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Research paper

Roadmap for achieving energy sustainability in Sub-Saharan Africa: The mediating role of energy use efficiency

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ABSTRACT

The core objective of this study is to evaluate whether improving energy use efficiency can help Sub-Saharan African nations to attain their energy sustainability objectives. As opposed to the conventional approaches, the multidimensional aspects of energy sustainability are captured in this study by predicting an energy sustainability index using data related to four key targets mentioned under the seventh sustainable development goal declared by the United Nations. Overall, for the entire panel, the findings reveal that a 1% rise in the energy efficiency level increases the energy sustainability index by around 11% in the long run. Thus, energy efficiency improvements can be expected to complement the energy sustainability agenda of the Sub-Saharan African nations. In contrast, economic growth is witnessed to impede energy sustainability within these nations. However, the results also certify that energy efficiency improvement performs a mediating role in neutralizing the energy sustainability-inhibiting effects of economic growth. In addition, higher emissions of carbon dioxide found to encourage the Sub-Saharan African nations to implement policies related to attainment of energy sustainability. Besides, trade and financial globalization are also witnessed to impede and stimulate energy sustainability, respectively. Furthermore, the results reveal that financial development facilitates energy sustainability attainment while higher population growth inflicts opposite impacts. Finally, implementation of the Kyoto Protocol is evidenced to be contributing to the attainment of energy sustainability in the selected Sub-Saharan African nations. In light of these findings, several energy sustainability-related policies are recommended.

1. Introduction

Ensuring sufficient availability of energy resources is a major concern worldwide since achieving energy security goes hand in hand with maintaining a steady rate of economic growth (Le and Nguyen, 2019). In contrast, negative energy supply shocks disrupt the economic development momentum by hampering national output production, in particular. This is because in the contemporary context energy resources are considered as important as the conventional factors of production like labor and capital (Murshed, 2021). Besides, several preceding studies have also acknowledged that energy plays a key role in driving industrialization (Tvaronavičiene et al., 2015), generating employment (WEF, 2012), and facilitating several other economic activities. Accordingly, the World Economic Forum has recognized energy as the lifeblood of the world economy courtesy of the paramount importance of energy in the production of almost all goods and services (WEF, 2012). Moreover, having adequate access to modern energy resources is also linked with the prospects of attainment of the 2030 Sustainable Development Goals (SDG) agenda of the United Nations (Nepal and Paija, 2019).

In simple terminology, energy sustainability refers to enhancing access to certain energy resources that can be utilized to meet current energy demand without compromising the future energy supply requirements (Kreith and Krumdieck, 2013). More importantly, since the consumption of traditional unclean energy resources is associated with adverse environmental issues, energy sustainability particularly emphasizes on sustaining the supply of modern and cleaner energy options (Grigoroudis et al., 2021; Murshed et al., 2022). Accordingly, energy sustainability is said to be imperative for tackling climate change-related issues as well (Pliousis et al., 2019). In the same vein, the seventh SDG (SDG7) of the United Nations has also highlighted the importance of ensuring the sustainable supplies of affordable, clean, and

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renewable energy resources worldwide[1] (Ahmed et al., 2021). Hence, it is necessary to discover the relevant factors that can drive energy sustainability, especially across global regions that predominantly rely on unclean energy resources to meet their own energy requirements.

Among the many factors that can ensure energy sustainability, improving the rate of energy use efficiency can be hypothesized one of the most relevant ones for various reasons. For instance, one of the major targets mentioned under SDG7 is to increase universal access to electricity. It is estimated by the International Energy Association that around 950 million people would not be connected to the grid by 2030 whereby the goal of ensuring maximum electrification globally is likely to be unrealized. The issue of inadequate electricity access is relatively higher for the Sub-Saharan African (SA) nations as almost 85 million people would need to be given access to electricity year-on-year through 2030 (IBRD, 2021). In this regard, improving the rate of energy use efficiency can be linked with efficient management of electricity demand and electricity savings which, in turn, could be expected to create opportunities for bringing more people under electricity coverage. On the other hand, another key feature of SDG7 is improving the availability and use of clean cooking fuels around the globe (Murshed, 2022). It is assumed that if the global economies refrain from making a transition from unclean to clean cooking options, almost 2.4 billion people in the world would have to rely on traditional unclean sources of cooking fuel (IBRD, 2021). Energy efficiency gains, in this regard, have been acknowledged to play a decisive role in the development of clean cooking fuels such as Liquefied Petroleum Gas and electricity (Al-Tal et al., 2021).

Furthermore, SDG7 also calls for significantly increasing the share of renewables in the global energy portfolio. In 2018, merely 18% of the world's aggregate primary energy demand was met by renewables (IBRD, 2021). It is well-known that technological and financial barriers impede renewable energy transition (Geng and Ji, 2016). More importantly, it also requires time to develop the relevant technologies that can enable the world economies to phase-out their non-renewable energy dependency. Hence, improving the rate of energy use efficiency or reducing the energy intensity level could provide the buffer time needed to stimulate this clean energy transition (IBRD, 2021; Al-Tal et al., 2021). In addition, several studies have attempted to proxy technological innovation related to the energy sector as a proxy for technology in studies related to environmental impact assessments (Ghazali and Ali, 2019). As a result, energy efficiency gains can be indicative of the technological innovation that is necessary for driving the renewable energy transition. Hence, considering these multidimensional linkages between energy efficiency and energy sustainability, SDG7 also targets to double the average annual rate of global energy use efficiency from the mean level of 1.3% between 1990 and 2010 to 2.6% on average by 2030 (IBRD, 2021).

Against this backdrop, this study predicts whether or not amplifying the level of energy efficiency can ensure energy sustainability across 32 SA countries[2] between 2002 and 2016. The decision to choose this region is based on the understanding that the SA nations have traditionally banked on both locally and internationally sourced fossil fuels to meet their energy requirements (Aly et al., 2019). Besides, these nations have also remained predominantly reliant on traditional and dirty cooking fuel sources which can be realized from the statistic that almost 900 million people across the SA nation rely on solid biomass for cooking purposes (Dagnachew et al., 2020; Uchenna and Oluwabunmi, 2020). Moreover, as per the latest report on energy efficiency by the International Energy Association, most of the global population not having access to electricity in 2020 were from Sub-Saharan Africa and Asia (IEA, 2021a). Furthermore, only one-fifth of Africa's total electricity output in 2018 was generated from renewable resources whereby this statistic implicates that undergoing renewable energy transition is a cumbersome task for the concerned governments (IRENA, 2020). Alongside these issues, the population of the SA nations is projected to double by 2050 (IEA, 2021b). As a consequence, the energy demand of the SA countries can be expected to substantially surge in the upcoming decades whereby achieving energy sustainability is of utmost importance for these nations.

On the other hand, energy efficiency improvement has also been a problematic issue for the SA nations particularly due to these countries being largely dependent on low-efficiency fuels (IEA, 2019). The primary energy inefficiency level of these nations is regarded as one of the highest in the world (Kohler, 2014). Besides, the low growth in energy efficiency-related spending has largely dampened the average rate of improvement in energy-use efficiency across this region (IEA, 2020). Also, the electricity sectors of the SA nations are characterized by high rates of transmission and distribution losses. In 2016, these losses cumulatively summed up to around 23% which further portrays the dismal state of energy efficiency in this region (Trimble et al., 2016). Moreover, compared to the northern African nations, the transmission and distribution losses are relatively higher in the SA nations (IRENA, 2020). Therefore, considering the theoretical associations between energy efficiency and energy sustainability, it can be hypothesized that the slow progress made by the SA nations in respect of energy efficiency improvement is largely responsible for their poor performances in attaining the energy sustainability-related targets mentioned under SDG7.

This study makes four major contributions to the current stock of knowledge. Firstly, while the preceding studies have mostly focused on the energy sustainability issue across the SA nations using different indicators of energy sustainability (Behera and Ali, 2016; Baye et al., 2021a), this current study constructs a more inclusive indicator of energy sustainability by combining data of several indicators of key targets mentioned under SDG7 declarations. Hence, the outcomes from this study can be utilized for the conceptualization of comprehensive policies that can proactively enable the SA nations to achieve SDG7 by 2030. Secondly, this study is also one of the few studies that link energy efficiency with energy sustainability in the SA context. Contrarily, existing studies have assessed the impacts of other macroeconomic factors on energy sustainability indicators for the SA countries (Ankrah and Lin, 2020; Akintande et al., 2020). Thirdly, for identifying possible heterogeneous outcomes, the analysis is conducted for both the full panel of the selected SA nations as well as for sub-samples of these nations classified across different categories of income groups and energy efficiency improvement performances. Lastly, apart from assessing only the independent impacts, this study also emphasizes on the possible mediating roles of energy efficiency improvement on the issue of energy sustainability in the SA nations.

In the next section, the trends in the key indicators of energy sustainability across the selected SA nations are presented. Subsequently, the remaining sections provide the literature study, empirical model and data, estimation strategy, results and discussion, and concluding remarks with policy recommendations.

[1] For more information regarding SDG7 see https://www.un.org/sustainabledevelopment/energy/.

[2] These countries include Angola, Benin, Burkina Faso, Cabo Verde, Cameroon, Central African Republic, Congo Democratic Republic, Cote d'Ivoire, Eswatini, Gabon, Ghana, Guinea, Kenya, Lesotho, Madagascar, Malawi, Mali, Mauritius, Mozambique, Namibia, Niger, Nigeria, Rwanda, Sao Tome and Principe, Senegal, South Africa, Sudan, Tanzania, Togo, Uganda, Zambia, and Zimbabwe.

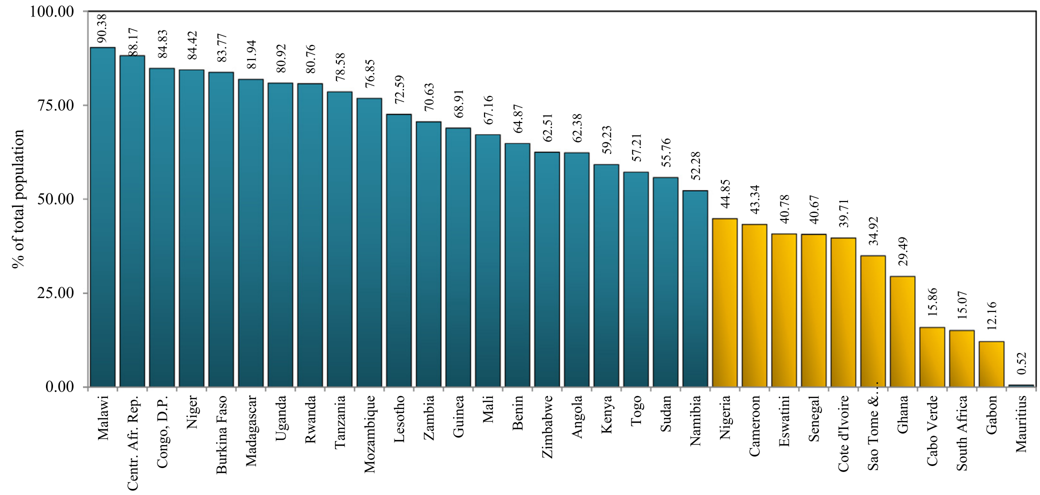

Fig. 1. Share of the population having no electricity access. Note: The figures are mean shares of the population without access to electricity between 2002 and 2016.. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
Source: WDI (2021).

2. Trends in key energy sustainability-related indicators

As per the declaration of SDG7 by the United Nations, there are three broad targets to be achieved by 2030. These include:

- **Target 7.1:** guarantee access to affordable, uninterrupted, and modern energy options worldwide (especially enhancing rates of access to electricity and clean cooking fuels)
- **Target 7.2:** facilitate renewable energy transition by significantly enhancing the share of renewables in the global energy portfolio
- **Target 7.3:** improving the global energy use efficiency level by two-fold

Therefore, keeping into consideration the prospects of the SA nations in attaining these targets, it is important to have a clear picture of the state of these indicators across these nations. SDG target 7.1.1 emphasizes on enhancing global electricity access by 2030. As far as accessibility of energy is concerned, it is essential to get an idea of the shares of the respective population of the SA nations having no access to electricity. Fig. 1 illustrates the average electricity inaccessibility rates across the selected SA nations. It is evident from this figure that lack of access to electricity is a significant issue of concern for the SA nations. It can be observed that 21 out of the 32 SA nations considered in this study (denoted by the blue bars in Fig. 1) had more than half of their respective population without electricity access. As a whole, considering all the selected 32 SA nations, the average share of the population without electricity access was close to 58% which further gives an impression of the dismal state of electrification in this part of the globe.

Regarding clean cooking fuel transition, especially from traditional solid biomass-fired cookstoves to electricity and gas-based modern cookstoves, SDG target 7.1.2 stresses on improving access to clean cooking fuel and technology for the global population. In this regard, Africa is one of the poorest performing global regions that have not managed to significantly increase access to clean cooking fuel and technology for the population (WDI, 2021). Between 2010 and 2018, the number of people not having access to clean cooking fuels surged from 750 million to 890 million (United Nations, 2020). Especially for the selected low- and middle-income SA nations, the average level of access to clean cooking fuel and technology was less than 15% in 2016 (WDI, 2021) which implies that a huge segment of the total population still depends on unclean fuels for cooking purposes. Table 1 provides a clear picture of the acute unclean cooking fuel dependency in the SA nations considered in this study. It can be seen that only Mauritius has ensured 100% clean cooking fuels and technology access for its people while South Africa, Gabon, and Cabo Verde are the other SA nations that have ensured clean cooking fuels and technology for more than 70% of their respective population. Besides, as far as reducing the share of the population without access to clean cooking fuel and technology is concerned, it can be observed that between 2010 and 2016 only Zimbabwe, Senegal, Sao Tome and Principe, Mali, and Madagascar have managed to achieve this objective. In contrast, the rest of the selected SA nations have not succeeded in undergoing clean cooking fuel transition within this period.

Now referring to the renewable energy transition issue, Fig. 2 depicts the mean shares of renewable and non-renewable electricity outputs in the total electricity output figures of the selected SA nations between 2011 and 2016. The dependency of the majority of these SA nations on traditional non-renewable energy for generating electricity is clearly observed from this figure. In 14 of these SA nations, less than half of the total electricity output was produced by utilizing fossil fuels like petroleum oil and natural gas, in particular (World Bank, 2021). Among these, Angola, Benin, and Burkina Faso are the three least renewable energy-dependent SA nations. In contrast, although Zimbabwe's renewable electricity output share had reached 100%, Togo, Uganda, and Zambia were also extremely close to achieving this status. However, a more concerning issue is identified from Fig. 3 which provides the differences in the renewable electricity output shares of these countries between 2002 and 2016. It is witnessed that between 2002 and 2016, 20 of these SA nations had not been able to improve their respective renewable electricity output shares which further indicates that these nations had largely been unsuccessful in undergoing renewable energy transition.

Now focusing on the energy efficiency improvement target of SDG7, the trends in the illustrations of the average annual changes in the energy efficiency levels across the SA nations between 2002 and 2016 (shown in Fig. 4) reveal that 24 of the 34 countries had managed to improve the efficiency at which energy is utilized while in the rest of the selected SA nations the energy efficiency level had on average declined. Besides, among the 24 energy efficient SA nations, 12 of these have not been able to double their annual energy efficiency improvement figures in accordance with the SDG7 target of doubling the energy use efficiency level year-on year. The poor performances

Table 1
Share of the population without access to clean fuel and technology for cooking.
Source: WDI (2021).

Country	Year 2016	Δ (2010–2016)	Country	Year 2016	Δ (2010–2016)
Mauritius	0.00	0.00	Kenya	86.58	5.41
South Africa	15.25	8.12	Burkina Faso	91.07	2.92
Gabon	20.88	5.55	Togo	93.29	2.69
Cabo Verde	28.95	3.88	Benin	93.56	1.66
Eswatini	50.3	8.13	Nigeria	95.09	2.47
Angola	51.95	3.95	Congo, Dem. Rep.	95.98	0.24
Namibia	57.8	3.32	Mozambique	96.31	0.29
Sudan	58.71	12.35	Malawi	97.5	0.32
Lesotho	64.39	5.75	Tanzania	97.84	0.51
Senegal	68.35	−0.29	Niger	98.09	0.36
Zimbabwe	70.95	−1.41	Guinea	98.76	0.02
Cameroon	76.96	5.44	Central African Republic	99.03	0.19
Ghana	78.29	7.66	Mali	99.04	−0.06
Cote d'Ivoire	81.77	0.32	Madagascar	99.09	−0.05
Sao Tome and Principe	83.19	−4.72	Uganda	99.23	−0.06
Zambia	83.57	0.96	Rwanda	99.43	0.12

Note: The figures are the latest available figures as of 2016; Δ denotes change between the figures in 2010 and 2016.

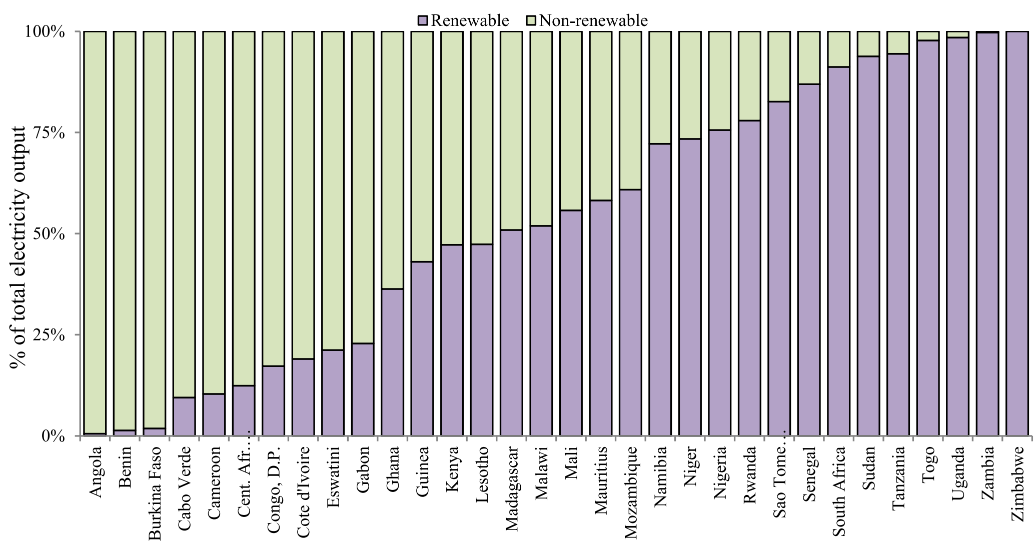

Fig. 2. Shares of renewable and non-renewable energy-utilized electricity output shares. Note: The figures are mean figures between the 2011–2016 period. *Source:* World Bank (2021).

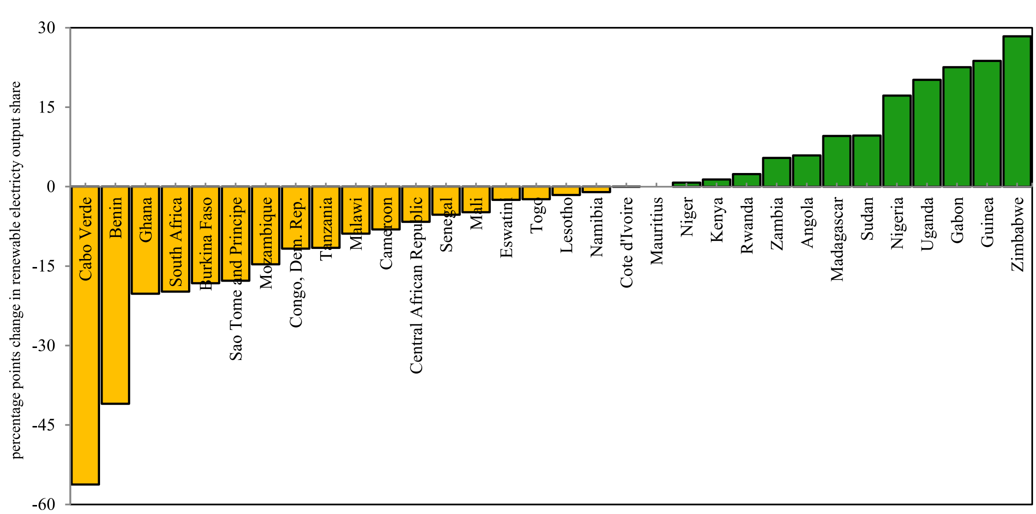

Fig. 3. Differences in renewable electricity output shares. Note: The figures are differences in figures between 2002 and 2016. *Source:* World Bank (2021).

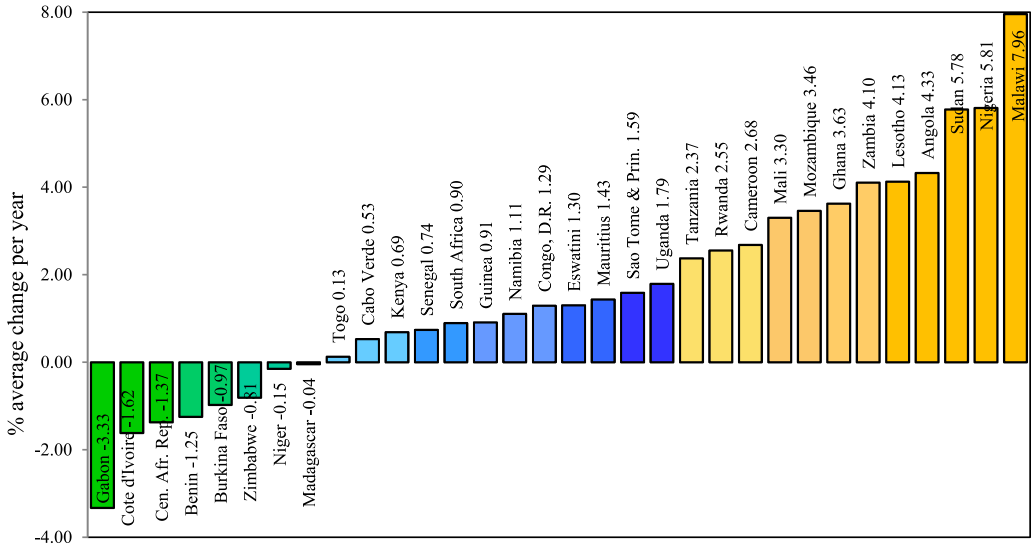

Fig. 4. Average yearly changes in energy efficiency levels. Note: The figures are average annual changes in the energy efficiency level between 2002 and 2016. The green bars refer to SA countries that have not improved their energy efficiency levels; the blue and orange bars represent the SA nations that have achieved low and high energy efficiency gains, respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
Source: World Bank (2021).

in respect of energy efficiency improvement corroborate the assertion regarding the lack of investments in energy efficiency improvement-related projects across this region (IEA, 2020). Besides, these statistics also support the statements put forward in the report by the International Renewable Energy Agency regarding the severity of transmission and distribution losses within the electricity sectors of the SA nations (IRENA, 2020). Accordingly, several preceding studies have recommended scaling up private investments in order to reduce these inefficiency-related losses within the power sector and, thereby, help the SA nations in ensuring universal access to electricity for their respective populations (Falchetta et al., 2021).

3. Literature review

Amidst the growing concerns regarding energy use-associated climate change adversities, the macroeconomic determinants of the clean energy transition have acquired significant interest in the corresponding literature. However, these existing studies have mostly limited the analyses to focusing on particular indicators of clean energy transition without assessing this issue using a holistic approach. Besides, the role of energy efficiency gains in respect of stimulating the renewable energy transition, in particular, has also been largely overlooked in the literature. Hence, in this section, these literature gaps are identified by summarizing the major findings documented in the previous studies that are related to this current study. The review of the literature is distributed across three sub-sections. In the first, the studies focusing on the macroeconomic determinants of access to electricity are summarized followed by the ones emphasizing on the determinants of clean cooking fuel access in the second. Lastly, in the third, relevant studies on the macroeconomic factors influencing renewable energy use are discussed. Since SDG7 aims to achieve energy sustainability by simultaneously enhancing electricity access and renewable energy use across the globe, the literature review section presented in this study can be used to identify the possible channels through which energy sustainability can be attained.

3.1. The determinants of electricity accessibility

Theoretically, energy efficiency is primarily targeted as making efficient use of non-renewable energy resources such as conventionally consumed fossil fuels (Goswami and Kreith, 2007). As a result, improving the rate of energy use efficiency can be expected to play a role in curtailing energy demand (Hadjadj et al., 2021) and, therefore, ensuring energy sustainability. Besides, the energy resources through more efficient uses can be utilized to meet the future energy demand. In addition, reducing energy wastage by improving the energy efficiency level is also likely to enhance the prospects of supplying energy to more people. Accordingly, energy efficiency improvement can be associated with higher access to electricity for the population of a given country. It is believed that exploring the synergy between energy efficiency and the status of electricity access is critically important for addressing the unreliability concerning electricity supply in developing nations, in particular (World Bank, 2017). Especially in the context of the SA nations, the average level of industrial energy efficiency across this region is comparatively lower than the global average; thus, the electricity access rate in most of these nations is considerably low (Kohler, 2014). Under such circumstances, imposing progressive tariffs on electricity consumption (the higher the inefficient use of electricity the higher the tariffs charged) has been identified as a potential means of enhancing electricity access within this region.

Similarly, in the context of the Philippines, Pacudan and De Guzman (2002) highlighted that adoption of appropriate energy efficiency improvement-related policies can be effective in addressing the distributional inefficiencies within the electricity sector so that the overall electricity supply can be improved. Among the other determinants, Mwizerwa and Bikorimana (2018) found evidence of enhancing gross capital formation-level can improve electricity access in Rwanda. Similarly, emphasizing on the role of investment, Panos et al. (2016) used data from countries belonging to the SA, Asian, and Latin American regions and found that scaling up investments in energy infrastructure can help to improve the overall access to electricity. In another relevant study on 14 West African nations, Tehero (2021) recently concluded that higher national income per capita, a better quality of governance, and higher rates of urbanization and population density positively influence electricity access rates of these countries. Likewise, Boräng et al. (2021) claimed that better institutional quality is a prerequisite for democratic institutions to be effective in enhancing electricity access.

3.2. The determinants of clean cooking fuel and technology accessibility

Energy efficiency improvement is relevant for stimulating the replacement of unclean cooking fuels by cleaner clean cooking fuels from the perspective that the modern cooking fuel stoves are relatively more energy efficient; therefore, a rise in the energy efficiency level can be an indication of energy innovation which is pertinent for developing the clean cooking fuel production technologies (USAID, 2017). In this regard, the Efficient, Clean Cooking and Heating program initiative of the World Bank was launched at the United Nations 2019 Climate Summit in order to provide green finance to research and development projects for enhancing clean cooking fuel and technology access across the globe (World Bank, 2020). The funds released through this initiative have facilitated the development of comparatively more energy-efficient cooking fuels to drive clean cooking fuel adoption in several developing SA nations like Uganda and Senegal (World Bank, 2020). Although the pertinence of improving the level of energy use efficiency for undergoing clean cooking fuel transition has been widely acknowledged, very few studies have explored the nexus between these variables. Recently, Al-Tal et al. (2021) found evidence of energy efficiency improvement to ultimately drive clean cooking switches across the SA countries.

Among the other key factors of clean cooking fuel transition that have been identified in the preceding studies, Murshed (2020a) used data from a global sample of low- and middle-income countries including those from the SA region as well, and found that international trade helps to enhance clean cooking fuel and technology access only across the lower-middle-income nations while inhibiting it for the cases of low-income and upper-middle-income groups. On the other hand, using the level of access to clean cooking fuel as a proxy for energy poverty in Sengal and Togo, Gafa and Egbendewe (2021) asserted that a higher per capita national income level is associated with higher access to clean and modern cooking fuel sources. Similarly, using data from 31 SA nations between 2000 and 2015 and employing panel fixed effects, random effects, and fully-modified ordinary least squares regression techniques, Kwakwa et al. (2021) stated that higher levels of national income, foreign direct investment influx, and employment rate are efficient in improving clean cooking fuel access. Murshed (2018), for selected South Asian nations, claimed that greater openness to international trade, higher emissions of carbon dioxide, better levels of educational attainment and health quality, and economic growth are some of the major macroeconomic factors that can improve the clean cooking fuel and technology access rates. Further, the development of information and communications technology was found as another important driver of clean cooking fuel adoption in South Asia (Murshed, 2020b).

Although national-level analysis of the determinants of clean cooking fuel access across the SA nations has not been extensively explored before, a large number of the existing studies have used household-level data to identify the factors that can stimulate the transition from unclean to clean cooking fuels within this region. Among these, Shupler et al. (2021) opined that higher socioeconomic status is likely to motivate the peri-urban households in Cameroon, Ghana, and Kenya to switch from solid biomass to the relatively cleaner option of liquefied petroleum gas (LPG) for cooking purposes. Similarly, in the context of Cameroon, LPG adoption was also found to be positively influenced by higher education levels of household members and a greater stock of household wealth (Pye et al., 2020). In another study on rural households in Ethiopia, Guta (2020) remarked that a rise in the household income level is likely to enhance the affordability of adopting clean energy-fired cookstoves. Furthermore, Hsu et al. (2021) and Stevens et al. (2020) recently opined that higher availability of microloans facilitates the uptake of clean and improved cooking fuels in Kenya and East African nations, respectively. On the other hand, for non-SA nations, Carter et al. (2020) and Bakhsh et al. (2020) also found evidence that a rise in the household income level is effective in suspending unclean cooking fuel use and adopting cleaner alternatives in China and Pakistan, respectively.

3.3. The determinants of renewable energy use

In simple terms, renewable energy refers to certain energy sources that can be naturally replenished and used over and over again for generating power; these include solar, wind, geothermal, hydropower, and biomass (Lebbihiat et al., 2021). Although not all types of renewable energy are completely environmentally-friend, it is often mentioned in the literature as a relatively cleaner source of energy compared to conventional fossil fuels (Awan et al., 2022). However, undergoing a transition from non-renewable to renewable energy does not take place instantaneously since the development of renewable energy production technologies requires large volumes of investment and time. As a result, gaining energy efficiency can help to manage the energy demand and provide the time needed to develop the relevant technologies for enabling renewable energy transition (Al-Tal et al., 2021). Besides, energy efficiency improvement is also believed to facilitate the integration of renewable energy into the national energy mix (Oró et al., 2015). Moreover, in line with the objectives of SDG7, simultaneously achieving energy efficiency gains and deploying renewable energy can help to reduce fossil fuel consumption; thus, the dependency on fossil fuels can gradually be relaxed to a large extent (Tin et al., 2010). Although both these factors are believed to contribute to the attainment of energy sustainability, not much emphasis has been given to exploring the linkage between energy efficiency gains and renewable energy adoption. Among the few studies that have assessed the energy efficiency-renewable energy use nexus, Li et al. (2020) asserted that energy efficiency improvement drives up the share of renewables in the total energy consumption level of countries that are members of the Organization for Economic Cooperation and Development (OECD), both in the short and long-run.

However, using other relevant explanatory variables, the determinants of higher renewable energy consumption share have been extensively explored in the related literature. For a panel of 21 African nations, Ergun et al. (2019) utilized annual frequency data spanning from 1990 to 2013 and found that rises in the level of economic growth and human development reduce the share of renewables in the energy consumption profiles of these African countries. Contrarily, an influx of foreign direct investments was evidenced to increase this share while the quality of the democratic institutions played no role in explaining the variations in this share. In another study on 32 SA nations over the 1990–2015 period, Baye et al. (2021b) documented evidence of rising carbon dioxide emissions, technological innovation, and good governance being effective in enhancing the share of renewables in the energy consumption profiles of these nations while human capital development, economic globalization, and biomass consumption were identified as some of the key factors that reduce this share. Similarly, financial development through enhancing the share of private credit provided by financial institutions in the GDP of selected European Union member countries can be effective in increasing the share of renewable energy in total energy consumption profiles of these nations (Anton and Nucu, 2020). On the other hand, focusing on renewable energy production in the context of 17 SA countries from 1990 through 2014, da Silva et al. (2018) concluded that in order to increase the share of renewables in the aggregate electricity outputs these nations need to enhance their respective per capita national income level, reduce the share of imported energy in the total volume of energy consumed, mitigate carbon dioxide emissions, and curb the population growth rate.

Among the related studies on countries other than the SA nations, Mac Domhnaill and Ryan (2020) pointed out that concerns regarding carbon dioxide emissions-led environmental problems motivate the transition from non-renewable to renewable energy-based electricity output generation in the European Union. In an identical study on 27 post-socialist across Asia and Europe, Przychodzen and Przychodzen (2020) found that higher annual national income growth rate, unemployment rate, the share of government debt in the Gross Domestic Product (GDP), and carbon dioxide emissions increase the renewable electricity output shares while increments in total natural resource rents, coal rents, per capita carbon dioxide emissions inhibit these shares. Besides, the authors also found that compared to the era before the Kyoto Protocol was implemented in 2005, the shares of renewable electricity output are relatively higher in the post-implementation period. Khan et al. (2020) evaluated the determinants of both renewable and non-renewable energy shares in the total energy consumption levels of the Group of Seven (G7) countries. The results revealed that higher energy prices, human capital development, economic growth, trade openness, and eco-innovation increase renewable energy consumption shares while financial development reduces this share both in the short- and long run. Besides, the author also found that human capital development and technological innovation jointly enhance the renewable energy consumption shares in the G7 countries.

4. Empirical model and data

4.1. Empirical model

As per the objective of this current study of assessing the impacts of energy efficiency gains on energy sustainability in selected SA nations, a baseline model is constructed which can be shown below:

$$\textbf{Model 1}: ESI_{it} = \beta_0 + \beta_1 lnEE_{it} + \beta_2 YGR_{it} + \beta_3 CGR_{it} + \beta_4 TGI_{it} + \beta_5 FGI_{it} + \beta_6 FD_{it} + \beta_7 PGR_{it} + \beta_8 KP_{it} + \varepsilon_{it} \quad (1)$$

where the subscripts i and t stand for cross-sectional units and period, respectively. The parameters $\beta_j (j = 0, 1, \ldots, 8)$ are the intercept and elasticities to be predicted. The outcome variable ESI stands for the energy sustainability index which is used as a proxy for the level of energy sustainability within the selected SA nations. This index is constructed using the principal component analysis[3] technique by compiling data of four specific indicators of the progress towards the attainment of the SDG7 targets. These include (a) share of population having access to electricity, (b) renewable energy consumption share in total energy consumption, (c) renewable electricity output share in total electricity output, and (d) share of population having access to clean fuel and technology for cooking. Since higher shares of all these four variables indicate greater accessibility, availability, and affordability of reliable and clean energy resources, the energy sustainability index ranges from 0 (lowest degree of energy sustainability) to 100 (highest degree of energy sustainability).

Among the explanatory variables, lnEE stands for the natural logarithm of the energy use efficiency level of the respective SA nations which is given by the value of the national output per unit of energy resource consumed. Hence, a higher value of this ratio indicates greater efficiency at which energy is utilized. Given that energy efficiency improvement is hypothesized to be conducive to facilitating energy sustainability across the SA nations, the sign of the corresponding elasticity parameter can be expected to be positive ($\beta_1 > 0$). The variable YGR denotes the annual growth rate of per capita GDP which is considered as an indicator of the economic growth of the respective SA nations. Given the assumption that higher economic growth empowers a nation to achieve environmental sustainability, the sign of the corresponding elasticity parameter can also be expected to be positive ($\beta_2 > 0$). The variable CGR represents the annual growth rate of per capita carbon dioxide emissions which is considered as an indicator of environmental pollution. A rise in the volume of per capita carbon dioxide emissions is acknowledged in the literature as a deterioration in the quality of the environment (Ozcan and Ulucak, 2021). Since concerns arising from the aggravation of environmental quality are often associated with decisions to replace unclean energy usage with cleaner alternatives (Mac Domhnaill and Ryan, 2020), the corresponding elasticity parameter can be assumed to depict a positive sign as well ($\beta_3 > 0$).

The variable TGI stands for the trade globalization index which captures the degree of involvement of the SA nations in international trade (Gygli et al., 2019). This variable is included in the model to control for the impacts of international trade on energy sustainability. It is recognized in the literature that liberalizing trade barriers can be a mechanism of importing clean energy resources which can enhance the overall share of clean energy within the total energy consumption profile (Tortajada and Molden, 2021). Hence, the sign of the corresponding elasticity parameter is expected to depict a positive sign ($\beta_4 > 0$). Similarly, the variable FGI represents the financial globalization index of the respective SA nation which mostly takes into account the influx of foreign direct investments (Gygli et al., 2019). As a result, this variable is included in the model to identify the effect of foreign investments on energy sustainability across the selected SA nations. The justification behind the inclusion of this variable into the model is motivated from the point of view that influx of foreign direct investments can be expected to stimulate technological innovation that can enable the host countries to develop the clean energy sector to ensure energy sustainability (Grabara et al., 2021). As a result, the corresponding elasticity parameter is likely to depict a positive sign ($\beta_5 > 0$). Higher values of both the trade and financial globalization indices indicated greater degrees of economic globalization (Gygli et al., 2019) within the SA nations of concern.

The variable FD stands for financial development which is proxied by the share of private credit extended by banks in the GDP of the respective SA nation. A rise in the value of this share can be interpreted as the development of the financial sector (Saci et al., 2009). The relevance of including this variable in the model is based on the understanding that access to credit, loans, and microfinance can be effective in enhancing the affordability of end-users to consume and relaxing the financial constraints for producers to generate clean energy resources (Anton and Nucu, 2020; Przychodzen and Przychodzen, 2020). Therefore, the sign of the corresponding elasticity parameter is anticipated to be positive ($\beta_6 > 0$). The variable PGR denotes the annual population

[3] The details regarding the construction of the energy sustainability index are discussed in Section 4.2.

growth rate of the respective SA nation. It is important to include this variable since it has been acknowledged that a high rate of population growth worsens the clean energy access rates despite increasing the availability of clean energy resources (United Nations, 2020). In line with this notion, the sign of the corresponding elasticity parameter can be anticipated to depict a negative sign ($\beta_7 < 0$). Lastly, the variable KP is a time dummy variable that is included in the model to assess the effects of the Kyoto Protocol's implementation on energy sustainability. In this regard, following Przychodzen and Przychodzen (2020), the variable KP is assigned a value of 1 for the period spanning from 2005 to 2016 (since the Kyoto protocol came into effect in 2005) and a value of 0 for the preceding period. Since the implementation of the Kyoto Protocol is likely to influence the adoption of energy sustainability-related policies, the sign of the corresponding elasticity parameter is assumed to be positive ($\beta_8 > 0$).

Besides, to assess the possible role of energy efficiency improvement as a mediator between the impacts of economic growth on energy sustainability, the variable lnEE is interacted with the variable YGR and the interaction term is augmented into the baseline model as follows.

$$\textbf{Model 2}: \mathrm{ESI}_{it} = \partial_0 + \partial_1 \mathrm{lnEE}_{it} + \partial_2 \mathrm{YGR}_{it} + \partial_3 (\mathrm{lnEE}*\mathrm{YGR})_{it} + \partial_4 \mathrm{CGR}_{it} + \partial_5 \mathrm{TGI}_{it} + \partial_6 \mathrm{FGI}_{it} + \partial_7 \mathrm{FD}_{it} + \partial_8 \mathrm{PGR}_{it} + \partial_9 \mathrm{KP}_{it} + \varepsilon_{it} \quad (2)$$

where the variable lnEE∗YGR is the interaction term and the sign of the corresponding elasticity parameter (∂_3) would provide the joint impacts of these variables on energy sustainability within the SA nations of concern and also indicate whether or not energy efficiency gains can act as a mediator between economic growth and energy sustainability.

Both the models are estimated for the full panel of the 32 SA nations as well as for the sub-panels of low- and middle-income SA countries. In addition, the analysis is also conducted for two more sub-panels in which the selected SA nations are classified into two categories as per their performances in improving their respective energy efficiency levels from 2002 to 2016. One of these categories includes the SA countries that have managed to improve their energy efficiency level (i.e., the energy-efficient sub-panel) while the other contains the SA nations that have not been able to achieve energy efficiency improvement (i.e., the energy-inefficient sub-panel). The decision to conduct the analysis using sub-panels of the selected SA nations is driven by the objective of identifying the possible heterogeneity of the findings across these sub-panels.

4.2. Data

In this study, annual time series data from 2002 to 2016[4] is utilized for conducting the empirical analyses. Since clean energy-related data was unavailable beyond 2016, the study period could not be extended further. Besides, the data regarding all variables for the selected 32 SA nations were also unavailable before 2002; consequently, the sample of SA nations and the period of analysis was determined on the basis of data availability.

As mentioned earlier, the energy sustainability index is constructed using four vital indicators of progress towards achieving the energy sustainability targets of SDG7. The index is considered in this study since using individual indicators of energy sustainability may not precisely capture the true extent of energy sustainability across the SA nations of concern. For instance, considering the case of Burkina Faso, as per the latest available data, the percentage share of renewable energy in the nation's total final energy consumption figure is around 73%. Hence, this statistic suggests that the nation is well on course to achieving energy sustainability by undergoing renewable energy transition. However, this nation does not stand in such favorable positions considering other relevant energy sustainability indicators. Burkina Faso's electricity access rate, clean cooking fuel and technology access rate, and share of renewable electricity in the aggregate electricity output are merely 16%, 5.5%, and 9.35%, respectively. Hence, measuring this nation's energy sustainability performance solely based on the renewable energy consumption share or the other three indicators would not generate a comprehensive account of the status of energy unsustainability in this SA nation. Similar issues are witnessed for several of the other SA nations this study considers. Under such circumstances, the energy sustainability index constructed by considering all these four energy sustainability-related indicators is justified.

Table 2
Principal component analysis index of energy sustainability.

Principal component	Proportion explained		Cumulative		Eigenvalue
1	0.891		0.891		2.763
2	0.086		0.984		1.771
3	0.019		0.996		0.841
4	0.004		1.000		0.258
Indicators of SDG7 targets		**ATE**	**REC**	**RELECT**	**ACFT**
Factor loadings (Principal component 1)		0.592	0.725	0.961	0.982
Factor loadings (Principal component 2)		0.610	0.722	0.970	0.985
Kaiser–Meyer–Olkin (KMO)		0.822	0.771	0.702	0.700
Correlation with ESI		0.78	0.790	0.950	0.910

Note: ATE = access to electricity (% of the total population); REC = renewable energy consumption (% of total final energy consumption), RELECT = renewable electricity (% of total electricity output); ACFT = access to clean cooking fuel and technology (% of the total population); ESI = energy sustainability index.

Table 2 reports the outcomes from the principal component analysis involved in constructing the energy sustainability index. It can be seen that the first two principal components explain more than 98% of the total variations in the estimated energy sustainability index. Besides, the corresponding eigenvalues of these two components are over 1 whereby their significance can be confirmed. Since the explanatory powers of the third and fourth principal components are pretty low, we exclude them from the process of constructing the index. Furthermore, it is observed that all the four SDG7 indicators variables have high positive correlations with the energy sustainability index. Therefore, it can be claimed that the energy sustainability index is a good proxy of energy sustainability concerning these four vital SDG7 indicators.

Once the energy sustainability index is created using the principal component analysis, the goal post method of the United Nations is utilized for standardizing the indices and assigning them a range between 0 (lowest level of energy sustainability) and 100 (highest level of energy sustainability). Fig. 5 presents the average levels of energy sustainability index of the selected SA nations between 2010 and 2016. If we classify these nations in terms of their respective mean energy sustainability index scores, we can see that 15 of the selected SA nations have low levels of energy sustainability (i.e., having an energy sustainability index score of less than or equal to 33), 12 have medium levels of energy sustainability (i.e., having an energy sustainability index level of more than 33 and less than or equal to 67), and only 5 have high levels of energy sustainability (i.e., having an energy sustainability index level of more than 67). Hence, the overall poor state of energy sustainability across the SA nations is once again portrayed from these mean energy sustainability scores. Table 3 reports the units of the variables and the corresponding data source.

[4] The missing data issue is resolved by utilizing the linear interpolation technique.

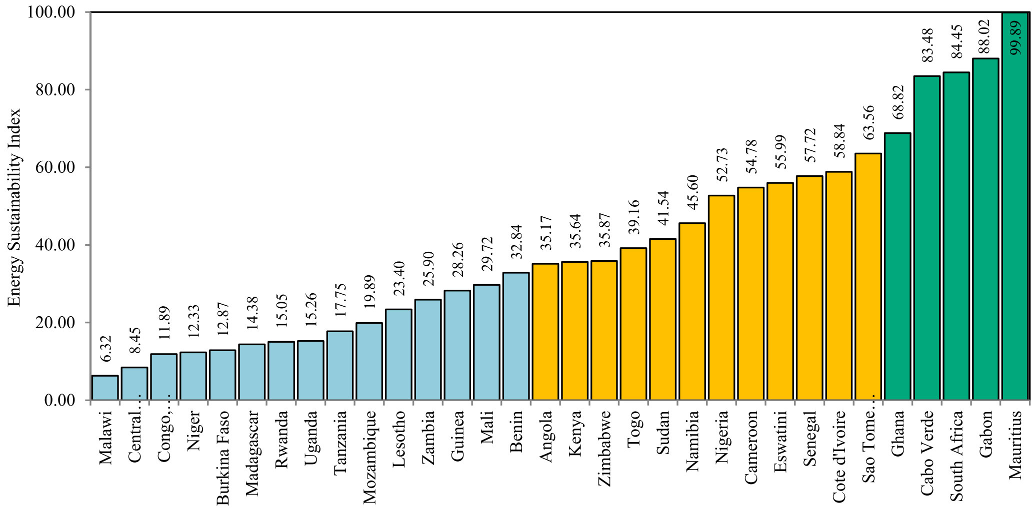

Fig. 5. The mean energy sustainability index scores (2010–2016). Note: The blue, orange, and green bars represent countries with low (≤33), medium (>33 & ≤67), and high (>67) levels of mean energy sustainability index between 2010 and 2016. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 3
Units and sources of data.

Symbol	Variable	Unit of measurement	Data source
ESI	Energy sustainability index	Index	Author's own estimation
EE	Energy efficiency	Constant 2011 PPP US$ per megajoules	Author's own estimation
YGR	Per capita real GDP growth rate		WDI (2021)
CGR	Per capita carbon dioxide emissions growth rate	Metric tonnes per capita	WDI (2021)
TGI	Trade globalization index	Index	Gygli et al. (2019)
FGI	Financial globalization index	Index	Gygli et al. (2019)
FD	Financial development (share of private sector credit provided by banks in GDP)	Percentage	WDI (2021)
PGR	Population growth rate	Percentage	WDI (2021)
KP	Dummy variable for implementation of Kyoto Protocol	Number	Author's own estimation

5. Estimation strategy

Firstly, a set of pre-estimation tests are performed to check whether or not there are issues of Cross-sectional Dependency (CD) and Slope Heterogeneity (SH) in the data. These two panel data problems have been recognized to compromise the unbiasedness and consistency of the unit root, cointegration, and regression outcomes (Sohag et al., 2017; Dong et al., 2020). It is always important to check for CD whenever we use panel data sets of regional countries since these countries are likely to be socioeconomically, geographically, and culturally integrated. As a result, a particular macroeconomic shock can be similarly weathered by a couple of the regional countries included in the panel data. Consequently, the CD issue can be anticipated to exist. In the same vein, the connections among the SA nations can also be assumed to contribute to CD concerns within the data set used in this study. To test for the existence of possible CD, the Pesaran (2004) method is employed in this study.

This method is a simple error-correction-based technique that checks for possible CD utilizing average pairwise correlation coefficients of the ordinary least squares residuals derived from the conventional Dickey–Fuller (Dickey and Fuller, 1979) regression analysis of each series (Munir et al., 2020). Considering an example of the pairwise correlation coefficients of the ordinary least squares residuals, the Pesaran (2004) CD test statistic can be derived as follows:

$$\hat{\varphi}_{ij} = \hat{\varphi}_{ji} = \frac{\sum_{t=1}^{T} e_{it} e_{ji}}{\left(\sum_{t=1}^{T} e_{it}^2\right)^{1/2} \left(\sum_{t=1}^{T} e_{t}^2\right)^{1/2}} \tag{3}$$

where $\hat{\varphi}_{ij}$ is the estimated pairwise correlation coefficients and e_{it} stands for the ordinary least square residuals for the *i*th cross-sectional unit. From Eq. (3), the Pesaran (2004) CD test statistic is predicted as follows:

$$\text{CD stat.} = \sqrt{\frac{2T}{N(N-1)} \left(\sum_{t=1}^{N-1} \sum_{j=i+1}^{N} \hat{\varphi}_{ij} \right)} \rightarrow N(0, 1) \tag{4}$$

where *N* and *T* refer to the number of cross-sectional and time dimensions, respectively; the CD test statistic is said to follow a standard normal distribution and assumes a null hypothesis of cross-sectional independence of the series. Hence, rejection of the null hypothesis affirms the issue of CD in the data. The corresponding results from the Pesaran (2004) CD analysis are reported in Table 4. The results reveal that in the cases of all five panels there are CD issues since the predicted test statistics are evidenced to be statistically significant whereby the null hypothesis of the CD test statistic is rejected. This finding is expected given the socioeconomic, geographic, and cultural integration among the SA nations and also due to these nations belonging to common income groups and energy efficiency performance-related categories. However, despite these connections, several country-specific attributes may exist which can lead to the other crucial issue of SH. Hence, the SH analysis is ten carried out.

To test whether the problem of SH exists, the Pesaran and Yamagata (2008) test of slope homogeneity is implemented. This test helps to identify the heterogeneous characteristics of different cross-sectional units within a panel data set. Based on the model employed by Swamy (1970), Pesaran and Yamagata (2008) introduced an adjusted version of that model to predict

Table 4
Results from Pesaran (2004) CD test.

Null hypothesis: CD does not exist					
Panel	Full	Low-income	Middle-income	Energy efficient	Energy inefficient
Variable					
ESI	31.011***	4.492***	12.698***	18.759***	3.904**
lnEE	2.161**	1.859*	1.906*	9.433***	4.426***
YGR	2.566**	2.650**	4.600***	3.285***	1.695*
CGR	2.650**	1.100	1.832*	1.322	1.436
TGI	3.380***	3.105**	5.610***	1.875*	2.378**
FGI	6.936***	1.200	4.496***	5.282***	1.910*
FD	7.205***	3.300**	1.744*	2.995***	1.117
PGR	3.173**	1.400	4.185***	1.730*	1.788*

Note: ***, **, & * denotes statistical significance at 1%, 5%, & 10% level, respectively.

Table 5
The results from Pesaran and Yamagata (2008) slope homogeneity test.

Null hypothesis: Homogeneous slope coefficients				
Panel	Model (1)		Model (2)	
	Δ-tilde stat.	$\Delta_{adj.}$–tilde stat.	Δ-tilde stat.	$\Delta_{adj.}$–tilde stat.
Full	1.719**	2.150***	3.209***	3.770***
Low-income	3.250***	3.504***	4.114***	4.205***
Middle-income	2.305***	2.401***	2.850***	3.010***
Energy efficient	1.857**	2.208***	3.556***	3.509***
Energy inefficient	3.101***	3.205***	4.440***	4.680***

Note: *** and ** denote statistical significance at 1% and 5% level, respectively.

a standardized dispersion test statistic as follows:

$$\widehat{\Delta_{\text{adj.}}} = \sqrt{N}\left[\frac{N^{-1}\bar{S} - E(\bar{Z}_{it})}{\sqrt{var(\bar{Z}_{it})}}\right] \tag{5}$$

where $\widehat{\Delta_{\text{adj.}}}$ is the adjusted version of Swamy's (1970) $\hat{\Delta}$ statistic. Both these test statistics consider the null hypothesis of the slope coefficients to be homogeneous across all cross-sectional units. Thus, the rejection of these test statistics would affirm the issue of SH in the data. Table 5 reports the outcomes from the Pesaran and Yamagata (2008) analysis. It can be clearly observed that the test statistics in the context of all five panels are statistically significant; thus, implying that there are SH issues in the data. This is also an anticipated finding since the SA nations not only differ in terms of their respective income group but there is also a great deal of difference in terms of their energy sustainability statuses (shown by the respective energy sustainability index scores) and energy efficiency levels. Since both CD and SH problems have been identified, the econometric techniques that can address these issues are then employed.

Secondly, following the pre-estimation tests, the panel unit root analysis is conducted to evaluate whether or not the variables considered in this study are stationary/integrated. The outcomes from the unit root analysis reveal the integrating order among the variables which is needed to design the appropriate panel regression technique; moreover, the stationarity of the variables is also imperative to avoid estimation of spurious regression findings (Dauda et al., 2021). Since there is CD in the data, the Cross-sectionally adjusted Augmented-Dickey Fuller (CADF) and the cross-sectionally adjusted Im–Pesaran–Shin (CIPS) methods are employed. These techniques were introduced by Pesaran (2007) which accounted for the limitations of the cross-sectionally unadjusted versions which do not take the issue of CD into consideration. Both these methods predict test statistics considering a general model as shown below:

$$\Delta Z_{it} = \alpha_i + \beta_i X_{it-1} + \beta_i \bar{Z}_{t-1} + \sum_{j=1}^{n} \varnothing_{ij} \Delta \bar{Z}_{i,t-j} + \sum_{j=1}^{n} \varnothing_{ij} \Delta Z_{i,t-j} + \mu_{it} \tag{6}$$

where Z refers to the particular series for which the unit root property is being tested, Δ is the difference operator, α_i stand for the individual intercepts, and the time trend is denoted by X (Haseeb et al., 2018). $\bar{Z}_{t-1}$ $\Delta\bar{Z}_{t-1}$ are the cross-sectional means. From Eq. (6), the CIPS test statistic is estimated based on ordinary least squares regression outcomes with t-ratio and can be expressed as:

$$\text{CIPS stat.} = N^{-1}\sum_{i=1}^{n} CADF_i \tag{7}$$

where $CADF_i$ refers to the CADF test statistic corresponding to the *i*th cross-sectional unit in Eq. (6). Both the CADF and CIPS test statistics are predicted considering the null hypothesis of the series being non-stationary. Hence, rejection of these test statistics would affirm the stationarity of the series.

Once the unit root analysis is implemented, the panel cointegration analysis is performed to check whether or not there are long-run relationships between the outcome and explanatory variables. Conducting the cointegration analysis is pertinent because it is believed that without the presence of cointegration among the variables, it is pointless to predict the long-run regression outcomes (Jamil et al., 2021). In this study, the Westerlund (2007) technique is utilized to evaluate the possible long-run associations amid the variables since it controls for both CD and SH concerns within the data (Boukhelkhal, 2021). The issue of CD is accounted for within the cointegration estimation procedure with the help of a bootstrapped approach. This technique is based on an error-correction model setup and predicts four test statistics namely Gt, Ga, Pt, and Pa. The test statistic Gt checks for cointegration among the variables between groups while Ga checks for it among the groups. On the other hand, the test statistic Pt checks for cointegration between panels and Pa checks for it among panels (Dauda et al., 2021). The null hypothesis assumptions of these test statistics are also different in the sense that the Ga and Gt test statistics assume the null hypothesis of no cointegration in all cross-sectional units but consider an alternative hypothesis of cointegration in at least one cross-sectional unit. In contrast, the Pa and Pt test statistics consider the null hypothesis of no cointegration and the alternative hypothesis of cointegration in

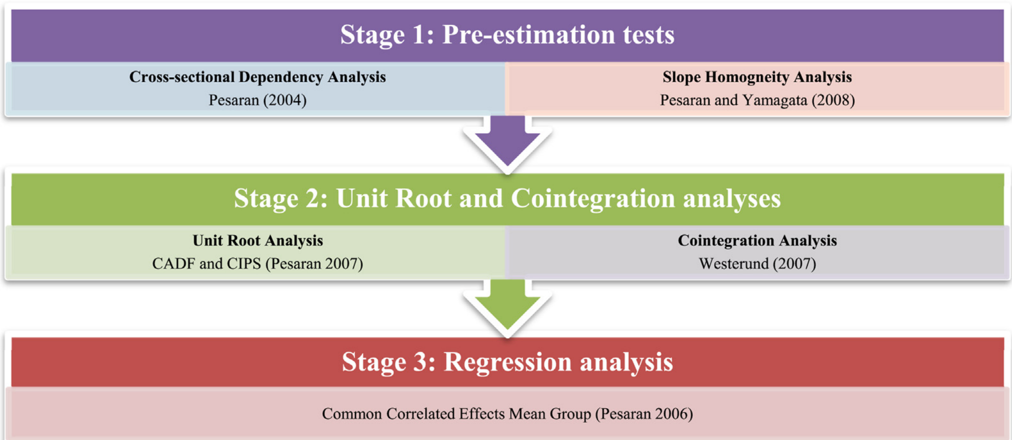

Fig. 6. A flowchart of the estimation strategy.

all cross-sectional units. The four test statistics can be expressed as follows:

$$\mathrm{Gt} = \frac{1}{\mathrm{N}} \sum_{\mathrm{i}=1}^{\mathrm{N}} \frac{\alpha_{\mathrm{i}}'}{\mathrm{SE}\left(\alpha_{\mathrm{i}}'\right)} \tag{8}$$

$$\mathrm{Ga} = \frac{1}{\mathrm{N}} \sum_{\mathrm{i}=1}^{\mathrm{N}} \frac{\mathrm{T}\alpha_{\mathrm{i}}'}{\alpha_{\mathrm{i}}'(1)} \tag{9}$$

$$\mathrm{Pt} = \frac{\alpha_{\mathrm{i}}'}{\mathrm{SE}\left(\alpha_{\mathrm{i}}'\right)} \tag{10}$$

$$\mathrm{Pa} = \mathrm{T}\alpha_{\mathrm{i}}' \tag{11}$$

where α_i' is the error-correction term. Once the integration and cointegration properties are determined, the panel regression analysis is performed.

Finally, this study utilizes a second-generation panel regression method that is robust to handling both CD and SH issues in the data. The first-generation methods either do not account for these panel data issues or focus only on the CD concern while overlooking the SH issue. However, failure to address these two issues simultaneously leads to the estimation of biased regression outcomes (Le and Sarkodie, 2020). Therefore, the Common Correlated Effects Mean Group (CCEMG) panel data regression technique of Pesaran (2007) is used which is efficient in handling cross-sectionally dependent heterogeneous panel data sets (Kapetanios et al., 2011). An additional benefit of this technique is its ability to handle endogeneity issues in the data (Damette and Marques, 2019). Endogeneity concerns within the model should be accounted for since it contributes to the prediction of inconsistent and biased outcomes. Although the mean group estimator of Pesaran and Smith (1995) has been used in the preceding studies, this method despite controlling for heterogeneous slope coefficients does not handle the CD issue. Thus, the CCEMG method is more appropriate in the context of this study. Related to the baseline model considered in this study (i.e., Model 1), the CCEMG model can be specified as follows:

$$\mathrm{ESI}_{\mathrm{it}} = \vartheta_{\mathrm{i}} + \varnothing_{\mathrm{i}}\mathrm{X}_{\mathrm{it}} + \mu_{\mathrm{i}}\mathrm{f}_{\mathrm{i}} + \rho_{\mathrm{i}}\widehat{\mathrm{ESI}}_{\mathrm{it}} + \tau_{\mathrm{i}}\hat{\mathrm{X}}_{\mathrm{it}} + \mathrm{e}_{\mathrm{it}} \tag{12}$$

where ESI_{it} is a vector of the dependent variable (energy sustainability index), X_{it} is a vector of the independent variables (energy efficiency, economic growth rate, carbon dioxide emission rate, trade and financial globalization indices, financial development, population growth rate, and dummy variable for Kyoto Protocol implementation), ϑ_i is the intercept, $\varnothing_i$ are the slope coefficients for the respective cross-sections (i.e., the individual SA countries), f_i refers to the unobserved common properties with the non-homogeneous variations, and e_{it} refers to the error-term. From this equation, the CCEMG estimator is predicted as the mean of the slope coefficients of the respective cross-section for each individual regression analysis:

$$\gamma_{\mathrm{CCEMG}} = \mathrm{N}^{-1} \sum_{\mathrm{i}=1}^{\mathrm{N}} \hat{\varnothing}_{\mathrm{i}} \tag{13}$$

Fig. 6 illustrates the estimation strategy followed in this study in the form of a flow chart diagram.

6. Empirical results and discussions

The outcomes from the CADF and CIPS unit root analyses are presented in Table 6. The results indicate that for the cases of all five panels the test statistics, for both the unit root estimation methods, are statistically significant at the first difference. Thus, the null hypothesis of non-stationarity is rejected at the 1% and 5% significance levels. In light of these findings, it can be asserted that all variables converge to their mean values and have a common integration order of I(1). Since all variables across all five panels are found to be stationary, there is no possibility of predicting spurious regression outcomes. Following the unit root analysis, the panel cointegration analysis is performed.

The findings from the Westerlund (2007) cointegration analysis are reported in Table 7. It is evident that for all five panels, there is the existence of at least one cointegrating equation within both models 1 and 2. The statistical significance of the predicted test statistics (Ga, Gt, Pa, and Pt) supports this statement by rejecting the null hypothesis of no cointegrating relationship among the variables in the respective model. Hence, these findings imply that energy sustainability in the SA nations has long-run associations with energy efficiency gains, economic growth, carbon dioxide emissions growth, trade and financial globalization, financial development, population growth, and the implementation of the Kyoto Protocol. As a result, the pre-requisite to predicting the long-run elasticities is fulfilled whereby the regression analysis follows.

The long-run marginal impacts of the explanatory variables on energy sustainability across the selected SA nations are predicted using the CCEMG estimator and corresponding results, in the context of the full, low-income, and middle-income panels, are reported in Table 8. The results show that making efficient use of energy can be a means of achieving energy sustainability irrespective of the respective income group of the SA nations.

Table 6
The results from panel unit root analysis.

Null hypothesis: Non-stationarity										
Cross-sectionally adjusted Augmented Dickey–Fuller (CADF) outcomes										
Panel	Full		Low-income		Middle-income		Energy efficient		Energy inefficient	
Variable	I(0)	I(1)	I(0)	I(1)	I(0)	I(1)	I(0)	I(1)	I(0)	I(1)
ESI	−1.445	−2.840***	−0.548	−3.192***	−1.402	−3.087***	−1.343	−2.875***	−0.550	−3.575***
lnEE	−1.228	−2.262***	−1.610	−2.693***	1.610	−2.535***	−1.453	−2.595***	−1.430	−2.535***
YGR	−1.272	−3.009***	−1.854	−3.098***	−1.011	−2.750***	−1.588	−2.920***	−1.617	−3.339***
CGR	−0.911	−3.440***	−1.233	−2.808***	−0.811	−3.669***	−1.343	−3.595***	−1.872	−2.693***
TGI	−1.269	−2.611***	−0.254	−2.895***	−1.722	−3.012***	−1.066	−2.616***	−1.560	−3.052***
FGI	−1.556	−2.531***	−0.660	−2.459***	−1.836	−2.304***	−1.582	−2.222**	−0.944	−2.667***
FD	−1.754	−2.881***	−1.366	−2.756***	−1.533	−3.247***	−1.305	−2.390***	−1.846	−2.498**
PGR	−1.735	−2.503***	−1.712	−2.367***	−1.209	−3.026***	−1.981	−2.313***	−0.523	−4.939***
Cross-sectionally adjusted Im–Pesaran–Shin (CIPS) outcomes										
Panel	Full		Low-income		Middle-income		Energy efficient		Energy inefficient	
Variable	I(0)	I(1)	I(0)	I(1)	I(0)	I(1)	I(0)	I(1)	I(0)	I(1)
ESI	−1.730	−4.583***	−1.555	−4.923***	−1.586	−4.059***	−1.980	−4.568***	−2.133	−4.526***
lnEE	−1.841	−3.008***	−1.868	−3.044***	−1.996	−3.229***	−1.392	−3.595***	−1.732	−2.935***
YGR	−1.850	−4.863***	−1.448	−4.878***	−1.715	−4.862***	−1.238	−4.671***	−1.782	−4.968***
CGR	−1.123	−3.105***	−1.982	−4.821***	−1.147	−5.060***	−1.235	−4.728***	−1.601	−4.862***
TGI	−1.818	−3.611***	−1.508	−3.827***	−1.697	−3.520***	−1.622	−3.499***	−2.004	−3.675***
FGI	−1.587	−3.784***	−1.604	−4.073***	−1.787	−3.439***	−1.690	−3.751***	−2.117	−3.504***
FD	−1.314	−3.215***	−2.042	−3.343***	−1.045	−2.323**	−1.983	−3.402***	−2.137	−3.160***
PGR	−1.047	−3.231***	−0.732	−2.302**	−0.984	−3.326***	−0.793	−2.356***	−1.484	−4.084***

Note: I(0) stands for Level and I(1) stands for first difference; The test statistics are predicted by considering trend; The optimal lags section is based on Bayesian Information Criterion (BIC); *** & ** denote statistical significance at 1% & 5% level, respectively.

Table 7
The results from the Westerlund (2007) cointegration analysis.

Null hypothesis: No cointegrating relationship						
Panel	Model	Ga	Gt	Pa	Pt	Decision
Full	(1)	−3.201***	−4.465	−6.155**	−4.230*	Cointegration
	(2)	−3.270***	−4.890	−7.805***	−6.450**	Cointegration
Low-income	(1)	−2.247***	−5.190	−10.300***	−7.450**	Cointegration
	(2)	−2.340***	−5.201	−12.230***	−7.760**	Cointegration
Middle-income	(1)	−2.980***	−5.380	−6.780***	−7.101**	Cointegration
	(2)	−2.810***	−5.105	−6.666***	−6.150*	Cointegration
Energy efficient	(1)	1.520	−3.520	−1.575*	−3.212*	Cointegration
	(2)	1.221	−3.220	−1.500*	−2.850*	Cointegration
Energy inefficient	(1)	−2.990***	−10.980***	−18.140**	−8.120**	Cointegration
	(2)	−3.140***	−11.230***	−21.150**	−8.888**	Cointegration

Note: The optimal lags section is based on BIC; ***, ** and * denote statistical significance at 1%, 5%, and 10% significance levels, respectively; the test statistics (Ga, Gt, Pa, and Pt) are estimated using 4000 bootstrapped replications.

However, it is evident that the positive impacts of energy efficiency improvement on energy sustainability are relatively larger for the middle-income SA nations. One of the possible reasons behind this finding could be due to the fact that in 2016 the average energy efficiency level of the middle-income SA countries is 1.25times higher than that of the low-income SA countries. Hence, it can be said that the higher the level of energy efficiency, the greater the possibility for the SA nations to achieve energy sustainability. These results support the findings reported in the preceding study by Li et al. (2020) in which the authors asserted that energy efficiency improvement can trigger renewable energy transition by increasing the share of renewables in the total energy consumption figures of selected OECD countries. Similarly, Al-Tal et al. (2021) recently concluded that energy efficiency gains can ultimately improve access to clean cooking fuel and technology across the SA region. Furthermore, Kohler (2014) remarked that low industrial energy efficiency has pinned down electricity access across the SA nations.

On the other hand, the results also highlight the detrimental effects of economic growth on energy sustainability, especially within the low-income SA nations. This is an expected finding because the majority of the SA nations considered in this study have traditionally been hugely dependent on fossil fuels to meet their own demand for energy. Among the 32 SA countries considered in this study, 18 of these nations generated more than 50% of their respective electricity output using non-renewable resources in 2016 (WDI, 2021). As a result, it can be assumed that these nations, in order to expedite their economic growth rates, have preferred utilizing both local and imported fossil fuel-generated electricity and have not emphasized the need of undergoing a clean energy transition. Besides, it has been established in the literature that the economic growth of the SA nations is largely driven by the consumption of unclean fossil fuels (Kebede et al., 2010). The finding of a higher economic growth rate inhibiting the prospects of attaining energy sustainability corroborate the assertions made in the existing study by Murshed (2020a) which concluded that economic growth initially reduces and eventually enhances the share of renewables in the total energy consumption figures of low- and middle-income countries across the globe, including the ones from the SA region as well. Accordingly, it can be presumed that the majority of the SA nations considered in this study are yet to attain the required level of per capita annual economic growth rate that can economically empower them to achieve energy sustainability by transitioning from traditional unclean to modern cleaner energy resources and improving electrification rates.

Table 8
The results from the CCEMG analysis for the full and income group-wise panels.

Dependent variable: ESI						
Panel	Full		Low-income		Middle-income	
Regressors	Model 1	Model 2	Model 1	Model 2	Model 1	Model 2
lnEE	10.735***	10.79***	1.182***	1.230***	16.106***	17.653***
	(2.322)	(2.459)	(0.201)	(0.325)	(3.385)	(3.227)
YGR	−0.156***	−0.179***	−0.299***	−0.293***	−0.168***	−0.181***
	(0.029)	(0.048)	(0.085)	(0.087)	(0.029)	(0.049)
(lnEE∗YGR)		0.962***		0.293***		1.402***
		(0.279)		(0.042)		(0.242)
lnCGR	0.041***	0.040***	−0.038***	−0.041***	0.155***	0.177***
	(0.014)	(0.014)	(0.006)	(0.006)	(0.008)	(0.009)
TGI	−0.157***	−0.161***	−0.286***	−0.271***	−0.398***	−0.366***
	(0.026)	(0.028)	(0.013)	(0.017)	(0.017)	(0.013)
FGI	0.473***	0.472***	0.170	0.164	0.303***	0.289***
	(0.019)	(0.019)	(0.192)	(0.153)	(0.015)	(0.014)
FD	0.683***	0.684***	0.655***	0.641***	0.608***	0.600***
	(0.017)	(0.018)	(0.015)	(0.022)	(0.007)	(0.007)
POPG	−0.905***	−0.918***	−2.098***	−1.986***	−0.991***	−1.042***
	(0.295)	(0.295)	(0.135)	(0.163)	(0.193)	(0.171)
KP	3.634***	3.653***	3.335***	3.222***	5.234***	4.928***
	(0.444)	(0.439)	(0.121)	(0.226)	(0.416)	(0.514)
Constant	26.270***	26.590***	7.991***	4.549***	60.982***	64.292***
	(1.232)	(1.334)	(0.500)	(0.806)	(0.901)	(1.125)
RMSE	0.026	0.021	0.017	0.022	0.019	0.025
Wald Statistics	40.340	65.401	33.190	60.604	41.130	39.450
Observations	480	480	195	195	285	285
Number of ids	32	32	13	13	19	19

Note: *** and ** denote statistical significance at 1% and 5% levels, respectively; the standard errors are reported within the (); RMSE refers to the root mean square error which indicates the residual size of the respective model.

However, a very interesting finding in this study is that the estimates in the context of model 2 statistically certify the mediating role energy efficiency can play to neutralize the adverse effects on economic growth on energy sustainability. The positive signs of the statistically significant regression parameters imply that energy efficiency gains and economic growth jointly contribute to energy sustainability with the selected SA nations. Once again we see that the joint impact is relatively larger for the middle-income SA nations which can also be accredited to the comparatively higher energy efficiency levels of these nations. Besides, these marginal joint impacts on the energy sustainability index are witnessed to be comparatively larger than the corresponding marginal negative marginal impacts of economic growth on the energy sustainability index; thus, highlighting the mediatory effect of energy efficiency improvement. These results are crucial from the perspective that they highlight that if the SA nations can manage to significantly improve their respective energy efficiency levels, they no longer have to be apprehensive regarding the adverse effects of economic growth on energy sustainability. Thus, energy efficiency improvement not only has a direct role but also has an indirect role to play in respect of enabling the selected SA nations to achieve the energy sustainability-related targets of SDG7 by the end of 2030.

Among the other relevant findings this study has to offer, the aggravation of environmental quality due to a rise in the annual carbon dioxide emissions growth rate is found to stimulate energy sustainability across the selected SA nations. However, this finding is not homogenous across the findings from the panels of low and middle-income SA nations. The results show that environmental degradation although stimulating energy sustainability within the middle-income SA countries is not effective in inducing energy sustainability amid the low-income SA nations. Since the yearly per capita carbon dioxide emission figures of the low-income SA nations were on average 7.5 times less than that of the middle-income SA nations in 2016 (WDI, 2021), it can be asserted that the relatively poor SA nations are yet to be apprehensive and concerned about the aggravation of environmental quality. In contrast, the significantly higher levels of per capita carbon dioxide emission figures of the middle-income SA nations are likely to have instigated the urgency to undergo a clean energy transition by the implementation of policies to achieve energy sustainability. Similar findings were reported in the study by Mac Domhnaill and Ryan (2020) where the authors concluded that rising environmental problems associated with higher carbon dioxide emissions motivate the European nations to enhance the share of renewable electricity in the total electricity output. Besides, similar environmental concerns were also claimed to enhance clean cooking fuel and technology access rates across South Asia (Murshed, 2018).

Regarding globalization, it is seen that greater trade globalization does not induce energy sustainability within the selected SA nations, overall, and this finding is also homogeneous across the cases of the low- and middle-income SA nations. These findings, alongside traditional fossil fuel dependency in most of the SA nations, indicate that participation in international trade is likely to have encouraged these nations to specialize in the production of unclean fuel-intensive production processes and thereby become net exporters of the related commodities. As a result, these nations have not managed to implement credible energy sustainability policies that could have enabled them to go through a clean energy transition. Contrasting findings have been documented by Khan et al. (2020) and Zhang et al. (2021) for the G7 and OECD nations, respectively. The contradictory findings are likely to be due to the fact that the SA nations are mostly developing countries as opposed to the G7 and OECD nations that are relatively more developed than the SA nations. Hence, these findings support the earlier findings of economic growth exerting unfavorable energy sustainability outcomes across the SA nations. Moreover, since the developed countries have stricter environmental laws, international trade may not lead to the expansion of the unclean fuel-intensive industries; rather, the stringent environmental regulations in these countries can also be expected to inhibit unclean energy use while promoting the use of cleaner alternatives. However, this is not the case for the SA nations since their environmental rules are neither strong nor effective (Mkandawire and Arku, 2009; Asongu and Odhiambo, 2021).

Table 9
The results from the CCEMG analysis for the energy-efficient and inefficient panel.

Dependent variable: ESI				
Panel	Energy efficient		Energy inefficient	
Regressors	Model 1	Model 2	Model 1	Model 2
lnEE	11.620***	7.740***	−1.070**	−1.650**
	(0.365)	(0.404)	(0.433)	(0.779)
YGR	1.321***	1.445**	−0.202**	−0.354**
	(0.325)	(0.762)	(0.098)	(0.171)
(lnEE∗YGR)		0.726***		0.104
		(0.040)		(0.100)
lnCGR	0.368***	0.315***	−0.172***	−0.175***
	(0.065)	(0.078)	(0.047)	(0.047)
TGI	−0.347***	−0.360***	−0.125**	−0.120**
	(0.019)	(0.014)	(0.060)	(0.056)
FGI	3.219***	3.232***	−0.284**	−0.304**
	(0.813)	(0.817)	(0.130)	(0.151)
FD	0.815***	0.825***	0.087	0.087
	(0.019)	(0.018)	(0.067)	(0.060)
PGR	−2.583***	−2.420***	−5.186***	−5.180***
	(0.250)	(0.225)	(0.704)	(0.724)
KP	2.021***	2.019***	0.223	0.294
	(0.279)	(0.198)	(0.316)	(0.317)
Constant	50.979***	43.372***	−76.683***	−78.418***
	(1.563)	(1.775)	(6.633)	(6.636)
RMSE	0.031	0.021	0.027	0.022
Wald Statistics	35.160	49.550	60.130	40.409
Observations	360	360	120	120
Number of ids	24	24	8	8

Note: *** and ** denote statistical significance at 1% and 5% levels, respectively; the standard errors are reported within the (); RMSE refers to the root mean square error which indicates the residual size of the respective model.

Now turning the focus onto the financial aspect of globalization, the results reveal that financial globalization, overall, promotes energy sustainability within the selected SA nations. However, the income group-based analysis reveals that financial globalization is energy sustainability-inducing only in the case of the middle-income SA economies. Therefore, these findings, alongside taking into consideration the potential technological spillover effects associated with the cross-border flows of foreign direct investments, the middle-income SA nations have probably attracted clean foreign direct investments that could have helped these nations to develop the relevant technologies needed for enhancing electricity access, increasing clean cooking fuel and technology access, and raising the shares of renewables in the total final energy consumption and electricity output figures. Similar findings can be compiled from the existing study by Doytch and Narayan (2016) in which the authors highlighted the importance of foreign direct investment inflows to boost renewable energy use. Besides, Wall et al. (2019) also emphasized the role of attracting relevant foreign direct investments for promoting renewable energy transition.

It is also observed that financial development is effective in driving energy sustainability within the SA nations. Besides, this finding is robust across the low- and middle-income SA countries' panels as well. Therefore, it can be assumed that higher access to credit for the private sector acts as a means of reducing the financial constraints that often inhibit the transition from the use of unclean to clean energy. Besides, the availability of microfinance has also been recognized to enhance the affordability of cleaner cooking fuels amid SA households since these modern cooking fuels are relatively more expensive than the traditional ones (Stevens et al., 2020; Hsu et al., 2021). Further, the favorable role of financial development on energy sustainability was also supported in the study by Anton and Nucu (2020) in which the authors remarked that enhancing provision for private sector credit helps to raise the share of renewables in the total final energy consumption levels of European nations.

Moreover, the results also reveal that a higher population growth rate inhibits the prospects of achieving energy sustainability across the elected SA nations. Besides, compared to the middle-income SA nations, a higher population growth rate exerts relatively higher energy sustainability-impeding impacts for the cases of the low-income SA nations. These findings are also expected from the understanding that if the size of the population grows too fast, it is likely that the overall access to electricity and clean cooking fuels, despite enhancing the levels of electricity output and clean cooking fuel and technology access rate, would decline. Similar conclusions were put forward in the study by da Silva et al. (2018) in which the authors highlighted the importance of reducing the annual population growth rate of selected SA nations in order to increase their renewable electricity output shares. Besides, the United Nations has also reported that despite increasing the availability of clean cooking fuels, the high growth rate of the population worsens the clean cooking fuel access rates across the SA region (United Nations, 2020).

Lastly, the regression outcomes in this current study certify that the ratification of the Kyoto Protocol has encouraged the SA nations to execute relevant policies to achieve energy sustainability. The corresponding estimates show that compared to the period before the Kyoto Protocol came into effect in 2005, the probability of attaining energy sustainability is relatively higher for the 2005–2016 period. This finding corroborates the results documented by Przychodzen and Przychodzen (2020) in the context of selected European countries. Furthermore, the favorable outcomes of the Kyoto Protocol in respect of the attainment of energy sustainability are also supported by the statistics that the average electricity and clean cooking fuel and technology access rates of the SA nations during the period after the Kyoto Protocol came into effect were around 8 and 3.5 percentage points higher than the corresponding rates during the period before the Kyoto Protocol was implemented (WDI, 2021). However, it is to be noted that following the implementation of the Kyoto Protocol, the average shares of renewables in total final energy consumption and electricity output levels of the SA nations have rather declined (WDI, 2021).

Since it was evidenced from the previous findings reported in Table 8 that energy efficiency gains play a major role in facilitating energy sustainability within the SA nations, it would be interesting to see whether these findings vary across energy efficient and energy inefficient groups of SA nations. To this end, we classify the selected SA nations into two categories based on the changes in their average energy efficiency levels over the 2002–2016 period. The SA nations that have managed to improve their levels of energy use efficiency are categorized as energy-efficient while the other SA nations are classified as energy-inefficient since their mean energy efficiency levels have declined during this period. The corresponding outcomes from the CCEMG analysis on the energy-efficient and inefficient SA panels are reported in Table 9.

It can be seen that energy efficiency gains stimulate energy sustainability only in the context of the energy-efficient panel but not in the case of the energy-inefficient panel of SA nations. This statement is affirmed by the positive and negative signs of the statistically significant elasticity parameters attached to the variable lnEE for the energy-efficient and energy inefficient panels, respectively. Besides, economic growth is also evidence to exert energy sustainability-enhancing effects for the energy-efficient panel while impeding energy sustainability for the case of the energy-inefficient panel. Furthermore, energy efficiency improvement performs a mediating role by interacting with economic growth to jointly facilitate energy sustainability only in the context of the energy-efficient panel of SA nations. Therefore, these contrasting findings indicate two major points. First, the SA nations that have not strived to improve their energy use efficiency levels over the study period are most likely to be more concerned about the development of their respective economies by utilizing the traditional energy resources. This is also supported by the statistics that on average in 2016 the energy efficiency level of the SA countries belonging to the energy-efficient panel was 1.5 times higher than that of the SA nations included in the energy-inefficient panel (WDI, 2021). Second, these findings support the earlier finding of energy efficiency improvement being more effective in stimulating energy sustainability in the middle-income SA nations compared to the effect in the low-income SA nations. In the same vein, since the average per capita real GDP level of the energy-efficient SA nations is comparatively higher than that of the energy-inefficient SA nations, it can be once again be understood that energy efficiency improvement is more effective in fostering energy sustainability in the relatively richer SA nations.

Besides, significant opposing impacts of higher carbon dioxide emissions growth rates, financial globalization, financial development, Kyoto Protocol implementation on energy sustainability are also witnessed across the energy-efficient and energy inefficient panels of SA nations. For instance, while higher carbon dioxide emission-induced adversities stimulate energy sustainability for the case of the energy-efficient SA panel, the same cannot be established for the energy-inefficient panel of SA nations. This finding is further supported by the result that the implementation of the Kyoto Protocol is efficient in driving energy sustainability only in the case of the energy-efficient SA nations. These imply that the SA nations in which the energy efficiency levels have declined between 2002 and 2016 are yet to be motivated to undergo the switch from unclean traditional to clean modern energy and to enhance their electricity access rates. These contrasting phenomena can probably be explained by the differences in the per capita level and growth rate of carbon dioxide emissions across the groups of energy-efficient and energy inefficient SA countries. It is important to note that the average growth rate of per capita carbon dioxide emissions and the corresponding level of per capita CO2 emissions in 2016 were significantly higher for the energy-efficient SA nations (WDI, 2021). AS a result, the relatively greater environmental adversities in these countries must have encouraged them to adopt energy sustainability-enhancing policies. In contrast, the energy-inefficient SA nations are likely to be waiting for their environmental problems to go up before they turn to the adoption and implementation of similar policies to achieve energy sustainability.

On the other hand, the results reported in Table 9 show that financial development induces energy sustainability only in the energy-efficient SA nations. Hence, it can be assumed that the credit facilities provided to the private sectors of these countries are likely to have been invested in enhancing electricity access rates and financing clean energy production and consumption-related activities. Besides, the mean share of private sector credit provided by financial institutions in the GDP of the energy-efficient SA countries, in 2016, was almost double that of the energy-inefficient SA nations (WDI, 2021). Therefore, it is evident that the financial sectors of the SA nations belonging to the energy-efficient category are comparatively more developed than those belonging to the energy inefficient SA countries' category. As a result, the financial development differentials across these two groups can further explain why financial development cannot influence energy sustainability within the energy-inefficient SA nations.

As far as the effects of financial globalization are concerned, it is evidenced that financial globalization facilitates energy sustainability within the energy-efficient SA nations while exerting energy sustainability-impeding effects for the energy-inefficient SA countries. These contrasting findings can also be explained from the point of view that the energy-efficient SA nations are more financially globalized than the energy-inefficient ones whereby the possible technological spillover effects, associated with the influx of foreign direct investments, may not be sufficient enough to develop the clean energy sectors of the energy-inefficient SA countries. However, the negative effects of trade globalization on energy sustainability are witnessed to be homogeneous across both these categories of SA nations. Lastly, upon comparing the estimates of the corresponding elasticity parameters attached to the variable PGR, it can be observed that a higher population growth rate is particularly energy sustainability-restraining for the energy-inefficient SA nations than it is for the energy-efficient ones. These findings not only support the parallel findings reported in Table 8 but also highlights the fact that since the energy-inefficient SA nations have relatively higher annual population growth rates, the overall access to electricity and clean energy resources in these countries do not improve much. This is because the increase in the electricity output and the clean energy supplies are neutralized by the high population growth rates. Furthermore, a higher population growth rate can be linked with a surge in energy demand. As a result, the surging energy demand is likely to exert pressure on the traditional unclean energy consumption levels; consequently, the access and use of modern cleaner energy resources cannot be improved significantly.

7. Conclusion

Achieving the energy sustainability targets of SDG7 has become an important agenda for the SA nations. In this regard, making efficient use of energy resources is hypothesized to be a credible means of achieving environmental sustainability by enhancing electricity and clean cooking fuel and technology access rates as well as increasing the shares of renewables in total final energy consumption and electricity output figures, in particular. Against this background, this study aimed to evaluate whether or not energy efficiency improvement can stimulate energy sustainability in 32 low- and middle-income SA nations between 2002 and 2016. Besides, the analysis controlled for economic growth, environmental pollution, trade and financial globalization, financial development, population growth, and the implementation of the Kyoto Protocol on the energy efficiency-energy sustainability nexus. As opposed to the conventionally adopted approaches in the preceding studies, this current study constructed a comprehensive index of energy sustainability by compiling several key indicators related to several targets mentioned under SDG7. Hence, the outcomes derived from this study are critically important in respect of enabling the SA and other similar global nations to achieve the different energy sustainability-related targets of SDG7 by the end of 2030.

The long-run associations among energy sustainability, energy efficiency, and other concerned variables were confirmed from the findings from the cointegration analysis. Overall, for the entire panel, the regression findings reveal that a 1% rise in the energy efficiency level increases the energy sustainability index by around 11% in the long run. Thus, energy efficiency improvements can be expected to complement the energy sustainability agenda of the Sub-Saharan African nations. Besides, this finding is also observed to be homogeneous for the low- and middle-income sub-panels of SA nations. However, heterogeneous impacts are also evidenced as energy efficiency gains are associated with energy sustainability within the energy-efficient SA nations but not within the energy-inefficient ones. Furthermore, the mediating role of energy efficiency gain in respect of neutralizing the energy sustainability-impeding effects of economic growth was established in the cases of all groups of SA nations apart from the cases of the energy inefficient SA countries. Apart from energy efficiency and economic growth, the results also revealed that aggravation of environmental quality encourages only the middle-income and energy-efficient SA nations to achieve energy sustainability. Besides, trade globalization is evidenced to inhibit energy sustainability within the SA nations. However, the corresponding effects of financial globalization are evidenced to be heterogeneous. The results showed that financial globalization stimulates energy sustainability within the middle-income and energy-efficient SA nations but not in the cases of the low-income and energy inefficient SA countries. In addition, financial development was witnessed to facilitate energy sustainability across the SA nations but in the context of the energy-inefficient SA economies, financial development was not seen to be effective in inducing energy sustainability. Further, higher population growth was observed as a major hindrance against energy sustainability across the SA nations of concern. Lastly, the implementation of the Kyoto Protocol is found to motivate the SA nations to attain environmental sustainability; however, the energy-inefficient SA countries are seen to be unaffected by the implementation of the Kyoto Protocol.

In line with these findings, several short and long-term policy recommendations can be put forward. As far as the immediate policy interventions are concerned, the SA countries should emphasize investing in energy efficiency improvement-related initiatives both from the public and private sectors. In this regard, financing research and development projects for improving the overall efficiency of energy use across the SA nations can help these nations achieve the energy sustainability agenda. Besides, such investments can also assist these nations to manage their respective energy demand which, in turn, can be expected to provide the opportunity to develop the cleaner energy sector across this region. Hence, it can be expected that financing energy efficiency improvement-associated projects would not only ensure demand-side management of energy sustainability by reducing energy wastage and enhancing the overall level of energy access but also contribute to supply-side management of energy sustainability by facilitating clean energy development across the SA countries. In the same vein, the SA countries should also consider liberalizing the financial barriers that can uphold the attainment of energy sustainability within this region. Accordingly, developing the financial sector, especially within the energy-inefficient SA nations, is vital since higher access to concessional credits for the private sector can not only scale up investments in energy efficiency improvement but also stimulate private investments in the development of the clean energy sectors. Furthermore, it is time the SA nations stress on strengthening their environmental regulations so that the energy sustainability-impeding effects associated with globalization can be negated. Besides, enacting strict environmental legislations can further encourage the SA nations to comply with their energy sustainability-related SDG7 and Kyoto Protocol commitments.

The possible long-term policy interventions, alongside persistent investments in energy efficiency improvement, could mostly be in the form of investing in clean energy development. It is without a doubt an accepted fact that making a transition from unclean to cleaner energy use is necessary for sustaining socioeconomic and environmental performances. However, the speed of this energy transition is usually quite slow. Hence, hefty investments in this regard on a long-term basis can be expected to enable the SA nations to undergo the desired clean energy transition to eventually attain the energy sustainability agenda by 2030. Accordingly, the SA nations can also think of participating in intra-regional trade to boost cross-border flows of clean energy, especially from the non-fossil fuel-dependent to the fossil fuel-dependent SA countries. Similarly, the fossil fuel-dependent SA can gradually cut down their imports of unclean fuels and rather focus on importing cleaner energy resources so that the adverse effects of trade globalization on energy sustainability can be minimized. Furthermore, the SA nations are also recommended to attract clean foreign direct investments, especially those that can induce a technological spillover impact to develop the relevant technologies required improving energy efficiency and stimulating clean energy transition to collectively ensure energy sustainability across Africa.

This current study faced limitations in the form of data unavailability whereby the study period and the chosen sample of the SA nations could not be extended. A similar limitation has also prevented us from incorporating other African nations into the analysis. Besides, the analysis is specifically focused on low- and middle-income countries from this region whereby the robustness of the findings across the high-income countries and other global regions could not be ensured. However, the outcomes from this study could be applicable for non-SA countries with similar macroeconomic profiles. Hence, to test the authenticity of this assumption, this study can be extended by conducting the analysis in the context of economies belonging to other parts of the globe. In addition, provided relevant data is available, similar country-specific studies can also be conducted to assess the validity of the findings documented in this study.

CRediT authorship contribution statement

Muntasir Murshed: Conceptualization, Formal analysis, Data curation, Writing – original draft, Writing – review & editing. **Samiha Khan:** Writing – original draft, Writing – review & editing. **A.K.M. Atiqur Rahman:** Formal analysis, Methodology, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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