CO$_2$ emissions-energy consumption-militarisation-growth nexus in South Africa: evidence from novel dynamic ARDL simulations

Charles Shaaba Saba

Received: 15 March 2022 / Accepted: 13 September 2022 / Published online: 7 October 2022
© The Author(s), under exclusive licence to Springer-Verlag GmbH Germany, part of Springer Nature 2022

Abstract
This study draws ardent attention to the Sustainable Development Goal 13 (climate change mitigation) of the United Nations by investigating the CO$_2$ emissions-energy consumption-militarisation-economic growth nexus for South Africa (SA) from 1960 to 2019. The researcher applied frequency domain causality and the novel dynamic autoregressive distributed lag (ARDL) simulation approaches to achieve the research objective. The main findings reflected that (i) there is a long-run equilibrium relationship between the variables; (ii) there is no causality between militarisation and energy consumption; (iii) unidirectional causality runs from militarisation to economic growth; (iv) there is no causality between militarisation and CO$_2$ emissions; and (v) unidirectional causality runs from energy consumption to economic growth. The dynamic ARDL simulations’ main results suggest that (i) in the short-run, a positive and insignificant relationship exist between militarisation and CO$_2$ emissions. Conversely, a negative and significant relationship was recorded in the long-run. Thus, the treadmill theory of destruction is not valid for SA. (ii) In the short-run, economic growth has a positive and significant impact on CO$_2$ emissions, while in the long-run, economic growth has a negative and significant impact on CO$_2$ emissions. This implies the environmental Kuznets curve (EKC) hypothesis holds for SA. Overall, this research suggests a synergy between defence, energy, growth, and environmental policies in the short- and long-run to promote and maintain environmental quality in SA.

Keywords Militarisation · Energy consumption · CO$_2$ emissions · Growth · ARDL simulations

JEL Classification C32 · Q5 · H56 · O47

Introduction
Energy use is a key contributor to worldwide ecological degradation, according to the growing body of studies (Intergovernmental Panel on Climate Change [IPCC] 2014). The release of greenhouse gases (GHGs) from fossil fuel combustion contributes to global warming and ozone layer depletion. In the last 50 years, according to Weiss (2008), over 1000 international legal instruments have been developed in an attempt to reduce air, land, and water pollution. However, in the last four decades, annual CO$_2$ emissions have increased by more than 100% (International Energy Agency [IEA] 2016). Thus, despite established agreements and technological developments, there has been no meaningful reduction in CO$_2$ and other harmful emissions (Charfeddine 2017). Furthermore, most international talks have failed to consider the economic and environmental consequences of militarisation. Militaries are among the most important institutions in modern community/society, with advanced weapons, massive infrastructure, military production industries, military bases, and manpower meant to provide internal and external security for any nation (Ahmed et al. 2020a). According to literature, defence institutions are essential for a country’s sovereignty, but how they operate can impact the economy and environment. Moreover, nations across the globe are continuously increasing their militarisation as a result of wars, terrorism, and political and regional crises. According to Bildirici (2017b) and Ahmed et al. (2021a), the past and current militarisation race
across the globe — and sometimes between nations — is raising energy consumption and CO₂ emissions by causing significant changes to production structures.

The militarisation activities of developed and less-developed countries have changed as a result of defence-oriented programmes/projects and increased CO₂ emissions (Ahmed et al. 2021b, 2020a). According to Ahmed et al. (2021a), “militarisation influences CO₂ emissions because military technologies and armaments consume a massive amount of energy, military production processes are highly energy-intensive, and military infrastructure relies on fossil fuels”. Conversely, the environmental ruin caused by militaries has gradually gained momentum in recent decades. Some scholars, such as Jorgenson et al. (2010), Singer and Keating (1999), Jorgenson and Clark (2009), Bildirici (2016a), Solarin et al. (2018), and others, suggest that military actions pollute the environment by (i) depleting resources; (ii) causing the extinction of natural flora and fauna; (iii) promoting the release of radioactive elements and pollutants; (iv) moving defence equipment by different means of transportation, which often requires the consumption of dirty energy (fossil fuel); (v) testing of nuclear bombs, etc. However, Solarin et al. (2018) claim that military expenditure reduces environmental degradation through several technological achievements in the realm of information and communications technology (ICT) by dematerialising production/manufacturing processes and creating a society that is less resource-intensive.

Increased energy consumption and high levels of defence spending as a share of gross domestic product (GDP) cause fundamental changes in national economies (Rice 2007; Ahmed et al. 2020b). Research by Jorgenson et al. (2010), Givens (2014), and Jorgenson et al. (2012), among others, revealed that there is a positive relationship between militarisation and energy consumption. One of the explanations for this relationship is that basic defence operations use fossil fuels (Givens 2014). Lawrence et al. (2015) and Ahmed et al. (2020a) similarly argued that nuclear weapons testing; the production of military equipment; aerial, terrestrial, and naval operations; involvement and active armed conflicts; thermal and radiation impacts; and pollution are some militarisation factors that impact the environment, as mentioned earlier. Therefore, militarisation poses a serious threat to the environment (York 2008).

In the empirical literature, the economic growth impact of environmental, social, and economic factors has gained wider attention at country-specific, regional, and global levels. At the country-specific level, studies investigating the growth-CO₂ emissions nexus (Shahiduzzaman and Alam 2017; Shahzad et al. 2017) and growth-energy use nexus (Chen et al. 2016; Omri 2014) have been examined. However, the incorporation/introduction of militarisation into this research field received scant attention until recently (inter alia: Solarin et al. 2018; Gilli and Gilli, 2018; Johnstone and McLeish 2020; Sohag et al. 2021). Past studies have been limited to investigating energy or electricity use (inter alia: Bekun et al. 2019, Saint Akadiri et al. 2019; Adebayo et al. 2021a), or exploring the environmental pollution-growth nexus (inter alia: Shahbaz et al. 2013; Adewuyi and Awodumi 2021; Adebayo and Odugbesan 2021; Udeagha and Muchapondwa 2022). An obvious gap exists in the empirical literature on the militarisation-energy consumption-CO₂ emissions-economic growth nexus, especially in South Africa (SA), to the best of the researcher’s knowledge.

Several studies have investigated the impact of SA’s defence spending on economic growth, with mixed conclusions about the effects of defence spending on economic growth and the causal direction of the two variables (inter alia: Birdi and Dunne 2002; Mosikari and Matlwa 2014; Aye et al. 2014; Phiri 2019; Saba 2021). Furthermore, the environmental consequences of defence spending in SA have not been studied. Polsterer (2015) agrees that militarisation is the leading source of environmental degradation, but it is an area that has received little attention. Therefore, it was critical for the researcher to examine militarisation’s influence on the rest of the variables presented in this study for the case of SA. The researcher focused on SA for the following reasons: (i) the Stockholm International Peace Research Institute’s (SIPRI) report over the years has shown that SA is among the highest defence spenders and has the most developed defence industries in Africa. Figure 1 provides a visual snapshot of this evidence from SIPRI’s data.

(ii) SA is one of the top CO₂ emitters (1.09 of the world emissions); the country is currently ranked 15th globally (World Bank 2021). (iii) One of the implications of military expenditure is that it could crowd out social spending (that is, scarce productive resources are being diverted to non-productive pursuits (classical school)), and CO₂ emissions lead to environmental degradation (see, for example, Saba 2021; Saba and Ngepah 2020a, b, 2022, among others). High military expenditure, according to the Keynesian school, boosts aggregate demand, improves infrastructure, boosts productivity, and lowers unemployment (see, for example, Saba 2020a, 2021a; Saba and Ngepah 2020a, b, 2022, among others). However, it is not only theoretical examinations that have failed to concur on the defence spending-growth nexus for SA; other empirical studies focusing on other countries/regions have also produced inconsistent results (inter alia: Mosikari and Matlwa 2014; Saba and Ngepah 2019c; Aye et al. 2014; Phiri 2019).

(4) SA’s economy currently relies heavily on coal as the source of its energy consumption, which has been known to seriously propel CO₂ emissions. According to the BP Statistical Review of World Energy (2021), the country now has 35,053 million tons (MMst) of coal reserves, accounting for around 3.68% of the world’s total coal reserves of 1,139,471
million tons. SA is ranked eighth globally in coal reserves. Figure 2 presents a visual inspection of the average trends in CO₂ emissions, militarisation (proxied by military expenditure), energy consumption, and economic growth (proxied by real GDP) over the period 1960 to 2019 for SA. The average trends show that economic growth is higher than other variables, while energy consumption follows economic growth, military expenditure comes after energy consumption, and CO₂ emissions follow military expenditure.

This study was worthwhile because of the possible impact climate change could have on the environment and the economy, which is becoming more and more evident in SA. For example, on April 11th and 12th 2022, the eastern coast of SA witnessed an exceptionally heavy rainfall of more than 300 mm in the provinces of KwaZulu-Natal (KZN) and the Eastern Cape (EC) within less than 24 h (South Africa Weather Services (SAWS) 2022); this was attributed to climate change. Socioeconomic losses were recorded from the event, lives were lost, and there were casualties and damage to infrastructure. Over 40,000 people were impacted by the rainfall and subsequent floods: 435 deaths were reported, at least 13,500 homes were destroyed, and 630 schools were affected, impacting around 270,000 students (Government of South Africa 2022a, b). Critical infrastructures such as bridges and roads, mobile phone towers, water treatment, and power plant stations were also severely damaged.
Since literature has established that militarisation could potentially contribute to CO₂ emissions and crowd out productive resources meant to develop other sectors of the economy (including the energy sector) and boost economic growth, it was important to undertake an empirical study. Such a study (i) would help provide up-to-date information on the possible role the defence sector has played in CO₂ emissions in SA; (ii) and help guide defence policy decisions so that the sector does not contribute/exacerbate the consequences of environmental degradation and economic hardship currently being experienced in SA. Since energy consumption and economic growth could also contribute to CO₂ emissions, up-to-date information is required. This information was obtained using a new and relatively longer dataset in the time dimension to gain insight into the nexus between the three variables in a specific country (like SA), which heavily relies on fossil fuel consumption, and for policy recommendation purposes. Also, due to unresolved debate around the nexus between energy consumption, economic growth and CO₂ emissions in the empirical literature,¹ it was crucial to undertake this study by utilising an econometric approach that would provide more reliable results than previous studies.

¹ Table 1 presents some of the examples of those studies; therefore, readers are encouraged to review those.
Based on the above discussion, SA was an intriguing option for a distinct study because of these qualities. While the pros and cons of militarisation in SA have been assessed, its step-by-step impact on energy consumption, the environment, and economic growth has received little attention in the empirical literature. Therefore, it is on this premise that this study addressed the following questions: (i) Does the environmental Kuznets curve (EKC) hypothesis, alongside the treadmill theory of destruction, exist in SA? (ii) What is the simulated short- and long-run impact of CO₂ emissions, energy consumption, and militarisation on economic growth? (iii) What is the simulated short- and long-run impact of CO₂ emissions, energy consumption, and economic growth on militarisation? (iv) What is the simulated short- and long-run impact of militarisation, energy consumption, and economic growth on CO₂ emissions? (v) What is the simulated short- and long-run impact of CO₂ emissions, militarisation, energy consumption, and economic growth on energy consumption? These questions represent the gaps identified in the literature for the case of SA, and the researcher intended to address them by answering the questions for the period 1960 to 2019. To do so, the researcher utilised various econometric approaches, particularly the novel dynamic ARDL simulations. Having an understanding of this topic at a country-specific level is essential in light of the United Nations’ (UN) policy objective aimed at achieving energy sustainability.

This study contributes to literature when compared to previous studies in a number of ways. (i) It identifies the short- and long-run consequences of CO₂ emissions, energy consumption, and militarisation on economic growth within the context of SA. (ii) It reveals CO₂ emissions’ short- and long-run consequences on real GDP/income levels, energy consumption, and militarisation within the context of SA. (iii) It shows energy consumption’s short and long-run consequences on real GDP/income levels, CO₂ emissions, and militarisation. (iv) It demonstrates militarisation’s short- and long-run consequences on real GDP/income levels, CO₂ emissions, and energy consumption. (v) Previous studies that examined the military expenditure-economic growth nexus, CO₂ emissions-energy consumption nexus, and CO₂ emissions-economic growth nexus basically applied the simple ARDL technique introduced by Pesaran et al. (2001) and other cointegration approaches to estimate and investigate the short- and long-run nexus between variables. However, from a methodological point of view, this study further contributes to the empirical literature by utilising Jordan and Philips’ (2018) proposed novel dynamic ARDL simulation model. This approach assists in effectively and efficiently overcoming the impediments associated with Pesaran et al.’s (2001) simple ARDL technique.

The academic and policy relevance of this study is fourfold. (i) The study provides important information on the CO₂ emissions-energy-militarisation-growth nexus under the context of the ARDL simulation approach over the short- and long-run for the case of SA. (ii) The study also illustrates the variable that plays a significant and insignificant role in reducing CO₂ emissions within the context of the ARDL simulation. (iii) The study proposes relevant policies based on the possible relationship between the variables. (iv) The study also presents an understanding of how CO₂ emissions, energy consumption, militarisation, and economic growth relate, which may have implications for SA’s defence, energy, environmental, and economic growth policies.

The main theoretical contributions of the study are as follows: First, it shows analytically that modified environmental Kuznets curve (EKC) framework and augmented endogenous growth model could be used to test the treadmill theory of destruction within the context of simulation approach. Second, it uses technology assumed to be endogenously determined by militarisation and integrated into the production function. The usefulness of our theoretical results can be illustrated by relating them to research work of (i) Yolcu Karadam et al. (2017), Saba and Ngepah (2019a, b, 2020a), Ahmed et al. (2020a), Saba et al. (2021), and among others, when it comes to militarisation-economic growth nexus; (ii) Halicioglu (2009), Salahuddin and Gow (2014), and Salahuddin and Alam (2015) when it comes to energy consumption-economic growth nexus; and (iii) Khobai and Le Roux (2017), Ali et al. (2017), Adebayo et al. (2021), and among others, when it comes to energy consumption-CO₂ emissions nexus.

In summary, the study’s findings suggest that the treadmill theory of destruction is not valid, while the EKC hypothesis holds for SA. Overall, this study suggests a synergy between defence, energy, growth, and environmental policies in the short- and long-run for the purpose of promoting and maintaining environmental quality in SA. The remaining sections of this article follow this order: “Literature review” section reviews some studies, “Methodology and data” section presents the methodology, “Methodology and data” section presents the results and discussion, and “Conclusion and policy recommendations” section concludes with policy implications.

**Literature review**

This section focuses on the theoretical background and empirical literature that examines the relationship between (i) CO₂ emissions and energy consumption; (ii)
militarisation and economic growth; (iii) CO₂ emissions and economic growth; and (iv) energy consumption and economic growth.

Theoretical background/literature

For more than 60 years, the link between growth and inequality has been established. Simon Kuznets investigated this relationship and proposed the Kuznets economic hypothesis. According to Kuznets (1955), income disparity rises throughout the early stages of economic expansion until it hits a peak, when it diminishes as the economy expands. Grossman and Krueger (1991) developed the EKC hypothesis based on Kuznets’ (1955) theory. According to the EKC, “the view that increased economic activity inevitably harms the environment is based on static assumptions about technology, tastes, and environmental investments,” and “as incomes rise, demand for improvements in environmental quality will rise, as will the resources available for investment”. Moreover, Beckerman (1992) wrote, “there is clear evidence that, although economic expansion normally leads to the deterioration of the environment in the early stages of the process, in the end, the best and probably the only way to achieve a decent environment in most nations is to become rich”. Grossman and Krueger (1991, 1994) thus supported the inverted U-form income (per capita)-environmental degradation nexus by applying the EKC theory.

The military-environment nexus is complex, and its neglect could be hazardous. According to the sociologist Gould (2007), “militarisation” is “the single most ecologically harmful human effort”. In support, Singer and Keating (1999) wrote, “from depleting resources to deteriorating the physical environment to destroying natural flora and wildlife to leaving behind a broad array of poisons and radioactive components, all facets of military activity pollute our environment in some manner”. Gould (2007) and Klopow (1997) also allude to the fact that military weaponry and operations can also be exempted from environmental restrictions “in the name of national security”. As a result, the world’s armed forces are among the largest polluters on the planet (Renner 1991).

The treadmill destruction perspective directly refers to the military-environment relationship and illustrates the military’s dynamics in causing significant environmental impacts. This theory is connected to the treadmill of production method, which refers to “the intrinsic character of competitiveness and capital concentration” that increases ecosystems’ demand and environmental degradation (Jorgenson and Clark 2009). However, while the treadmill destruction theory is related to the treadmill of production concept, it focuses on the military of the states. According to Clark and Jorgenson (2012), “Militarism fosters a cycle of devastation that effectively impact negatively on the environment”. The market competition that leads to expansion and increases in consumption and production is the basis for the theory of treadmill production. The competition of international systems, which seeks an advantage over the other system or state, is the foundation for the treadmill of destruction approach. According to Hooks and Smith (2005), the treadmill of destruction theory refers “to the actions where militaries make the destruction of the ecology and increase consumption of fossil fuels and high amount of toxic wastes”.

The theory also postulates that as governments’ military become more “capital-intensive”, their influence on the environment grows. The theory also states that military spending has a negative impact on the environment and increases CO₂ emissions.

There is no theoretical agreement on the impact and causal relationships between defence spending and economic growth. This is because economists have yet to agree on a theory; different schools of thought have instead evolved to appropriately incorporate defence spending into an economic growth model (Dunne and Coulomb 2008). These theories include neoclassical, Keynesian, institutional, Marxist, and international ideas, which allow scholars to identify and theorise multiple channels tying defence spending to economic growth. These channels can then be divided into three groups: demand, supply, and security. On the one hand, the neoclassical theoretical approach connects military spending to economic development via the supply side channel. The state is viewed as a rational actor in this theory, balancing the security gains and opportunity costs of defence spending in order to maximise national interest. The Keynesian and institutional theories, on the other hand, are linked to both demand and supply side impacts. When the state, as a proactive institution, spends state funds on defence expenditures, these two schools of thought postulate that output is raised through the Keynesian multiplier effect (Saba and Ngpah 2019a). According to Marxist theory, investing in the defence industry allows countries to postpone the collapse of the capitalist mode of production, resulting in capitalist expansion by escaping a reduction in the rate of profit (Coulomb and Bellais 2008). In a capitalist state that is often characterised by overproduction and stagnation, defence spending has an intrinsically detrimental influence on the economy; nevertheless, it still contributes towards aggregate demand without adding to aggregate supply, thus allowing firms to reduce their surplus, sell their goods, and realise profits (Gottheil 1986; Riddell 1986). The last theory is based on international relations, and it states that in the absence of international collaboration to lessen political tensions, a country can use higher defence spending to ensure its own security in the region.

In the literature, two theoretical views have been found on the energy consumption-economic growth nexus. The first is the neoclassical perspective, based on the “neutrality
hypothesis”. The theory argues that a country’s economic growth is considered unaffected by energy consumption; growth is maintained despite the implementation of energy conservation policies to decrease CO₂ emissions. Studies that present evidence supporting this hypothesis include that of Chiuo-Wei et al. (2008) for the USA, Thailand and South Korea; Lee (2006) for the UK, Germany, and Sweden; and Jobert and Karanfil (2007) for Turkey. The second theory suggests that a country’s economic growth is inversely proportional to its energy consumption, with energy utilisation and other factors of production acting as limiting constraints to the relationship between the two variables (Alam et al. 2012). The studies of Fatai et al. (2004) for India and Indonesia; Lee and Chang (2005) for Taiwan; and Wolde-Rufael (2005) for Algeria, Cameroon, DR Congo, Egypt, and Nigeria, among others, support this theory.

**Empirical studies**

Using a simulation approach to investigate the CO₂ emissions-energy consumption-militarisation-growth nexus could have significant policy implications and aid in resolving misspecification issues. However, there is a large body of research on the (i) energy consumption-economic growth nexus; (ii) the CO₂ emissions-economic growth nexus; and (iii) the military expenditure-economic growth nexus. Climate change’s role in the defence decision-making process is as important as combat costs and effectiveness. Defence spending, according to Jorgenson et al. (2010), has a positive impact on both overall and per capita CO₂ emissions. In support, Closson (2013) claims that the US Department of Defence (DOD) is one of the largest consumers of oil fuel and, consequently, a major emitter of CO₂. Lawrence et al. (2015) also allude that the widespread use of oil fuels in national defence departments means defence spending boosts CO₂ emissions. In G7 countries, Bildirici (2017a) found that militarisation, economic development, CO₂ emissions, and energy consumption have strong linkages. Bildirici’s (2017b) study revealed that the CO₂-militarisation nexus in the USA demonstrates a significant positive relationship in the short- and long-run. As stated, militarisation causes a rise in CO₂ emissions (Bildirici 2017c), and the link between the two variables is particularly strong in developed countries with high defence spending.

Using data from 120 countries from 1980 to 2015, Afia and Harbi (2018) determined that defence spending has both indirect and direct positive effects on per capita CO₂ emissions. In addition, Samaras et al. (2019) claim defence decision-makers consider environmental performance to be one of their goals, which is influenced by US departmental and federal guidelines. Gilli and Gilli (2018) also found that a portion of defence spending is spent on research and development/innovations that are then applied to civil domains to improve production processes and, as a result, reduce environmental degradation. However, Johnstone and McLeish (2020) contend that military operations and wars are key drivers of historic carbon-intensive and environmentally destructive energy transmissions. In support, Sohag et al. (2021) claim greater military might increases access to natural resources and has a negative impact on the environment.

Some researchers claim that the first two strands of studies are intertwined, and in this study, the researcher thus included the third strand in order to overcome each strand’s inherent flaws. For example, the studies of Farhani and Ozturk (2015), Adewuyi and Awodumi (2017), and Acheampong (2018) suggested that growing income does not always enhance the environment because CO₂ emissions increase monotonically with income. This explains why they considered the investigation of energy consumption to be very important, given that it could also have an impact on CO₂ emissions. Bildirici (2016b, 2017a, b, c, 2018a, b) also argued that military actions pollute the environment through various means, as highlighted in his studies. Ultimately, a high level of militarisation could also retard/promote growth through the crowding-out effect/aggregate demand, respectively (Saba and Ngepah 2020b; Saba 2021). Thus, militarisation, CO₂ emissions, energy consumption, and economic growth are intertwined, and their nexus needed to be investigated in SA using a simulation approach to create appropriate predictions and policy recommendations.

Previous studies’ findings related to the above three strands/combination of them using different estimation techniques, data, countries, and regions are ambiguous. For instance, Mirza and Kanwal (2017) applied ARDL, VECM, and Johansen’s cointegration methods to investigate the dynamic causal nexus between CO₂ emissions, economic growth, and energy consumption in Pakistan from 1971 to 2009. They found bidirectional causality between the main variables used in their study. Focusing on global and regional data on a similar research topic to Mirza and Kanwal’s (2017), Acheampong’s (2018) study determined that (i) economic growth does not cause energy consumption at global and regional levels; (ii) at global and Caribbean-Latin American levels, economic growth negatively impacts CO₂ emissions; (iii) energy consumption positively and negatively impacts economic growth in the different regions; and (iv) finally, carbon emissions do not cause energy consumption, with the exception of the Middle East and North Africa (MENA) and the world sample.

Military expenditure’s influence on the environment was overlooked until Hooks and Smith (2005) coined the term “treadmill of destruction” to describe militaries’ destructive theory. The authors contend that militarism hurts the environment both in times of war and in times of peace. Following their early research, some studies have looked at the nexus between military expenditure
and CO₂ emissions and other macroeconomic/socioeconomic variables (see, for example, Clark et al. 2010; Bildirici 2016a, 2017a, b, c, 2018a, b; Solarin et al. 2018; Sohag et al. 2019, among others). Solarin et al. (2018) investigated the environmental impact of military expenditure in the USA from 1960 to 2015. Military expenditure, according to their findings, reduces the ecological footprint. Conversely, the impact of military expenditure on emissions remained mixed. According to the authors, military expenditure can both reduce and aggravate environmental concerns. On a different note, for Myanmar, Ahmed et al.’s (2020a) study used a time series approach alongside the ARDL method to examine the economic growth-militarisation-energy consumption and CO₂ emissions nexus over the period 1975 to 2014. Their findings revealed that (i) military spending retards growth; (ii) energy consumption promotes GDP; and (iii) a CO₂ emissions and energy consumption two-way causality exists, while one-way causality runs from economic growth to energy consumption. In a related study, Ahmed et al. (2020b) considered ecological footprint in place of CO₂ emissions for the case of Pakistan, from 1971 to 2016, using bootstrap causality and cointegration test approaches. Their findings revealed that (i) military expenditure promotes the ecological footprint, while it retards economic growth; (ii) economic growth causes military expenditure, while causality runs from military expenditure to the ecological footprint.

Isiksal (2021) investigated the environmental degradation effects of energy and military expenditure among the highest military spenders in the world from 1993 to 2017. The study employed both the common and dynamic correlated effects mean group estimator (CCEMG) and cross-sectional augmented autoregressive distributed lag (CS-ARDL) techniques. The findings reflected that military expenditure increases CO₂ emissions, while sustainable energy consumption decreases CO₂ emissions. Moreover, Sohag et al. (2021) examined the relationship between innovation, militarisation, and renewable energy and green growth for 21 OECD countries from 1980 to 2016. Their study applied a battery of econometric techniques. The findings suggest militarisation is antagonistic to green growth, while biomass and non-biomass types of renewable energy promote green growth. Bildirici and Kayıkçı (2022) also explored the militarisation-current account balance-economic growth-energy imports nexus in China, Israel, and South Korea. They applied the Markov Switching-Bayesian Vector Auto-Regressive approach and found that for all selected countries, militarisation, energy imports, economic growth, and current account balance were all related. Table 1 provides a summary of some empirical studies on the nexus between energy consumption, CO₂ emissions, and economic growth/GDP.

To summarise, the following observations can be made based on the previous studies. Firstly, studies on the militarisation-energy consumption-CO₂ emissions-growth nexus in SA are nowhere to be found to the best of the researcher’s knowledge. Secondly, none of the studies looked at the EKC hypothesis alongside the treadmill theory of destruction for SA, given that the country is among the highest defence spenders in Africa/sub-Saharan Africa (SSA). Thirdly, previous studies have failed to apply the econometric approaches (especially the novel dynamic ARDL simulations and frequency domain causality) used in this study for the topic under investigation. The researcher identified these gaps in the empirical literature, and this study intended to fill them by investigating the CO₂ emissions-energy consumption-militarisation-economic growth nexus for SA from 1960 to 2019. Since SA is leading economic, defence, and energy sectors in Africa, the question of how CO₂ emissions-energy consumption-militarisation-growth relates in the energy and environmental literature is yet to receive an answer. Therefore, this study used various econometric approaches to answer this question. For this study, novel dynamic ARDL simulations and frequency domain causality were utilised based on the advantages associated with their application. This approach helped the researcher to obtain more reliable results than previous studies.

The application of the innovative, dynamic ARDL simulation model is useful because it helps in simulating and plotting graphs by automatically predicting (positive and negative) changes in the variables. It also estimates their relationships in the short- and long-run. Therefore, this technique allowed the researcher to obtain more reliable, unbiased, and accurate results than the previous studies of Clark et al. (2010), Bildirici (2016b, 2017a, b, c, 2018a, b), Solarin et al. (2018), Sohag et al. (2019), Sohag et al. (2021), Ahmed et al. (2020a), 2021a, Isiksal (2021), Gokmenoglu et al. (2021), Ullah et al. (2021), Wang et al. (2021), and Bildirici and Kayıkçı (2022). The researcher also applied a frequency domain Granger causality technique to test the causality relationship between the variables under investigation. Previous research, to the best of the researcher’s knowledge, has not applied this causality technique in the CO₂ emissions-energy-militarisation-economic growth nexus, particularly in the context of SA. This study also applied the second-generation econometric technique to account for issues of structural breaks in data that, to some extent, have been ignored by previous studies. On this basis, the researcher applied the Lee and Strazicich (2003) multiple structural break unit root test, since the macroeconomic variables used in this study could be prone to issues of shocks, which consequently lead to structural breaks in data.
Methodology and data

Preliminary empirical strategies

In order to establish the CO₂ emissions-energy consumption-militarisation-economic growth nexus for SA, we used batteries of econometric approaches. For the purpose of avoiding a spurious regression and to also determine the order of integration of the series, we used the first- and second-generation time series unit root tests. The unit root tests employed include augmented Dickey-Fuller (ADF), Phillips-Perron (PP), Dickey-Fuller GLS (DF-GLS), and Kwiatkowski-Phillips-Schmidt-Shin (KPSS) and Elliott-Rothenberg-Stock (ERS) unit root tests. Given that macroeconomic series could be prone to issues of shocks/breaks, therefore, this was accounted for by applying the Lee and Strazicich (2003) Lagrange multiplier (LM) multiple structural break unit root test.

Analytical framework and empirical model specification

The study examines CO₂ emissions-energy consumption-militarisation-economic growth nexus for SA. To achieve this objective, we used (i) the military/defence expenditure/spending as a percentage of GDP as a proxy for militarisation; (ii) the GDP (constant 2010 US$) serves as a proxy for economic growth; energy use (kg of oil equivalent per capita) as a proxy for energy consumption; and (iii) CO₂ emissions (metric tons per capita) as a proxy for CO₂ emissions. One of the theoretical frameworks underpinning our econometric specifications below is the famous EKC theory. CO₂ emissions accelerate as economic growth accelerates, according to the EKC theory, especially in the early phases of a country’s development and then it begins to fall (Odhiambo 2017). This is because countries are more focused in attaining higher economic growth than mitigating CO₂ emissions; therefore, a rise in income (growth) leads to an increase in CO₂ emissions. There exists an inverted-U-shaped nexus between the two variables, and it has been supported by other theories such as Stokey Alternative, Green Solow, and the Composition Shifts (see for example Stokey 1998; Stern 2004; Brock and Taylor 2010). EKC theory has its foundation in the Kuznets hypothesis which explained the nexus between economic growth and inequality (Kuznets 1955). The theory of treadmill of destruction is another theory that highlights the military-CO₂ emissions nexus. As mentioned earlier, according to Hooks and Smith (2005), it refers “to the actions where militaries make the destruction of the ecology and increase consumption of fossil fuels and high amount of toxic wastes”. Militarisation impacts CO₂ emissions because military technologies and armaments use a lot of energy, military production processes are energy-intensive, and military infrastructure depends on fossil fuels (Ahmed et al. 2020a, b, 2021b). The neoclassical and Keynesian economists are the major contributors to the defence-growth theories. On the one hand, the neoclassical theory postulate that military spending retard economic growth because high military spending can crowd out private investment by pushing interest rates up. While on the other, the Keynesian theory argued that high military spending increases aggregate demand, improves infrastructure, upsurges production, and reduces unemployment (Saba and Ngepah 2018; Saba 2020b). Therefore, it becomes important to include military spending in our models to examine its relationship with other variables of interest used in this study. Two major theories have characterised the energy consumption-economic growth nexus. The first assumed “neutrality hypothesis” between energy consumption-economic growth nexus, while the second one assumed a negative relationship between the energy consumption and economic growth, with energy utilisation and other factors of production acting as limiting constraints (Alam et al. 2012). Studies that support this theory include Fatai et al. (2004), Lee and Chang (2005), Wolde-Rufael (2005), and among others. The above theories served as a foundation/reason behind the choice of our key variables of interest that were used in the estimated models for SA. The details of these variables are presented in Table 2 of this study as to warrant mentioning here again.

### Table 2: Definition of variables and data sources

| Variable   | Description                                                                 | Source                          |
|------------|-----------------------------------------------------------------------------|---------------------------------|
| LRGDP      | Log of GDP (constant 2010 US$) serves as a proxy for economic growth        | WDI database                    |
| LCO2       | Log of CO₂ emissions (metric tons per capita)                                | WDI database                    |
| LECOM      | Log of energy consumption/use (kg of oil equivalent per capita)              | WDI database                    |
| LMILEXY    | Log of military expenditure as a percentage share of GDP serves as a proxy for militarisation | SIPRI database                 |
| LTRD       | Log of trade (% of GDP) serves as a proxy for trade openness                | WDI database                    |

*Stockholm International Peace Research Institute (SIPRI) database; and World Bank Development Indicators (WDI) database*
The model specification of this study is based on augmented endogenous growth model. This is because economic growth is a function of energy use, capital, and labour. And the use of energy leads to the generation of CO₂ emissions. Human capital and capital stock play a critical role in the model (Barro 2003; Ahmed et al. 2020a). Apart from labour and capital, energy is an important input in the production function (Ahmed et al. 2020a). CO₂ emissions in applied econometric frameworks have been used in empirical literature to measure energy consumption and environmental quality when exploring the impact of the two series on growth (see for example, Sharma (2010), Omri (2013), Ahmed et al. (2020a), and among others). In order to specify an aggregate output function for the South African economy at time \( t \), the Cobb-Douglas production function was based on constant returns to scale which is as follows:

\[
Y_t = A_l K_t^{\beta_l} L_t^{\beta_l} ECOM_t^{\beta_l} CO2_t^{\beta_l} TRD_t^{\beta_l} e^t
\]  

where \( Y \) is the real GDP; \( ECOM \) is the energy consumption; \( CO2 \) is the CO₂ emissions; \( TRD \) is the trade openness; \( e \) is the error term which is assumed to be independently and normally distributed; and \( \beta_1, \ldots, \beta_5 \) are the output elasticities for the right-hand side variables. \( A \) is the technological parameter which is assumed to be endogenously determined by military/defence expenditure/spending as a percentage share of GDP (proxy for militarisation) and it is integrated into the production function. It is written as follows:

\[
A(t) = A_0 e^{gt} MILEXY(t)^g
\]

where \( MILEXY \) is the military/defence expenditure/spending as a percentage share of GDP (proxy for militarisation); \( g \) is the exogenous rate of Harrod-neutral technological advancement. According to Dunne et al. (2005), permanent changes in the share of defence spending have (i) a potentially permanent effect on per capita income along the steady-state growth path, but not in the long-run steady-state growth and (ii) can influence the rate of transient growth moving to a new equilibrium in the steady state. Following the empirical works of Bildirici (2017a, b, c), Ahmed et al. (2020a, b, 2021a), and among others and taking the logarithms (L) of the above specifications, our main model from which other models stems from can be written as follows:

\[
\Delta LRGDP_t = \beta_0 + \beta_1 \Delta MILEXY_t + \beta_2 LECOM_t + \beta_3 LCO2_t + \beta_4 LTRD_t + \epsilon_t
\]

The detailed of the variables in Eq. 2 can be found in Table 2. The model above shows a flexible and analytical approach for examining the links between CO₂ emissions, economic growth, militarisation, and energy consumption. This is because they are the main variables of concern for this study.

### ARDL bounds testing method

This article applied the ARDL bounds testing approach proposed by Pesaran et al. (2001) to examine the long-run relationship between the variables under investigation. The estimated models are specified below as:

**Model 1:**

\[
\Delta LRGDP_t = \phi_0 + \sum_{i=1}^{\infty} \phi_i \Delta LRGDP_{t-i} + \sum_{i=1}^{\infty} \phi_i \Delta LCO2_{t-i} + \sum_{i=1}^{\infty} \phi_i \Delta LTRD_{t-i} + \psi_1 \Delta LMILEY_{t-i} + \mu_1
\]

**Model 2:**

\[
\Delta LCO2_{t-i} = \phi_0 + \sum_{i=1}^{\infty} \phi_i \Delta LCO2_{t-i} + \sum_{i=1}^{\infty} \phi_i \Delta LMILEY_{t-i} + \sum_{i=1}^{\infty} \phi_i \Delta LRGDP_{t-i} + \sum_{i=1}^{\infty} \phi_i \Delta LTRD_{t-i} + \psi_1 \Delta LMILEY_{t-i} + \mu_1
\]

**Model 3:**

\[
\Delta LECOM_{t-i} = \phi_0 + \sum_{i=1}^{\infty} \phi_i \Delta ECOM_{t-i} + \sum_{i=1}^{\infty} \phi_i \Delta LMILEY_{t-i} + \sum_{i=1}^{\infty} \phi_i \Delta LCO2_{t-i} + \psi_1 \Delta LMILEY_{t-i} + \mu_1
\]

**Model 4:**

\[
\Delta LTRD_{t-i} = \phi_0 + \sum_{i=1}^{\infty} \phi_i \Delta LTRD_{t-i} + \sum_{i=1}^{\infty} \phi_i \Delta LMILEY_{t-i} + \sum_{i=1}^{\infty} \phi_i \Delta LCO2_{t-i} + \psi_1 \Delta LMILEY_{t-i} + \mu_1
\]

To estimate the possible CO₂ emissions-energy consumption-defence spending-economic growth nexus for SA, we specified Eq. 2 which consist of our variables of interest. Equation 2 is the reduced form of Eq. 1 which follows the empirical studies of Bildirici (2017a, b, c) and Ahmed et al. (2020a, b, 2021b) with modifications.
If the F-statistic $> upper bound value (I(1))$, we reject the null hypothesis and conclude cointegration among the variables; if the F-statistic $< lower bound value (I(0))$, we accept the null hypothesis and conclude no cointegration among the variables; while if the F-statistic lies between the lower bound and upper bound values, then the results are inconclusive. If a long-run relationship exists between the variables of interest, we shall then estimate a long-run ARDL model, which is as follows:

**Model 1:**

$$\Delta LRGDP_{2t} = \alpha_0 + \sum_{i=1}^{c} \Omega_{i1} LRGDP_{2t-i} + \sum_{i=0}^{c} \Omega_{i2} LCO2_{2t-i} + \sum_{i=0}^{c} \Omega_{i3} LECOM_{2t-i} + \mu_1$$  \hspace{1cm} (7)

**Model 2:**

$$\Delta LCO2_{2t} = \alpha_0 + \sum_{i=1}^{c} \Omega_{i1} LCO2_{2t-i} + \sum_{i=0}^{c} \Omega_{i2} LMILEY_{2t-i} + \sum_{i=0}^{c} \Omega_{i3} LECOM_{2t-i} + \mu_2$$  \hspace{1cm} (8)

**Model 3:**

$$\Delta LECOM_{2t} = \alpha_0 + \sum_{i=1}^{c} \Omega_{i1} LECOM_{2t-i} + \sum_{i=0}^{c} \Omega_{i2} LMILEY_{2t-i} + \sum_{i=0}^{c} \Omega_{i3} LRGDP_{2t-i} + \mu_3$$  \hspace{1cm} (9)

**Model 4:**

$$\Delta LMILEY_{2t} = \alpha_0 + \sum_{i=1}^{c} \Omega_{i1} LMILEY_{2t-i} + \sum_{i=0}^{c} \Omega_{i2} LRGDP_{2t-i} + \sum_{i=0}^{c} \Omega_{i3} LMILEY_{2t-i} + \mu_4$$  \hspace{1cm} (10)

From Eqs. 1 to 4, $\Omega$ represents the coefficient (that is, the short-run variance) of the variables. For short-run ARDL model, the error correction model used is as follows:

**Model 1:**

$$\Delta LRGDP_{2t} = \alpha_0 + \sum_{i=1}^{c} \xi_{i1} \Delta LRGDP_{2t-i} + \sum_{i=0}^{c} \xi_{i2} \Delta LMILEY_{2t-i} + \sum_{i=0}^{c} \xi_{i3} \Delta LECOM_{2t-i} + \sum_{i=0}^{c} \xi_{i4} \Delta LCO2_{2t-i} + \sum_{i=0}^{c} \xi_{i5} \Delta LTRD_{2t-i} + \mu_1$$  \hspace{1cm} (11)

**Model 2:**

$$\Delta LCO2_{2t} = \alpha_0 + \sum_{i=1}^{c} \xi_{i1} \Delta LCO2_{2t-i} + \sum_{i=0}^{c} \xi_{i2} \Delta LMILEY_{2t-i} + \sum_{i=0}^{c} \xi_{i3} \Delta LECOM_{2t-i} + \sum_{i=0}^{c} \xi_{i4} \Delta LCO2_{2t-i} + \sum_{i=0}^{c} \xi_{i5} \Delta LTRD_{2t-i} + \mu_2$$  \hspace{1cm} (12)

**Model 3:**

$$\Delta LCO2_{2t} = \alpha_0 + \sum_{i=1}^{c} \xi_{i1} \Delta LCO2_{2t-i} + \sum_{i=0}^{c} \xi_{i2} \Delta LMILEY_{2t-i} + \sum_{i=0}^{c} \xi_{i3} \Delta LECOM_{2t-i} + \sum_{i=0}^{c} \xi_{i4} \Delta LCO2_{2t-i} + \sum_{i=0}^{c} \xi_{i5} \Delta LTRD_{2t-i} + \mu_3$$  \hspace{1cm} (13)

**Model 4:**

$$\Delta LMILEY_{2t} = \alpha_0 + \sum_{i=1}^{c} \xi_{i1} \Delta LMILEY_{2t-i} + \sum_{i=0}^{c} \xi_{i2} \Delta LRGDP_{2t-i} + \sum_{i=0}^{c} \xi_{i3} \Delta LECOM_{2t-i} + \sum_{i=0}^{c} \xi_{i4} \Delta LCO2_{2t-i} + \sum_{i=0}^{c} \xi_{i5} \Delta LTRD_{2t-i} + \mu_4$$  \hspace{1cm} (14)

From Eqs. 1 to 4, $\xi$ represents the coefficient (that is, the short-run variance) of the variables, while $ECT$ (error correction term) captures the speed of adjustment speed. In order to ensure that our models are correctly specified, we carried out a series of diagnostic statistics tests which can be found in Table 7 of this study and the recursive CUSUM test was used to check for possible parameter stability in the models.

**Dynamic autoregressive distributed lag simulations**

In an attempt to move a step further from the previously introduced ARDL model of long- and short-run estimation approach, Jordan and Philips (2018) proposed a novel dynamic ARDL simulation model. The advantage of ARDL simulation technique over the initial ARDL model is that, it has the ability to estimate, simulate, and plot graphs that shows the predictions of counterfactual change in one explanatory variable on the outcome variable while putting other independent variables on hold. Two conditions are required to estimate the novel dynamic simulated ARDL model, namely (i) the variables must be integrated of order one; and (ii) the variables must be cointegrated. It is worth noting that the variables used in this study actually fulfilled the conditions. Therefore, we proceeded with the estimation of the novel dynamic ARDL simulation model. For the four estimated models, each of them used 1000 simulations of the vector of parameters from a multivariate normal distribution for the dynamic ARDL error correction algorithm. The dynamic stimulated ARDL error correction models’ results are presented in Table 8. The study also investigated the impact of the counterfactual change in the explanatory variables on the regressands by means of graphical representations portrayed in Figs. 4, 5, 6, and 7. The proposed dynamic ARDL simulations model can be found below:

**Model 1:**
\[ \Delta LRGDP_{t} = \theta_{0} + \psi_{1} LRGDP_{t-1} + \psi_{2} LMLEXY_{t-1} + \psi_{3} LMLEXY_{t-1} + \psi_{4} LMLEXY_{t-1} + \nu_{t} \]

\[ \Delta LCO2_{t} = \theta_{0} + \psi_{1} LCO2_{t-1} + \psi_{2} LMLEXY_{t-1} + \psi_{3} LMLEXY_{t-1} + \psi_{4} LMLEXY_{t-1} + \nu_{t} \]

\[ \Delta LCOM_{t} = \theta_{0} + \psi_{1} LCOM_{t-1} + \psi_{2} LMLEXY_{t-1} + \psi_{3} LMLEXY_{t-1} + \psi_{4} LMLEXY_{t-1} + \nu_{t} \]

\[ \Delta LMLEXY_{t} = \theta_{0} + \psi_{1} LMLEXY_{t-1} + \psi_{2} LMLEXY_{t-1} + \psi_{3} LMLEXY_{t-1} + \psi_{4} LMLEXY_{t-1} + \nu_{t} \]

Model 2:

Model 3:

Model 4:

\[ y_{j} = \Gamma_{0} + \sum_{j=1}^{m} \theta_{j} y_{t-j} + \sum_{j=1}^{m} \lambda_{j} x_{t-j} + \mu_{t} \]

where \( y_{j} \) is the response variables and \( x_{i} \) is the predictor/explanatory variable. \( y_{j} \) is considered within the framework of a bivariate VAR(\( m \)) model. The null hypothesis of no Granger-causality from \( y_{j} \) to \( x_{i} \) can be stated as \((\text{Granger 1969}) H_{0}: \lambda_{1} = \lambda_{2} = \ldots = \lambda_{m} \). We used the graphical representation of bivariate spectral Granger causality test in frequency domain for the analysis.

**Data**

This study used a quantitative annual time series data spanning 1960 to 2019. The data for the variables were sourced majorly from two recognised and widely used international databases, namely Stockholm International Peace Research Institute (SIPRI) and World Bank Development Indicators (WDI) database. Some series such as military expenditure as percentage share of GDP and energy consumption had few missing data which was taken care-off by means of extrapolation and interpolation of data. The details of the variables and their sources are provided in Table 2.

**Empirical results and discussion**

**Descriptive statistics, unit root, and lag length selection results**

This section starts with an analysis of the preliminary results, such as the descriptive statistics and unit root. Table 3 presents the descriptive statistics for the variables under investigation. The mean (median) for real GDP (LRGDP), energy consumption (LECOM), trade openness (LTRD), CO₂ emissions (LCO2), and military expenditure (LMILEXY) is 26.099 (26.110), 7.726 (7.813), 3.949 (3.946), 2.006 (2.010), and −3.858 (−3.749), respectively. The real GDP (LRGDP) has the highest mean, followed by energy consumption (LECOM), trade openness (LTRD), etc. Military expenditure (LMILEXY) has the highest standard deviation, followed by real GDP (LRGDP). The Jarque-Bera statistics show that the variables are normally distributed, except for military expenditure (LMILEXY) and energy consumption (LECOM). This illustrates that these two variables are volatile.

This study used Dickey-Fuller GLS-(DF-GLS), Phillips-Perron (PP), augmented Dickey-Fuller (ADF), Kwiatkowski-Phillips-Schmidt-(KPSS), Elliott-Rothenberg-Stock (ERS), and Lee and Strazicich’s (2003) LM unit root to establish the order of integration. This is important because the regres-
sands and the regressors must be integrated of order one (I (1)) before proceeding to the estimation of the cointe-
gation and dynamic ARDL simulation models. In Table 4, real GDP (LRGDP), CO₂ emissions (LCO2), and energy consumption (LECOM) variables for the ERS test reveal that

---

4 This study implemented the recently developed STATA code provided by Tastan (2015) for the execution of frequency domain spectral Granger causality test. The details of this causality approach can be found in the article of Tastan (2015).

5 Studies that have used these techniques include Saba and Ngepah (2019c, 2020a, b), Saba (2020a, 2021a, b), Saba et al. (2021), and Saba and David (2020, 2022).
they are stationary at levels. However, for the traditional and conventional unit root tests, the results strongly suggest that, at the first difference, all the series are integrated of order one (I(1)) at least at a 10% significance level. The researcher could thus proceed with the estimation of ARDL bounds cointegration and dynamic ARDL simulation models.

Before the ARDL bounds and stimulation tests, optimal lag length was first determined. The results for the most used optimal lag length criteria in the empirical literature are reported in Table 5. In Table 5, irrespective of the information criterion the researcher chose to use, lag 1 is henceforth maintained throughout the estimation of the models. Akaiki information criterion criterion (AIC) was used for the lag length selection in this study.

**ARDL bounds cointegration test results**

Table 6 presents the Pesaran et al. (2001) ARDL bounds cointegration test results for the four models. The decision whether cointegration exists between the series was based on the critical values and p-values developed by Kripfganz and Schneider (2018). Using each model’s F-statistics, the values are either above the lower/upper bound critical values I(0)/I(1), with corresponding p-values, which are statistically significant (at least at 1% significance). Therefore, the researcher rejects the null hypothesis of no cointegration. This implies that there is a long-run equilibrium relationship between CO2 emissions, energy consumption, militarisation, and economic growth in SA. The conclusion of the cointegration results is consistent with the findings of Bildirici (2017a, b, c) and Ahmed et al. (2020a, 2021a).

**Diagnostic statistics and stability tests’ results**

To ascertain whether the researcher was estimating correctly specified models, diagnostic statistic tests were performed (see Table 7). Table 7 presents diagnostic statistics test results, and the empirical results for each of the diagnostic statistics suggest that the four models do not suffer from (i) first- and higher-order serial correlation (Durbin-Watson & Breusch Godfrey LM tests); (ii) heteroscedasticity (Breusch-Pagan-Godfrey & ARCH tests); (iii) omitted variables (Ramsey RESET test); and (iv) estimated residual are normally distributed (Jarque-Bera test). Figure 3a, b, c, and d present the recursive cumulative sum (CUSUM) plot for all the models. This is meant to test the stability of the models. Given that the recursive CUSUM plots in Fig. 3 reveal all the variables fall within the 95% confidence band, the researcher therefore concluded that the models’ parameters were stable over time.

**Dynamic ARDL simulations model results**

Beginning with the analysis of model 1, the results in Table 8 presents the dynamic simulated ARDL results revealing the relationship that exists between the series. Column 1 reveals a statistically significant and negative error correction term of −0.05, which represents a 05% speed of adjustment as the series moves to a stable long-run relationship. A similar interpretation holds for columns 2, 3, and 4, whose statistically significant and negative error correction terms are −0.11, −0.08, and −0.40, respectively. In column 1, the estimated short-run coefficient of militarisation reveals a negative and statistically insignificant result of −0.03, which makes it impossible for a meaningful statistical inference. This result is contrary to Atesoglu and Mueller’s (1990) findings, which revealed the existence of a positive and significant relation between defence spending and economic growth for the USA from 1990 to 1995. Kollias et al. (2007) also reported similar results to Atesoglu and Mueller (1990) for the case of European countries. Likewise, Augier et al. (2017), who examined the association between defence spending and economic growth, claimed support for the positive and significant relationship between the two variables for China for the 1952 to 2012 period.

The contrast between this study’s results and those of previous studies could be attributed to differences in methodological approaches and timespans. The negative and statistically insignificant impact of military spending on economic growth in the short-run could be linked to the fact that defence spending’s effect on the economy could be short-lived when a country has not experienced a major prolonged war (d’Agostino et al. 2017). Conversely, in the long-run, the estimated coefficient of militarisation reveals a negative and statistically significant result of −0.02. This implies that a 1% increase in militarisation decreases growth
by 0.02% in the long-run for SA. This outcome is consistent
with the findings of previous empirical works conducted
for different countries and regions (see, for example, Dunne
and Mohammed 1995; Yildirim et al. 2005; Yolcu Karadam
et al. 2017; Saba and Ngepah 2019a, b, 2020a; Ahmed et al.
2020a; Saba 2021, among others). The long-run result points
to the crowding-out impact of militarisation on the SA econ-
omy. Excessive militarisation, according to the literature,
discourages private investment and raises the tax burden on members of the public. Therefore, this result calls for caution on the part of SA’s government and all concerned military stakeholders to avoid allocating large sums of funding to the defence sector. Funds should instead be available for social investments in order to reduce inequality challenges in SA. The authoritarian apartheid rule of the early years of the country’s government, and SA’s continuous direct and indirect involvement in some southern African countries’ conflicts, could have contributed to militarisation’s negative impact on growth (Saba 2021).

The estimated short-run coefficient of energy consumption reveals a positive and statistically significant result of 0.17, which makes it possible for a meaningful statistical inference, while the estimated long-run coefficient of energy consumption is positive and insignificant. This implies that a 1% increase in energy consumption increases economic growth by 0.17% in the short-run for SA. This signifies how crucial energy development is to the country’s economy. The results are found to be in line with the studies of Halicioglu (2009), Salahuddin and Gow (2014), and Salahuddin and Alam (2015). However, it is contrary to Ahmed et al.’s (2020a) findings, which revealed a positive and significant long-run relationship between energy consumption and economic growth in Myanmar. The positive and statistically significant impact of energy consumption on economic growth may be attributed to gradual changes in energy consumption, improvements in the energy sector, and progressive structural changes in the economy (Bekun et al. 2019; Sarkodie and Strezov 2018).

The estimated short-run coefficient of CO₂ emissions shows a negative and statistically significant approximated result of −0.001. This implies that a 1% change in CO₂ emissions reduces growth by −0.00% in the short-run for SA. The implication of this result is that CO₂ emissions are detrimental to growth in the short-run, and policies are thus needed to mitigate emissions. When the CO₂ emissions problem is addressed in the short-run, this may be reflected in its insignificant impact on growth in the long-run. This may also be why the long-run result reveals CO₂ emissions’ positive and insignificant effect on growth. The long-run result aligns with Bekhet et al. (2017) and Aung et al.’s (2017) studies, but contradicts the contributions of Saidi and Hammami (2015b), Ahmed et al. (2020a), and Salahuddin et al.’s (2018) research. One of the possible arguments that could be linked to CO₂ emissions’ negative and statistically significant impact on economic growth is that mitigated CO₂ emissions will slow growth. Ultimately, firms will need to

---

**Table 6 ARDL bounds test results**

| Models          | F-value | 10%  | 5%   | 1%   | p-value  |
|-----------------|---------|------|------|------|----------|
| LRGDP = f(LMILEX, LECOM, LCO2, LTRD) | 9.564   | 2.584 | 3.790 | 3.083 | 0.000*** |
| LCO2 = f(LMILEX, LECOM, LRGDP, LTRD) | 5.662   | 2.584 | 3.790 | 3.083 | 0.010*** |
| LECOM = f(LMILEX, LRGDP, LCO2, LTRD) | 8.666   | 2.584 | 3.790 | 3.083 | 0.000*** |
| LMILEX = f(LECOM, LRGDP, LCO2, LTRD) | 2.584   | 3.790 | 3.083 | 0.000*** |

Note: The null hypothesis of no cointegration is rejected when the F-statistic is above the 10%, 5%, and 1% upper bound critical values, corroborated by the p-value. *, **, and *** respectively.
adjust or limit the growth of high-carbon-intensive firms/industries that contribute considerably to economic growth (Acheampong 2018; Acheampong et al. 2021).

While keeping other independent variables on hold, the dynamic ARDL simulations were predicted by plotting the graph of the actual regressor change and its impact on dynamic ARDL simulations were predicted by plotting reduced a similar positive effect of $CO_2$ emissions on growth, both in the short- and long-run. This implies that an increase in militarisation reduces economic growth, while a decrease in militarisation increases economic growth. Figure 4e shows that a +1 shock at 10th scenario time represents mobilisation’s positive effect on economic growth in the short- and long-run. Although the effect is positive, economic growth can also be seen rising/increasing more in the long-run. Conversely, Fig. 4f reveals that a −1 shock at 10th scenario time denotes energy consumption’s positive effect on economic growth in the short-run, and its positive effect on economic growth in the long-run (although falling). This implies that a rise/fall in energy consumption has a positive effect on economic growth. A similar line of interpretation holds for the remaining figures (5, 6, and 7), even though the shocks differ from one variable to another. Column 2 in Table 8 shows that in the short-run, (i) a positive and significant relationship exists between energy consumption and $CO_2$ emissions at a 1% significance level; and (ii) a positive and significant relationship exists between trade openness and $CO_2$ emissions at a 5% significance level. The dynamic simulated ARDL results reveal that an increment of 1% in energy consumption and trade openness increases $CO_2$ emissions by 0.62% and 0.26%, respectively. One of the explanations for energy consumption intensifying $CO_2$ emissions in SA, both in the short- and long-run, could be related to the fact that the country’s economy still largely depends on the consumption of fossil fuel energy, which has been identified in literature as immensely contributing to $CO_2$ emissions (see, for example, Kohler 2013; Khobai and Le Roux 2017; Ali et al. 2017; IEA 2017, 2020; Adebayo et al. 2021, among others). Studies by Sarkodie and Strezov (2018) and Bekun et al. (2019) allude that, even though fossil fuel energy technologies dominate SA’s energy mix, infusing clean and renewable energy technologies into this mix could contribute tremendously to energy efficiency and reduce $CO_2$ emissions.

In column 2, the estimated short-run coefficient of militarisation reveals a positive and statistically insignificant result of 0.10, while in the long-run, the estimated coefficient of militarisation reveals a negative and statistically significant result of −0.02. This implies that a 1% increase in militarisation, in the long-run, reduces $CO_2$ emissions by -0.02%; it appears militarisation does not pose much threat to environmental quality in SA. Thus, the treadmill theory of destruction is not valid for SA because the theory postulates that military expenditure increases $CO_2$ emissions (Hooks and Smith 2005). This result is not in line with Bradford and Stoner’s (2017) findings for 54 cross-sectional and 36 unique

### Table 7 Diagnostic statistics tests

| Diagnostic statistics tests | Model 1: $X^2$ (p-values) | Model 2: $X^2$ (p-values) | Model 3: $X^2$ (p-values) | Model 4: $X^2$ (p-values) | Decision |
|-----------------------------|---------------------------|---------------------------|---------------------------|---------------------------|----------|
| Durbin-Watson               | 1.577                     | 1.824                     | 1.859                     | 1.679                     | No first-order serial correlation for model 1, 2, 3, and 4 |
| Breusch Godfrey LM test     | 2.207 (0.137)             | 0.126 (0.722)             | 0.306 (0.580)             | 1.859 (0.173)             | No serial correlation for model 1, 2, 3, and 4 |
| Breusch-Pagan-Godfrey test  | 0.03 (0.858)              | 5.05 (0.125)              | 0.78 (0.378)              | 5.38 (0.203)              | No problem of heteroscedasticity for model 1, 2, 3, and 4 |
| ARCH test                   | 4.553 (0.133)             | 0.008 (0.928)             | 3.391 (0.066)             | 10.147 (0.0014)           | No problem of heteroscedasticity for model 1, 2, 3, and 4 |
| Ramsey RESET test           | 1.42 (0.248)              | 1.17 (0.332)              | 3.57 (0.120)              | 0.13 (0.943)              | Model has no omitted variables for model 1, 2, 3, and 4 |
| Jarque–Bera test            | 3.168 (0.205)             | 1.681 (0.432)             | 0.509 (0.775)             | 3.234 (0.199)             | Estimated residual are normal for model 1, 2, 3, and 4 |

Source: authors’ computations
Fig. 3  a Recursive CUSUM plot for model 1; b recursive CUSUM plot for model 2; c recursive CUSUM plot for model 3; d recursive CUSUM plot for model 4
Table 8 Dynamic ARDL simulations results

| Variable          | (Model 1) | (Model 2) | (Model 3) | (Model 4) |
|-------------------|-----------|-----------|-----------|-----------|
| $\Delta \text{LGDP}_t$ | $-0.054^{**}$ | $-0.145^{*}$ | $0.080^{*}$ | $-0.256^{*}$ |
|                   | (0.023)   | (0.078)   | (0.047)   | (0.150)   |
| $\Delta \text{LGDP}_{t-1}$ | $5.429^{***}$ | $0.642^{**}$ | $-1.188$ | $0.881$ |
|                   | (0.369)   | (0.262)   | (0.262)   | (0.171)   |
| $\Delta \text{CO}_2_t$ | $-0.000^{*}$ | $0.218^{**}$ | $0.348$ | $0.881$ |
|                   | (0.043)   | (0.079)   | (0.079)   | (0.171)   |
| $\text{CO}_2_{t-1}$ | $0.001$ | $-0.271^{***}$ | $0.070$ | $0.434^{**}$ |
|                   | (0.029)   | (0.086)   | (0.055)   | (0.170)   |
| $\Delta \text{MLEXY}_{t-1}$ | $-0.030$ | $0.095$ | $-0.037$ | $0.044$ |
|                   | (0.022)   | (0.074)   | (0.044)   | (0.171)   |
| $\Delta \text{LECOM}_{t-1}$ | $0.170^{**}$ | $0.624^{***}$ | $0.388$ | $0.458$ |
|                   | (0.069)   | (0.224)   | (0.044)   | (0.171)   |
| $\Delta \text{LTRD}_{t-1}$ | $0.153^{***}$ | $0.258^{**}$ | $-0.123$ | $0.243$ |
|                   | (0.032)   | (0.122)   | (0.074)   | (0.171)   |
| $\Delta \text{MLEXY}_{t-1}$ | $-0.021^{***}$ | $-0.017^{*}$ | $0.024$ | $-0.167^{***}$ |
|                   | (0.010)   | (0.033)   | (0.019)   | (0.058)   |
| $\Delta \text{LECOM}_{t-1}$ | $0.037$ | $0.370^{***}$ | $-0.224^{***}$ | $-0.150$ |
|                   | (0.042)   | (0.128)   | (0.076)   | (0.264)   |
| $\Delta \text{LTRD}_{t-1}$ | $0.045$ | $0.231^{***}$ | $-0.032$ | $0.130$ |
|                   | (0.027)   | (0.084)   | (0.053)   | (0.171)   |
| Constant          | $0.894^{***}$ | $0.489$ | $-0.277$ | $5.854^{***}$ |
|                   | (0.285)   | (1.023)   | (0.605)   | (1.771)   |
| Observations      | 59        | 59        | 59        | 59        |
| R-squared         | 0.622     | 0.404     | 0.569     | 0.504     |
| Adj R-squared     | 0.552     | 0.295     | 0.490     | 0.413     |
| Root MSE          | 0.016     | 0.052     | 0.031     | 0.985     |
| $F$-sta (P-val)   | $8.95^{**}$ | $3.69^{**}$ | $7.18^{***}$ | $5.53^{**}$ |
|                   | (0.000)   | (0.001)   | (0.000)   | (0.000)   |
| Simulations       | 1000      | 1000      | 1000      | 1000      |

Note: Standard errors in parentheses ***p<0.01, **p<0.05, *p<0.1.
Source: authors' computations

In column 3 of Table 8, in the short- and long-run, economic growth has a positive significant impact on energy consumption; economic growth increases energy consumption by 0.64% and 0.08%, respectively. This implies that both in the short- and long-run, economic growth promotes energy consumption/demand in SA, but the impact seems to diminish over time. This is consistent with the findings of Richmond and Kaufmann (2006), Fang and Chang (2016), and Shahbaz et al. (2022), and among others. Firstly, one of the possible explanations linked to economic growth’s short- and long-run positive significant impact on energy consumption is that the income level is needed and used by the government to invest in the energy sector to provide affordable energy-efficient renewable energy technologies to mitigate CO2 emissions. Also, Sarkodie and Adom (2018) and Acheampong et al. (2021) argued that higher economic growth (when other variables are held constant) translates into higher household income levels. This tends to replace the purchase and replacement of old-fashioned energy-consuming appliances with fewer and more energy-efficient appliances (energy conservation alternatives), thus boosting energy efficiency. These are some of the reasons that could be linked to economic growth’s negative significant impact on CO2 emissions in the long-run.
Fig. 4  

Model 1: change (±1%) in predicted CO₂ emissions on real GDP. 

Model 1: change (±1%) in predicted militarisation on real GDP. 

Model 1: change (±1%) in predicted change in predicted energy consumption on real GDP. Note: dots represent average predicted value while dark blue to light blue lines stands for 75, 90, and 95% confidence interval.
Fig. 5  a and b Model 2: change (±1%) in predicted real GDP on CO₂ emissions. c and d Model 2: change (±1%) in predicted militarisation on CO₂ emissions. e and f Model 2: change (±1%) in predicted change in predicted energy consumption on CO₂ emissions. Note: dots represent average predicted value while dark blue to light blue lines stands for 75, 90, and 95% confidence interval.
Model 3

Fig. 6  a and b Model 3: change (±1%) in predicted CO$_2$ emissions on energy consumption.  c and d Model 3: change (±1%) in predicted real GDP on energy consumption.  e and f Model 3: change (±1%) in predicted change in predicted militarisation on energy consumption. Note: dots represent average predicted value while dark blue to light blue lines stands for 75, 90, and 95% confidence interval.
Fig. 7  Model 4: change (±1%) in predicted CO\textsubscript{2} emissions on militarisation. e and f Model 4: change (±1%) in predicted real GDP on militarisation. e and f Model 4: change (±1%) in predicted change in energy consumption on militarisation. Note: dots represent average predicted value while dark blue to light blue lines stand for 75, 90, and 95% confidence interval.
different types of energy for consumers within the economy. Secondly, national income translates into higher household income levels, which consequently drive energy consumption (Sarkodie and Adom, 2018; Acheampong et al. 2021). This shows that economic growth is crucial for energy consumption in the SA economy.

In the short-run, CO₂ emissions have a positive significant impact on energy consumption. CO₂ emissions increase energy consumption by 0.22%, while in the long-run, CO₂ emissions’ impact on energy consumption is positively insignificant. This implies that the levels of CO₂ emissions still encourage energy use in SA. The previous studies of Saidi and Hammami (2015a, b) supported CO₂ emissions’ positive and significant effect on energy consumption. However, Pao and Tsai (2010) found that CO₂ emissions had a significant and positive impact on energy consumption in the long-run for BRICS countries, spanning 1971 to 2005. Their study was conducted by applying panel data, error-correction model, and vector auto-regression estimation approaches. The contradiction between this study’s long-run result and that of Pao and Tsai (2010) could be linked to differences in estimation approaches, sample period, etc.

In column 4 of Table 8, economic growth has a negative significant impact on militarisation in the long-run. This implies that economic growth reduces militarisation by −0.26%. Likewise, in the long-run, CO₂ emissions have a positive significant impact on militarisation. This also implies that CO₂ emissions increase militarisation by 0.43%. Other variables have no significant impact on militarisation in column 4.

**Frequency domain causality analysis**

Breitung and Candelon (2006) frequency domain causality test, as Abbasi et al. (2021a) pointed out, enabled the researcher to establish model stability, especially for this study’s variables. The frequency-domain causality test results were thus obtained using the Breitung-Candelon Spectral Causality approach. Figure 8’s panel A test statistics reveal that militarisation does not cause CO₂ emissions and vice versa for panel B at all frequencies. Therefore, Fig. 8 reflects that there is no causality between militarisation and CO₂ emissions. This implies that militarisation and CO₂ emissions are independent of each other in SA. The causality result between militarisation and CO₂ emissions, in a way, supports the dynamic ARDL simulation results, which revealed militarisation does not pose a threat to environmental quality in SA; *thus, supporting the absence of the treadmill theory of destruction in SA*. One of the arguments for this result is explained by Solarin et al.’s (2018) findings that militarisation may not pose a threat to environmental quality due to technological development. Moreover, since SA has the most developed defence and ICT sectors in SSA and Africa as a whole, this could have contributed to the absence of causality between the two variables. This finding is inconsistent with Bildirici’s (2017c) for the USA and Bildirici (2016a) for China. Possible explanations for differences in results could be that (i) Bildirici (2017c) used a Toda and Yamamoto (1995) and Rao’s F tests (Rao 1973), which differ from this study’s econometric approach; and (ii) Bildirici (2017c) used a sample period (1960–2013) smaller than the one used in this study. Furthermore, Bildirici 2016a, 2017c focused on countries that are among the leading defence spenders with the most advanced defence sectors in the globe compared to SA.

Figure 9’s panel A reveals that economic growth does not cause militarisation at all frequencies, while the test statistics reveal militarisation causes economic growth because the test statistics are significant at the 5% and 10% levels for frequencies between 0 and 1. This reveals that unidirectional causality runs from militarisation to economic growth, implying that defence spending plays a crucial role in SA’s economic activity. This result aligns with those of Karagol (2006) and Karagol and Palaz (2004) for Turkey, and Farzanegan (2014) for Iran, all of whom found unidirectional causality running from defence spending to economic growth. However, the growth-defence spending nexus cannot assume the same outcome for all countries and may
differ for some countries (Chowdhury 1991). The unidirectional causality suggests that policies to reduce militarisation should be implemented with caution so that it does not retard growth/economic development negatively. Caution is advised since the government’s defence spending is used to provide some level of security for economic and investment activities (Saba and Ngepah 2020a).

Figure 10’s panel A test statistics reveal that militarisation does not cause energy consumption at all frequencies, while the test statistics also indicate that energy consumption does not cause militarisation at all frequencies. This illustrates that there is no causality between militarisation and energy consumption, contrary to the findings of Bildirici (2016a), Bildirici (2017b), and Ahmed et al. (2020a). One of the possible explanations for this causality outcome may be attributed to the weak/absence of strong policy integration between defence and energy sectors in SA. Thus, there is an inter-independency between militarisation and energy consumption in SA.

Figure 11’s panel A test statistics reveal that energy consumption does cause economic growth at all frequencies, while the test statistics reveal that economic growth does not cause energy consumption at all frequencies in panel B. This reflects the existence of unidirectional causality between energy consumption to economic growth, implying that a higher level of economic performance requires more energy use in SA. This finding contradicts those of (i) Ahmed et al. (2021a), who reported unidirectional causality running from economic growth to energy consumption for global data; and (ii) Bildirici (2017a), who reported bidirectional causality between the two variables for the G7 countries. The differences in findings between this study and that of Ahmed et al. (2021b) for the modern world, and Bildirici (2017a) for G7 countries, could be associated with the type of data used. Ahmed et al. (2021a) and Bildirici’s (2017a) studies used panel data, while this study used a time series approach. The evidence of this study’s result infers that a decrease in energy use may retard economic growth in SA; hence, energy use policies should be growth-friendly.

From panels A and B of Fig. 12, the researcher concludes that unidirectional causality runs from CO2 emissions to economic growth. The result is not in line with the studies of Ahmed et al. (2021b) for the globe and Ahmed et al. (2021a) for Japan. It suggests that CO2 emissions increase economic growth and that policies to mitigate CO2 emissions would likely reduce economic growth. This is because the SA economy largely depends on fossil fuel consumption, a major source of CO2 emissions (IEA 2019). From panels A and B of Fig. 13, the researcher concludes that unidirectional causality runs from CO2 emissions to energy consumption. The summary of the frequency domain causality results is visually presented in Fig. 14.

**Conclusion and policy recommendations**

This study examined the CO2 emissions-energy consumption-militarisation-growth nexus for SA between 1960 and 2019. The researcher undertook this study because (i) according to the SIPRI report, SA is among the highest
defence spenders and also has the most developed defence industries in Africa; (ii) SA is one of the top CO$_2$ emitters (1.09 of the world emissions — currently ranked 15th globally) (World Bank 2021); (iii) SA’s economy currently relies heavily on coal for the source of its energy consumption, which has been known to seriously propel CO$_2$ emissions; and (iv) SA is among the leading economies in Africa. Therefore, having an understanding of the relationship that exists between these variables could inform policymakers and relevant stakeholders on how to better place SA’s economy on the path of environmental sustainability by managing the level of militarisation, energy consumption, and real
income. An understanding of this topic at a country-specific level is essential in light of the policy objective set by the UN, aimed at achieving energy sustainability.

These research findings contribute to the literature by testing whether or not the EKC hypothesis, alongside the treadmill theory of destruction, holds in SA. Precious studies failed to apply the estimation techniques used in this study for the thematic under consideration. Therefore, this study further contributes to the literature by applying the novel dynamic ARDL simulations and the frequency domain spectral causality test to achieve its objective.

The cointegration results suggest that there is a long-run equilibrium relationship between CO₂ emissions, energy consumption, militarisation, and economic growth in SA. This result is consistent with the earlier findings of Bildirici (2017a, b, c) and Ahmed et al. (2020a, 2021a). The causality results obtained from the frequency domain spectral causality test show that (i) there is no causality between

---

Fig. 12 Spectral causality between CO₂ emissions and economic growth

Fig. 13 Spectral causality between CO₂ emissions and energy consumption
militarisation and energy consumption; (ii) unidirectional causality runs from militarisation to economic growth; (iii) there is no causality between militarisation and CO2 emissions; (iv) unidirectional causality runs from energy consumption to economic growth; and (v) unidirectional causality runs from CO2 emissions to economic growth.

The main findings from the novel dynamic ARDL simulation results from the first model are that (i) militarisation negatively and significantly impacts growth in the long-run, and it has an insignificant negative impact on economic growth in the short-run. (ii) Energy consumption has a positive and significant impact on economic growth in the short-run, and it has an insignificant impact on growth in the long-run; (iii) CO2 emissions have a negative and significant impact on economic growth in the short-run, and an insignificant impact on economic growth in the long-run. The second model results suggest that (i) energy consumption has a positive and significant impact on CO2 emissions both in the short- and long-run; (ii) in the short-run, a positive and insignificant relationship exists between militarisation and CO2 emissions, while in the long-run, a negative and significant relationship was recorded. Thus, the treadmill theory of destruction is not valid for SA. Also, (iii) in the short-run, economic growth has a positive and significant impact on CO2 emissions, while in the long-run, economic growth has a negative and significant impact on CO2 emissions. This implies the EKC hypothesis holds in SA. The third model’s main results suggest that (i) in both the short- and long-run, economic growth has a positive and significant impact on energy consumption; (ii) in the short-run, CO2 emissions have a positive and significant impact on energy consumption, while in the long-run, the relationship between the two variables is insignificant. Lastly, the fourth model’s main results suggest that, in the long-run, economic growth and CO2 emissions have a negative and a positive significant impact on militarisation, respectively. Other variables in the model do not have a significant impact on militarisation.

To ensure long-term economic growth/development, the following policy discussions should be considered. The empirical results reveal that unidirectional causality runs from energy consumption to economic growth. This shows that programmes promoting energy management.conservation will boost economic growth and, as economic growth is boosted, it will further promote environmental quality in SA, particularly in the long-run. This is because economic growth has a negative and significant impact on CO2 emissions in the long-run. In order to further boost economic growth, there is a need for policies that will help reduce military expenditure in SA without compromising/failing to provide the required internal and external security. The recommended reduction in military expenditure is aimed at freeing up scarce productive resources for other sectors of the economy that will help stimulate economic growth, since military expenditure has a negative and significant impact on economic growth in the long-run. The government should implement the recommended reduction in military expenditure with caution, because the spectral causality results reveal that military spending causes economic growth. This is because the causality result reveals that defence spending is still needed by the government in order to provide some level of security to deal with both internal and external threats to economic and investment activities, even though...
funds allocated to the defence sector may bear an opportunity cost, as this diverts resources away from activities that may directly boost growth and development progress (Saba and Ngepah 2020c). Since it is evident from our result that there is currently an absence of the theory of treadmill of destruction, we therefore recommend that this should not make the South African government to relax when it comes to enacting policies that will promote investment in fuel-efficient defence technologies. This is because policies and program to develop environmentally friendly defence technologies will help to meet future national security needs without causing/contributing to environmental degradation.

To begin with, the SA government and policymakers should place greater emphasis on the production and consumption of renewable energy from the country’s plentiful natural resources to ensure a sufficient and efficient energy supply. The percentage of renewable energy sources in the economy’s overall energy mix should be raised since renewable energy sources are good examples of new carbon-free energy that can help reduce CO₂ emissions without compromising economic growth and development. Policies meant to increase investment in clean energy projects, provide additional subsidies, and tax exemptions can all help to develop the renewable energy sector. Since exchanges of goods and services (for example, capital and final goods) take place, tax exemptions should focus more on the importation of renewable energy products coming into SA. Subsidies should also be provided for the use of renewable energy. Policies encouraging public-private partnerships in renewable energy projects would also help ensure energy supply in the long- and short-run.

The defence sector engages in research and development activities that promote the development of many essential technologies cutting energy consumption. However, the defence sector’s use of fossil fuels and massive resource consumption exacerbates environmental issues. Therefore, policies that encourage research and development funding in the defence sector should be promoted and focus on creating and implementing green carbon-free defence technologies that emit low CO₂ emissions. The results revealed militarisation has a tendency to reduce CO₂ emissions by −0.02% when military expenditure increases by 1% in the long-run. One of the ways the defence sector could achieve this is by enhancing its use of renewable energy sources (biofuel) in its operational actions and avoiding the use of fossil fuels. Militarisation policies in SA will thus be environmentally friendly if the defence sector is directed to consume less energy that deteriorates the environment.

The non-causality between militarisation and CO₂ emissions also illustrates that policymakers can formulate and implement defence and environmental policies independently for the purpose of achieving specific objectives in each of the sectors without necessarily interfering with each other. To further facilitate the shift to a low-carbon economy, the SA government and policymakers need to enshrine environmentally friendly policies into their trade agreement regulations, given that trade increases CO₂ emissions in the short- and long-run, according to the empirical results. Given that EKC holds in SA, there is a need for policies that will promote and intensify environmental awareness through the energy sector; as a result, the reform of environmental policies should be encouraged, as they are currently insufficient to address environmental degradation problem that is currently affecting SA. Overall, based on this study’s empirical findings, policies that encourage the synergy between defence, energy, growth, and environmental policies in the short- and long-run, for the purpose of promoting and maintaining environmental quality in SA, should be formulated, implemented, evaluated, and reviewed whenever the need arises.

The limitation of this study is that it could not extend to cover the COVID-19 pandemic period due to data challenges. Therefore, future studies should consider the pandemic period to attain a better understanding of the role COVID-19 played in the nexus between the variables used in this study for SA and other countries. Also, future research can include more macroeconomic variables into the model and account for the COVID-19 pandemic period to investigate the CO₂ emissions-energy consumption-militarisation-growth nexus for other regions such as SSA, MENA, Asia, and America.

Acknowledgements The author would like to thank the editor(s) and the anonymous reviewer(s) for their valuable comments that assisted in improving the quality of this article. The usual disclaimer applies.

Author contribution CSS conceptualised the study idea, drafted the paper, collected data, analysed data, wrote the introduction section, organised the literature review, drafted the methodology section, interpreted the results and provided the discussions, concluded the study with policy implications, and organised the reference list. CSS proofread, edited, and finalised the article.

Data availability All data generated or analysed during this study are not included in this submission but can be made available upon reasonable request.

Declarations

Ethics approval This article does not contain any studies with human participants or animals performed by the author.

Consent to participate Not applicable.

Consent for publication This manuscript is an original work produced by the author. CSS is aware of its content and approves its submission. It is also important to mention that the manuscript has not been published elsewhere in part or in entirety and is not under consideration by another journal. The author has given consent for this article to be submitted for publication in Environmental Science and Pollution Research.
Conflict of interest The author declares no competing interests.

References

Abbasi K, Jiao Z, Shahbaz M, Khan A (2020) Asymmetric impact of renewable and non-renewable energy on economic growth in Pakistan: new evidence from a nonlinear analysis. Energy Explor Exploit 38(5):1946–1967

Abbasi KR, Abbas J, Tufail M (2021a) Revisiting electricity consumption, price, and real GDP: a modified sectoral level analysis from Pakistan. Energy Policy 149:112087

Abbasi KR, Hussain K, Abbas J, Adedoyin FF, Shaikh PA, Yousaf H, Muhammad F (2021b) Analyzing the role of industrial sector’s electricity consumption, prices, and GDP: a modified empirical evidence from Pakistan. Aims Energy 9(1):29–49

Abokyi E, Appiah-Konadu P, Sikayena I, Oteng-Abayie EF (2018) Determinants of consumption-based carbon emissions in Chile: an application of non-linear ARDL. Environ Sci Pollut Res 1-15. https://doi.org/10.1007/s11356-021-13830-9

Abedayo TS, Udembta EN, Ahmed Z, Kirikkaleli D (2021) Determinants of consumption-based carbon emissions in Chile: an application of non-linear ARDL. Environ Sci Pollut Res 1-15. https://doi.org/10.1007/s11356-021-13830-9

Abedayo TS, Awosusi AA, Bekun FV, Altuntaş M (2021a) Coal energy consumption beat renewable energy consumption in South Africa: developing policy framework for sustainable development. Renew Energy 175:1012–1024

Adedoyin FF, Zakari A (2020) Energy consumption, economic expansion, and CO2 emission in the UK: the role of economic policy uncertainty. Sci Total Environ 738:140014

Adewuyi AO, Awodumi OB (2017) Biomass energy consumption, economic growth and carbon emissions: fresh evidence from West Africa using a simultaneous equation model. Energy 119:453–471

Adewuyi AO, Awodumi OB (2021) Environmental pollution, energy import, and economic growth: evidence of sustainable growth in South Africa and Nigeria. Environ Sci Pollut Res 28(12):14434–14468

Afia NB, Harbi S (2018) The relationship between CO2 emissions and military effort. J Econ Stud Res 2018:1–10 https://ibimapublishing.com/articles/JESR/2018/342225/342225.pdf. Accessed 12 Aug 2022

Ahmed S, Alam K, Rashid A, Gow J (2020a) Militarisation, energy consumption, CO2 emissions and economic growth in Myanmar. Defence Peace Econ 31(6):615–641

Ahmed Z, Zafar MW, Mansoor S (2020b) Analyzing the linkage between military spending, economic growth, and ecological footprint in Pakistan: evidence from cointegration and bootstrap causality. Environ Sci Pollut Res 27(33):41551–41567

Ahmed Z, Ahmad M, Mursheed M, Vaseer AI, Kirikkaleli D (2021a) The trade-off between energy consumption, economic growth, militarization, and CO2 emissions: does the treadmill of destruction exist in the modern world?. Environ Sci Pollut Res 29(12):18063–18076

Ahmed Z, Cary M, Ali S, Mursheed M, Ullah H, Mahmood H (2021b) Moving toward a greener revolution in Japan: symmetric and asymmetric relationships among clean energy technology development investments, economic growth, and CO2 emissions. Energy Environ. Available at: https://doi.org/10.1177/0958305X211041780

Alam MJ, Begum IA, Baysse J, Van Huylenbroeck G (2012) Energy consumption, carbon emissions and economic growth nexus in Bangladesh: cointegration and dynamic causality analysis. Energy Policy 45:217–225. https://doi.org/10.1016/j.enpol.2012.02.022

Alharthi M, Dogan E, Taskin D (2021) Analysis of CO2 emissions and energy consumption by sources in MENA countries: evidence from quantile regressions. Environ Sci Pollut Res 28(29):38901–38908

Ali W, Abdullah A, Azam M (2017) Re-visiting the environmental Kuznets curve hypothesis for Malaysia: fresh evidence from ARDL bounds testing approach. Renew Sust Energ Rev 77:990–1000. https://doi.org/10.1016/j.rser.2016.11.236

Alsaeedi YH, Tularam GA (2020) The relationship between electricity consumption, peak load and GDP in Saudi Arabia: a VAR analysis. Math Comput Simul 175:164–178

Atesoglu HS, Mueller MJ (1990) Defence spending and economic growth. Defence Peace Econ 2(1):19–27

Augtier M, McNab R, Guo J, Karber P (2017) Defense spending and economic growth: evidence from China, 1952–2012. Defence Peace Econ 28(1):65–90

Aung TS, Saboori B, Rasoulinezhad E (2017) Economic growth and environmental Kuznets curve in Myanmar: an analysis of environmental Kuznets curve. Environ Sci Pollut Res 24(25):20487–20501

Aye GC, Balciyar M, Dunne JP, Gupta R, Van Eyden R (2014) Military expenditure, economic growth and structural instability: a case study of South Africa. Defence Peace Econ 25(6):619–633

Barro RJ (2003) Determinants of economic growth in a panel of countries. Ann Econ Financ 4:231–274

Bayar Y, Özbel HA (2014) Electricity consumption and economic growth in emerging economies. J Knowl Manag Econ Inform Technol 4(2):1–18

Bekerman (1992) Economic growth and the environment: whose growth? Whose environment? World Dev 20(4):481–496

Bekhet HA, bin Tuan Abdullah TAR, Yasmin T (2016) Measuring output multipliers of energy consumption and manufacturing sectors in Malaysia during the global financial crisis. Proc Econ Finance 35:179–188

Bekhet HA, Matar A, Yasmin T (2017) CO2 emissions, energy consumption, economic growth, and financial development in GCC countries: dynamic simultaneous equation models. Renew Sust Energ Rev 70:117–132. https://doi.org/10.1016/j.rser.2016.11.089

Bekun FV, Emir F, Sarkodie SA (2019) Another look at the relationship between energy consumption, carbon dioxide emissions, and economic growth in South Africa. Sci Total Environ 655:759–765

Ben-Salha O, Hkiri B, Aloui C (2018) Sectoral energy consumption by source and output in the US: new evidence from wavelet-based approach. Energy Econ 72:75–96

Bibi F, Jamil M (2021) Testing environment Kuznets curve (EKC) hypothesis in different regions. Environ Sci Pollut Res 28(11):13581–13594

Bildirici M (2016a) Defense, economic growth and energy consumption in China. Proc Econ Finance 38:257–263
Das A, McFarlane A (2019) Non-linear dynamics of electric power losses, electricity consumption, and GDP in Jamaica. Energy Econ 84:104530

Dunne P, Coulomb F (2008) Peace, war and international security: economic theories. In: War, Peace and Security. Emerald Group Publishing Limited, Emerald, pp 13–36

Dunne JP, Mohammed NA (1995) Military spending in sub-saharan africa: Some evidence for 1967-85. J Peace Res 32(3):331–343

Dunne JP, Smith RP, Willenbockel D (2005) Models of military expenditure and growth: a critical review. Defence Peace Econ 16(6):449–461

Fang Z, Chang Y (2016) Energy, human capital and economic growth in Asia Pacific countries—evidence from a panel cointegration and causality analysis. Energy Econ 56:177–184

Farhani S, Ozturk I (2015) Causal relationship between CO2 emissions, real GDP, energy consumption, financial development, trade openness, and urbanization in Tunisia. Environ Sci Pollut Res 22(20):15663–15676

Farzaneghan MR (2014) Military spending and economic growth: the case of Iran. Defence Peace Econ 25(3):247–269

Fatai K, Oxley L, Scrimgeour FG (2004) Modelling the causal relationship between energy consumption and GDP in New Zealand, Australia, India, Indonesia, The Philippines and Thailand. Math Comput Simul 64(3-4):431–445

Geweke J (1982) Measurement of linear dependence and feedback between multiple time series. J Am Stat Assoc 77(378):304–313

Gilli A, Gilli M (2018) Why China has not caught up yet: military-technological superiority and the limits of imitation, reverse engineering, and cyber espionage. Int Secur 43(3):141–189

Givens JE (2014) Global climate change negotiations, the treadmill of destruction, and world society: an analysis of Kyoto Protocol ratification. Int J Sociol 44(2):7–36

Gokmenoglu KK, Taspinar N, Rahman MM (2021) Military expenditure, financial development and environmental degradation in Turkey: a comparison of CO2 emissions and ecological footprint. Int J Financ Econ 26(1):986–997

Gottheil FM (1986) Marx versus Marxists on the role of military production in capitalist economies. J Post Keynesian Econ 8(4):563–573

Gould KA (2007) The ecological costs of militarization. Peace Rev 19(3):331–334

Government of South Africa (2022a) KZN flood victims to get temporary accommodation by weekend. Available at: https://www.news24.com/south-africa/kenya-flood-victims-get-temporary-accommodation-weekend. Accessed 14 June 2022

Government of South Africa (2022b) Over 600 schools impacted by KZN floods. Available at: https://www.sanews.gov.za/south-africa/kenya-flood-victims-get-temporary-accommodation-weekend. Accessed 14 June 2022

Granger CW (1969) Investigating causal relations by econometric models and cross-spectral methods. Econometrica: Journal of Economic and Social Measurement 37(3):429–444

Grossman GM, Krueger (1994) Environmental impacts of the North American free trade agreement. In: Working paper 3914. National Bureau of Economic Research, Cambridge
Renner M (1991) Assessing the military’s war on the environment. In: Starker L (ed) State of the world. W.W. Norton & Company, New York, p 117136

Rice J (2007) Ecological unequal exchange: consumption, equity, and unsustainable structural relationships within the global economy. Int J Comp Sociol 48(1):43–72

Richmond AK, Kaufmann RK (2006) Is there a turning point in the interaction between military expenditure, economic growth, and CO2 emissions? Ecol Econ 56(2):176–189

Riddell T (1986) Marxism and military spending. J Post Keynesian Econ 8(4):574–580

Saba CS (2020a) Convergence or divergence patterns in global defence spending: further evidence from a nonlinear single factor model. Peace Econ Peace Sci Public Policy. https://doi.org/10.1515/peps-2020-0012

Saba CS (2020b) Military expenditure and security outcome convergence in Africa: an application of the club clustering approach. Afr Secur 13(3):260–295

Saba CS (2021a) Defence spending and economic growth in South Africa: evidence from cointegration and co-feature analysis. Peace Econ Peace Sci Public Policy. https://doi.org/10.1515/peps-2021-0017

Saba CS (2021b) Convergence and transition paths in transportation: fresh insights from a club clustering algorithm. Transp Policy 112:80–93. https://doi.org/10.1016/j.tranpol.2021.08.008

Saba CS, David OO (2020) Convergence patterns in global ICT: fresh insights from a club clustering algorithm. Telecomun Policy 44(10):102010

Saba CS, David OO (2022) Identifying convergence in telecommunication infrastructures and the dynamics of their influencing factors across countries. J Knowl Econ 1-54. https://doi.org/10.1007/s13132-022-00967-2

Saba CS, Ngepah N (2018) Military expenditure, industrialisation and economic growth in Africa: evidence from a panel causality analysis. Afr J Bus Econ Res(AJBER) 13(3):29–48

Saba CS, Ngepah N (2019a) Military expenditure and economic growth: evidence from a heterogeneous panel of African countries. Econ Res-Ekonomiska istraživanja 32(1):3586–3606

Saba CS, Ngepah N (2019b) A cross-regional analysis of military expenditure, state fragility and economic growth in Africa. Qual Quant 53(6):2885–2915

Saba CS, Ngepah N (2019c) Empirical analysis of military expenditure and industrialisation nexus: a regional approach for Africa. Int Econ J 34(1):1–27

Saba CS, Ngepah N (2020a) Nexus between defence spending, economic growth and development: evidence from a disaggregated panel data analysis. Econ Chang Restruct:1–43. https://doi.org/10.1007/s10644-020-09311-7

Saba CS, Ngepah N (2020b) Convergence in military expenditure and economic growth in Africa and its regional economic communities: evidence from a club clustering algorithm. Cogent Econ Finance 8(1):1832344

Saba CS, Ngepah N (2020c) Military expenditure and security outcome convergence in African regional economic communities: evidence from the convergence club algorithm. Peace Economics, Peace. Sci Public Policy 26(1). https://doi.org/10.1515/peps-2019-0014

Saba CS, Ngepah N (2020) Convergence in renewable energy sources and the dynamics of their determinants: an insight from a club clustering algorithm. Energy Rep. https://doi.org/10.1016/j.egyrep.2022.01.190

Saba CS, Ngepah N, Odhimbo NM (2021) Analysis of convergence in transport infrastructure: a global evidence. Euro J Trans Infrast Res 21(2):137–160

Saidi K, Hammami S (2015a) The impact of energy consumption and CO2 emissions on economic growth: fresh evidence from dynamic simultaneous-equations models. Sustain Cities Soc 14:178–186

Saidi K, Hammami S (2015b) The impact of CO2 emissions and economic growth on energy consumption in 58 countries. Energy Rep 1:62–70. https://doi.org/10.1016/j.egyrep.2015.01.003

Saint Akadiri S, Bekun FV, Sarkodie SA (2019) Contemporaneous interaction between energy consumption, economic growth and environmental sustainability in South Africa: what drives what? Sci Total Environ 686:468–475

Salahuddin M, Alam K (2015) Internet usage, electricity consumption and economic growth in Australia: a time series evidence. Telematics Inform 32(4):862–878

Salahuddin M, Gow J (2014) Economic growth, energy consumption and CO2 emissions in Gulf Cooperation Council countries. Energy 73:44–55. https://doi.org/10.1016/j.energy.2014.05.054

Salahuddin M, Alam K, Ozturk I, Sohag K (2018) The effects of electricity consumption, economic growth, financial development and foreign direct investment on CO2 emissions in Kuwait. Renew Sust Energ Rev 81:2002–2010. https://doi.org/10.1016/j.rser.2017.06.009

Samaras C, Nuttall WJ, Bazilian M (2019) Energy and the military: convergence of security, economic, and environmental decision-making. Energy Strategy Rev 26:100409. https://doi.org/10.1016/j.esr.2019.100409

Sarkodie SA, Strezov V (2018) Assessment of contribution of Australia’s energy production to CO2 emissions and environmental degradation using statistical dynamic approach. Sci Total Environ 639:888–899

Sarkodie SA, Adam PK (2018) Determinants of energy consumption in Kenya: a NIPALS approach. Energy 159:696–705. https://doi.org/10.1016/j.energy.2018.06.195

Shahbaz M, Zeshan M, Afza T (2012) Is energy consumption effective to spur economic growth in Pakistan? New evidence from bounds test to level relationships and Granger causality tests. Econ Model 29(6):2310–2319

Shahbaz M, Tiwari AK, Nasir M (2013) The effects of financial development, economic growth, coal consumption and trade openness on CO2 emissions in South Africa. Energy Policy 61:1452–1459

Shahbaz M, Song M, Ahmad S, Vo XT (2022) Does economic growth stimulate energy consumption? The role of human capital and R&D expenditures in China. Energy Econ 105:105662

Shahiduzzaman M, Alam K (2017) Trade-off between CO2 emissions and income: is there any evidence of an environmental Kuznets curve in Australia. Appl Econ Q 63(2):211–231

Shahraz SJH, Kumar RR, Zakaria M, Hurr M (2017) Carbon emission, energy consumption, trade openness and financial development in Pakistan: a revisit. Renew Sust Energ Rev 70:185–192

Sharma SS (2010) The relationship between energy and economic growth: empirical evidence from 66 countries. Appl Energy 87(11):3565–3574

Singer JD, Keating J (1999) Military preparedness, weapon systems and the biosphere: a preliminary impact statement. New Polit Sci 21(3):325–343

Sohag K, Taşkınp FD, Malik MN (2019) Green economic growth, cleaner energy and militarization: evidence from Turkey. Res Policy 63:101407

Sohag K, Husain S, Hammoudah S, Omar N (2021) Innovation, militarization, and renewable energy and green growth in OECD countries. Environ Sci Pollut Res 28(27):36004–36017

Solarin SA, Al-Mulali U, Ozturk I (2018) Determinants of pollution and the role of the military sector: evidence from a maximum likelihood approach with two structural breaks in the USA. Environ Sci Pollut Res 25(31):30949–30961

South Africa Weather Services (SAWS) (2022) Extreme rainfall and widespread flooding overnight: KwaZulu-Natal and parts of Eastern Cape. Available at:https://www.weatherco.za/Documents/Corporate/Medrel12April2022_12042022142120.pdf. Accessed 14 June 2022

Springer
Stern DI (2004) The rise and fall of the environmental Kuznets curve. World Dev 32(8):1419–1439
Stokey NL (1998) Are there limits to growth? Int Econ Rev 1:31
Tang CF, Shahbaz M (2013) Sectoral analysis of the causal relationship between electricity consumption and real output in Pakistan. Energy Policy 60:885–891
Tastan H (2015) Testing for spectral Granger causality. Stata J 15(4):1157–1166
Tech Central (2022) Floods knock out telecoms infrastructure in KZN. Available at: https://techcentral.co.za/floods-knock-out-telecoms-infrastructure-in-kzn/210004/. Accessed 14 June 2022
Toda HY, Yamamoto T (1995) Statistical inference in vector autoregressions with possibly integrated processes. J Econ 66(1-2):225–250
Udeagha MC & Ngepah, N. (2021). Does trade openness mitigate the environmental degradation in South Africa? Environ Sci Pollut Res 29:19352–19377. https://doi.org/10.1007/s11356-021-17193-z
Udeagha MC, Breitenbach MC (2021) Estimating the trade-environmental quality relationship in SADC with a dynamic heterogeneous panel model. Afr Rev Econ Finance 13(1):113–165
Udeagha MC, Muchapondwa E (2022) Investigating the moderating role of economic policy uncertainty in environmental Kuznets curve for South Africa: evidence from the novel dynamic ARDL simulations approach. Environ Sci Pollut Res. https://doi.org/10.1007/s11356-022-21107-y
Ullah S, Andlib Z, Majeed MT, Sohail S, Chishti MZ (2021) Asymmetric effects of militarization on economic growth and environmental degradation: fresh evidence from Pakistan and India. Environ Sci Pollut Res 28(8):9484–9497
Varma R (2019) Bridging the electricity demand and supply gap using dynamic modeling in the Indian context. Energy Policy 132:515–535
Wang KH, Su CW, Loboń OR, Umar M (2021) Whether crude oil dependence and CO2 emissions influence military expenditure in net oil importing countries? Energy Policy 153:112281
Weiss EB (2008) Climate change, intergenerational equity, and international law. Vermont J Environ Law 9(3):615–627
Wolde-Rufael Y (2005) Energy demand and economic growth: the African experience. J Policy Model 27(8):891–903
World Bank (2021) World development indicators. http://www.worldbank.org. Accessed 30 Feb 2022
Yildirim J, Sezgin S, Ocal N (2005) Military expenditure and economic growth in Middle Eastern countries: a dynamic panel data analysis. Defence Peace Econ 16(4):283–295
Yolcu Karadam D, Yildirim J, Ocal N (2017) Military expenditure and economic growth in Middle Eastern countries and Turkey: a non-linear panel data approach. Defence Peace Econ 28(6):719–730
York R (2008) De-carbonization in former Soviet republics, 1992–2000: the ecological consequences of de-modernization. Soc Probl 55(3):370–390
Zaman M, Shaheen F, Haider A, Qamar S (2015) Examining relationship between electricity consumption and its major determinants in Pakistan. Int J Energy Econ Policy 5(4):998–1009

Publisher’s note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Springer Nature or its licensor holds exclusive rights to this article under a publishing agreement with the author(s) or other rightsholder(s); author self-archiving of the accepted manuscript version of this article is solely governed by the terms of such publishing agreement and applicable law.