports and 60% of the country's total income (ADBG 2018). This problem of falling oil revenues has contributed to the decline in the country's industrial growth since 2010, as shown in Fig. 7. The government, which wanted to keep the country growing, was forced to increase the sector's energy consumption from the same period. This contributed to the reduction of CO_2 emissions due to the economic structure effect, as shown in Table 3, while other factors contributed to the increase in CO_2 emissions and therefore played a negative role in decoupling.

Conclusion and policy implications

Conclusion

North Africa is the region that emits the most GHGs on the African continent. To this end, a decoupling analysis between CO_2 emissions and economic growth is important for the development of a common carbon mitigation policy in this region. The Tapio and LMDI models were applied in this study based on an extended Kaya identity to break down, identify, and analyze the main CO_2 emission factors as well as decoupling indicators in North African countries over the period 1990–2016. The main results were summarized as follows.

During this research, we found that the trend of current CO_2 emissions in North African countries contrasted with the GHG reduction goals of these countries. CO_2 emissions are slightly decoupled from economic growth in the North Africa region. This low decoupling has been intensely achieved in Tunisia, compared with Morocco and Egypt, where a strong decoupling occurred significantly during the study period. Due to the economic and political crisis, the decoupling analysis did not give satisfactory results in the case of Algeria. Over a few periods of this study, we have found that the phasing out of coal and the adjustment of oil and natural gas supplies to industrial sectors in North African countries have helped promote decoupling, which implies that there is a need for an effective energy policy to promote decoupling in this region.

However, the results also showed that scale effects contributed to the reduction of CO_2 emissions only in Algeria, whereas they played a negative role in decoupling in Tunisia, Egypt, and Morocco. Unlike Tunisia, the effect of energy intensity played an important role in decoupling in Algeria, Morocco, and Egypt. The energy structure effect only helped to promote decoupling in Egypt and Tunisia, while helping to prevent decoupling in Algeria and Morocco. The economic structure effect has contributed to reducing the decoupling index only in Morocco, compared with Tunisia, Egypt, and Algeria where a reverse phenomenon has been observed.

Policy implications

Based on the results presented above, the following policy recommendations are needed not only to enable North African countries to achieve their GHG emissions targets but also to develop a low-carbon industrial system.

In contrast to scale effects, energy structure effect, and economic structure effect, we found that energy intensity was the main force that contributed to promoting decoupling among North African countries over the period of 1990–2016. As a result, governments in North Africa need to pay particular attention to this factor by developing dynamic and effective policies to improve the energy intensity of their industrial sectors. Given the current evolution of CO_2 emissions in North Africa, the energy intensity of the industrial sector can be improved based on three main aspects: adjustment of economic and energy structures, improvement of energy efficiency, and optimization of technology and management methods of the sector. To this end, the industrial restructuring of North African countries should aim not only to adjust the proportion of the industry but also to further modernize this sector. There is a need to increase the proportion of high-tech industries using clean energy, to improve market access standards, and to control high value-added carbon products. Besides, the energy efficiency of the industrial sector should be improved by increasing the share of renewable energy in the region's energy packages (Engo 2019d). This means that governments in North Africa should implement effective policies that promote the development of solar and wind energies, which are the most available energy resources in the entire region.

The proposed model and analysis of North African CO_2 emissions in this paper can be a powerful tool and reference for policymakers. Furthermore, although this study was carried out in the context of the North African region, countries and regions with similar economic development characteristics to those of North African countries can rely on this paper to revitalize their carbon mitigation policy. In this study, we explored the decoupling of CO_2 emissions from economic growth at the macro level. However, we did not focus on the detail of the decoupling status of carbon emissions from each subsector of industrial sectors in North African countries, due to lack of data. A more detailed and specific analysis is required to overcome this limitation in the future.

Author contribution I am the sole author in this research.

Data availability Not applicable

Compliance with ethical standards

Competing interests The authors declare that they have no competing interests.

Ethical approval Not applicable

Consent to participate Not applicable

Consent to publish Not applicable

Appendix

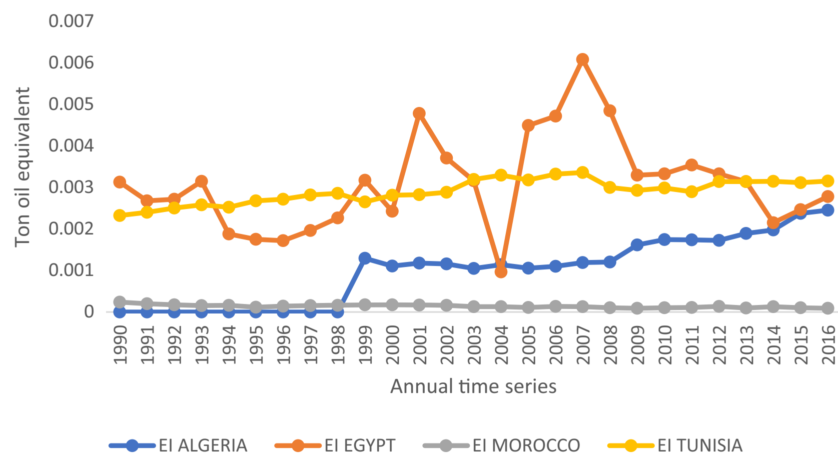

Fig. 5 Change in the energy intensity factor from the industrial sector of North African countries during the period 1990-2016. Source: WDI (2019)

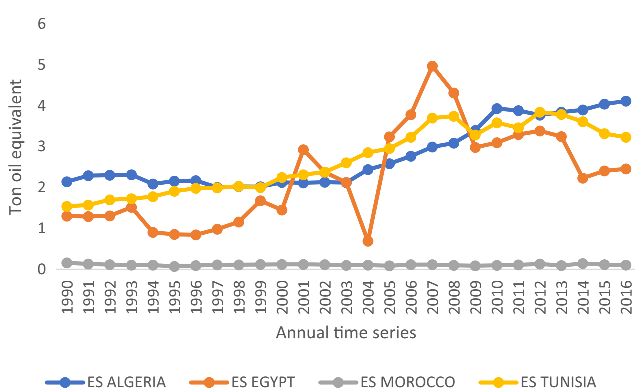

Fig. 6 Change in the energy structure from the industrial sector of North African countries during the period 1990-2016. Source: WDI (2019)

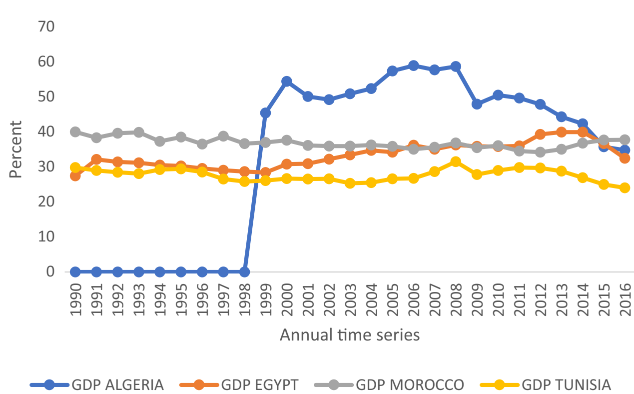

Fig. 7 Evolution of the GDP from the industrial sector of North African countries during the period 1990-2016. Source: WDI (2019)

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