RESEARCH ARTICLE

Energy efficiency evaluation, changing trends and determinants of energy productivity growth across South Asian countries: SBM-DEA and Malmquist approach

Wasi Ul Hassan Shah[1] · Gang Hao[2] · Hong Yan[1] · Rizwana Yasmeen[3] · Yuting Lu[1]

Abstract
Energy efficiency is widely regarded as the most efficient means of supplying additional energy to meet the rising demand. However, extensive energy consumption causes greenhouse emissions, environmental destruction, and a decrease in energy efficiency (EE). This study investigates the role of energy efficiency and productivity growth in the ecological improvement of South Asia. Moreover, it evaluates the determinants (efficiency change or technology change) of energy productivity change across different SA (South Asian) countries. To estimate the energy efficiency and productivity change, we employed SBM-DEA and Malmquist Productivity Index methods with three inputs (capital stock, labor, and energy consumption), a single desirable output (gross domestic product) and a single undesirable output (CO_2 emissions) on the well-extended dataset (2001–2019) for 6 South Asian countries. Furthermore, to check the impact of energy policy (2010) over the study period, the statistical significance of the change in mean scores for energy efficiency and productivity over two time periods (2001–2010 and 2011–2019) and six countries was examined using the Mann–Whitney U and Kruskal–Wallis tests. Results reveal that the average EE score of all 6 SA countries for the study period is 0.7278. This score shows that SA countries still have the potential of 27.22% to improve their energy efficiency to minimize the inputs to get the optimum output level with the least emissions. The primary determinant of energy productivity growth is technological change instead of efficiency. The average energy efficiency level is significantly different for two time periods, 2001–2010 and 2011–2019. Results conclude that energy efficiency and productivity in SA declined over the period, and potential causes are an inefficiency in the energy conversion process, extensive utilization of inputs, and less output growth.

Keywords Energy efficiency · Technological advancement · DEA · Malmquist Productivity Index, South Asia

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Introduction

Sustainable economic development with the least energy consumption and emission reduction is a global challenge for developed and developing economies. Economic growth increases energy consumption and carbon emissions, resulting in global warming and natural disasters. Economic growth can be decoupled from greenhouse gas (GHG) emissions in two ways. Firstly, solar and wind technologies are pollution-free alternatives that can be used with dirty energy inputs to generate clean power. This green path to technological advancement has received much attention in recent years. Renewable energy sources such as solar, geothermal, and wind generally do not contribute to global warming or local air pollution because no fossil fuels are burned. The second method of reducing GHG emissions is to improve the efficiency of the energy-intensive production

units through technological advancement, resulting in more production with fewer emissions Witajewski-Baltvilks et al. 2017. Although heavy investments have been made in recent decades to improve the share of renewable energy sources that are low-carbon emitters and environmentally friendly, non-renewable sources are still dominating with 89% of the World's total energy consumption Ritchie & Roser 2020.

It is widely accepted that the most effective strategy for mitigating global warming is to implement policies that reduce carbon emissions, promote energy efficiency, and decouple energy demand and environmental pollution Iqbal et al. 2019; Adom et al. 2018. In recent years, energy efficiency and sustainable economic growth with the least environmental impact have been a popular research topic Wang & Dao 2019; Yao et al. 2021a, b. Technological advancement and energy efficiencies are the essential factors in energy transformation and emission reductions. It is interesting to note that energy efficiency is the most crucial component in decarbonizing and reshaping the energy sector through technological advances in environmental friendliness. Advanced technologies are helpful in the energy transformation process to produce more energy quantity and decrease emissions (Hassan et al. 2022).

Similarly, energy productivity change[1] and environmental innovation[2] are two critical aspects of environmental protection that technological advancements in the energy production process could be enhanced. Energy productivity could be further decomposed into technical efficiency and technological change, which could explore the impact of technological advancement on energy productivity growth or decline. Therefore, improving advanced technologies to increase energy productivity growth with less emission is the common global target for sustainable economic development Cheng et al. 2021a, b.

With one-fourth (24.89%) of the World's population and a high population growth rate, South Asia is a major energy consumer and carbon emitter, resulting in massive environmental destruction Worldometers, 2022. Fifteen of the World's 20 most polluted cities are in the South Asian region, causing severe health risks to the local population, disrupting ecological balance, and contaminating water reservoirs Vanzo 2022; Lozano-Gracia & Soppelsa 2019. South Asian countries are ecologically valuable due to their diverse natural resources and ecosystems Hasnat et al. 2019. The transitional nature of South Asian countries shows that environmental quality, behavior, and resource utilization are all interconnected Sarker et al. 2019. Member states raised several main concerns[3] at the third South Asian Association of Regional Cooperation (SAARC) Environment Ministers'

Meeting (held in Male on 15–16 October 1997) that were addressed in "SAARC Environment Action Plan." The regional countries initiate numerous environmental protection policies, including carbon reduction, energy efficiency, and sustainable energy productivity growth.

Specifically, as a part of the 16th SAARC summit, held in Thimphu, Bhutan, on April 28–29, 2010, energy conservation was given the highest priority. "Towards a Green and Happy South Asia" was the SAARC's Silver Jubilee Declaration theme. The participant agreed that to remain competitive in the global market, member states must improve their energy efficiency. Therefore, SAARC Energy Centre prepared an Action Plan on Energy Conservation with input from the Member States and presented its recommendations to the intergovernmental mechanism for consideration which member states accepted and implemented in their respective countries Centre 2012. However, this energy efficiency policy (2010) impact on EE level and productivity change in south Asian countries are unexplored.

Furthermore, South Asian countries also enforced policies at the country level to minimize carbon emissions in the energy transformation process Zafarullah & Huque 2018. However, the extent to which South Asia has succeeded in reducing carbon emissions, improving energy efficiency, and boosting productivity is unknown and should be investigated. Statistics show that compared to other world regions, energy consumption and emissions in Asia have increased dramatically over the last two decades (see Figs. 1 and 2). Energy consumption in SA has increased from 63.23 in 2001 to 157.19 (quadrillion Btu) in 2019, resulting in an emission incline 182,283.3 (kt) in 2001 to 462,648.34 (kt) in 2019 (Eia, 2022; World Bank 2021. Furthermore, India is the major energy consumer and carbon emitter with 88.5% of total carbon emissions. Pakistan and Bangladesh account for 10%, while Nepal, Sri Lanka, and Bhutan account for the remaining 1.5% of total emissions (see Fig. 3).

To this end, our study investigates the effects of South Asian countries' energy consumption and environmental protection policies on productivity and energy efficiency growth. This study makes numerous contributions to the current literature on energy efficiency and productivity by measuring the SA country-level growth in energy efficiency and productivity to examine the improvement in environmental quality. First, SBM-DEA measures the energy efficiency scores of 6 SA countries across a wide range of years, from 2001 to 2019. It quantifies the discrepancy between estimated and optimum energy efficiency levels in SA countries. The study further splits the period into two Sects. (2001–2010) and (2010–2019) to investigate the statistically significant difference (as determined by the Mann–Whitney U test) between the average energy efficiency scores of the two time periods (pre- and post-energy efficiency policy of 2010), which explains the degree of success in EE targets and environmental improvement over the study period. The Malmquist

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[1] Changes in energy productivity are the result of improvements in both technical efficiency and technology.
[2] Eco-friendly organizational initiatives and reforms.
[3] Natural disasters and environmental preservation and protection.

Fig. 1 Annual CO2 emissions growth (%) in different regions of the World from 2001 to 2019
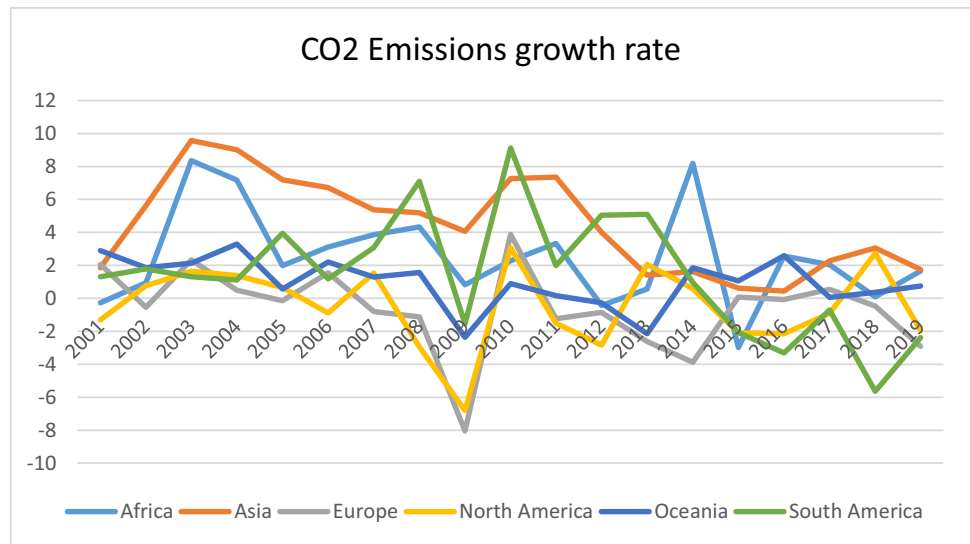

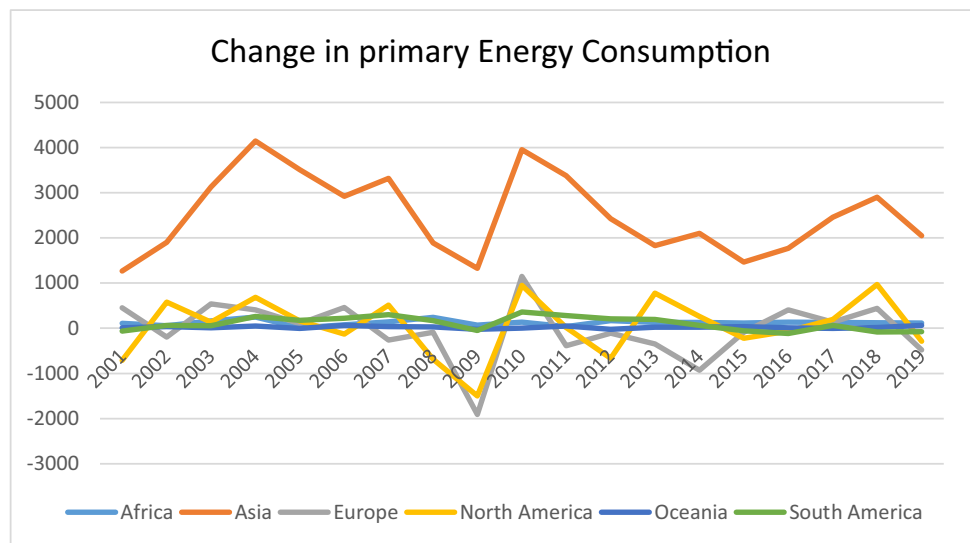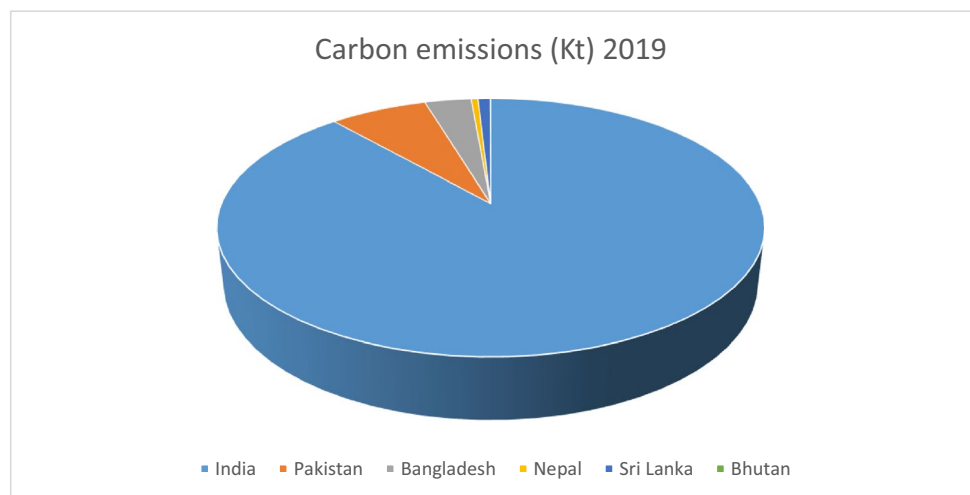**Fig. 2** Annual change in primary energy consumption (TWh) in different regions of the world from 2001 to 2019

Fig. 3 The ratio of carbon emissions by each country in 2019

Year-on-year change in CO₂ emissions, 2019

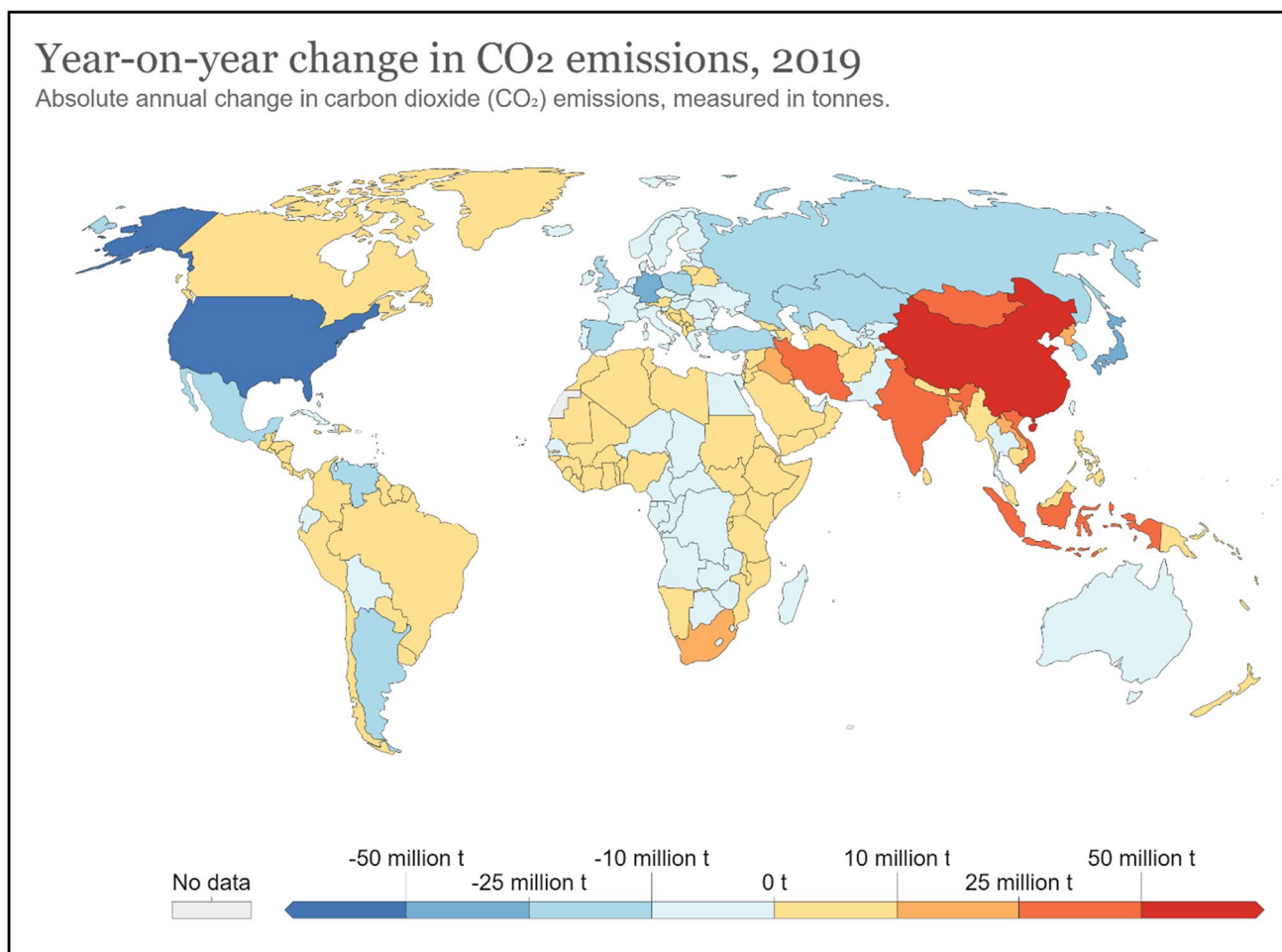Absolute annual change in carbon dioxide (CO₂) emissions, measured in tonnes.

Fig. 4 Global carbon emission in 2019. Source: Our World in Data

Productivity Index is used to assess the total factor energy productivity (TFEP) change across the study period to determine whether variations in TFEP are caused by energy efficiency or technological advancement.

It explains the impact of technological advancement on energy productivity growth or decline from 2001 to 2019. SA countries will be reminded to make energy and economic decisions based on quantitative and empirically grounded systematic analyses to mitigate environmental hazards. Finally, research decomposes each SA country's energy productivity change and explores its determinants (efficiency change or technology change). Kruskal–Wallis test gauges the significant difference among six SA countries' energy efficiency, productivity growth, and technology level. This study will advise the policy implication for each SA country to determine the influencing factor of energy productivity change and take adequate steps to improve particular determinants of energy productivity change and environmental protection.

The structure of this article is as follows: the "Literature review" section consists of the study's extensive literature review. The "Literature review" section explains the study's methodology in depth. The "Data sources" section details the data sources. Results and discussions are discussed in the "Results and discussion" section. The "Conclusion and policy recommendations" section offers the conclusions and policy implications.

Literature review

Energy efficiency and constant energy productivity growth are critical for long-term sustainable economic development. Even though clean energy is on the rise, most of the world's energy comes from fossil fuels like oil and natural gas. About half of the world's electricity comes from coal Li et al. 2017, causing a rise in global emissions, and South Asia is not distinct (see Fig. 4). Therefore, the general public, scientists, and governments pay more attention to energy efficiency and productivity for environmental concerns. In recent years, researchers have focused more on

comparing the energy efficiency and productivity of various regions, countries, and industries to shed light on inconsistencies in the energy transformation process and provide a quantitative foundation for improving the efficiency of this transformation Song et al. 2015; Patterson (1996) was the first academic to coin the phrase "energy efficiency" and propose four metrics for assessing a system's ability to use its resources effectively. It is impossible to overestimate the significance of reliable energy efficiency and productivity assessments. Energy efficiency and total factor productivity are commonly measured through a well-known linear programing technique known as data envelopment analysis (DEA). According to the literature, DEA methods have been utilized widely to quantify energy efficiency and productivity change in numerous regions and nations worldwide Xu et al. 2020.

Energy efficiency and environmental protection

All power generation sources affect our air, water, and land, but the impact varies. Power generation accounts for most of the total energy consumption, making it an essential portion of each person's carbon footprint. Wang and Dao 2019 argue that energy efficiency is vital in upgrading environmental quality and sustainable economic development. Shah et al. 2019 found that financial development increases carbon emission, which causes a decline in energy efficiency. In addition, numerous research utilized DEA to measure energy efficiency in various regions and countries worldwide W. U. Hassan Shah et al. 2022; Yao et al. 2021a, b; Yao et al. 2021a, b; Tang et al. 2015. To expose discrepancies in energy efficiency and provide a quantitative foundation for efficiency improvement, it is crucial to measure the energy efficiency of different regions and industries Song et al. 2015). Initially, Patterson 1996 introduced the notion of energy efficiency, which he described as "using fewer resources at the same output," and provided four metrics for quantifying it. This approach divides energy efficiency measures into economic and physical energy efficiency. According to the usual definition of "energy efficiency," Hu and Wang 2006 proposed the concept of total factor energy efficiency, TFEE, which has been widely accepted because standard energy efficiency measurement methods neglect other factors. Energy cannot generate any output within the TFEE architecture without being coupled with other elements. The TFEE index considers all three factors (energy, labor, and capital) in the input system that generates economic output. W. U. Hassan Shah et al. 2022 employed DEA to evaluate the EE in Chinese belt and road countries from 2003 to 2014 and argue that the average energy efficiency of six regions in B&R has been below 1% is not satisfactory. However, under the B&R, the Europe and Central Asia region is more efficient than the others. The region

of Europe and Central Asia is taking steps to strengthen its energy supply. The average efficiency levels of Sub-Saharan Africa and South Asia are 0.06 and 0.07, respectively, which demonstrates the wastage of energy resources. Choosing the correct input and output variables is critical to the DEA model evaluation of EE. Despite several energy efficiency analysis studies, the input and output variable selection is still not uniform. Hu and Wang 2006 used labor and capital for the first time as inputs into the energy efficiency evaluation system to evaluate the energy efficiency of 29 Chinese provinces and cities.

In contrast, conventional energy efficiency measurements only employ energy as one input to generate GDP Patterson 1996. From 1993 to 2003, Honma and Hu 2008 used the same variables to calculate the energy efficiency of a Japanese region. The energy efficiency of 27 emerging nations was examined by Zhang et al. 2011. SBM DEA is the most common way to evaluate DEA models with bad output. More specifically, Hu and Kao 2007 used the SMB-DEA to evaluate 17 APEC member countries' economies based on their energy-saving goals. Hu and Kao 2007 used an SBM model to determine how well the Organisation for Economic Co-operation and Development (OECD) countries used energy. Shang et al. 2020 used the SBM-DEA model to account for an undesirable generation when calculating the regional energy efficiency of China.

Masuda (2018) further applied the SBM model to analyze energy and CO_2 emission efficiency with various inputs and favorable and unfavorable output. From 1990 to 2015, 44 countries in Europe were studied for their energy efficiency Khraiche et al., 2021. Between 1990 and 1998, 1999 to 2007, and 2008–2015, trends in average energy efficiency across countries were studied. Results show that energy efficiency gains in European countries increased at 67.44% in the first period and declined to 59.09% in the second period, suggesting spillover effects; improvements in energy efficiency may be plateauing or decreasing over time; and when countries achieve their highest levels of energy efficiency, there is evidence of spillover effects. Thermal power plants in South Asia have relatively low efficiency and reliability.

In contrast, electricity transmission and distribution systems have a disproportionately high loss rate, affecting energy efficiency on a national level Wijayatunga & Siyambalapitiya 2017). Besides this, numerous research studies measure the EE of many regions and countries around the globe Shah et al. 2022; Ul et al. 2022. Jain and Goswami 2021 measure the EE in SA countries using Logarithmic Mean Divisia Index-I, which decomposes the energy consumption change into activity, structure, and intensity effects. However, the application of DEA evaluates the overall EE using a bundle of inputs and outputs; hence, overall EE level in SA is still missing, and a comprehensive evaluation of SA countries for EE and productivity evaluation is a substantial research

gap. The difference between the optimum and current energy efficiency levels in SA countries remains undiscovered and needs to be explored.

Technological advancement and energy productivity

Different energy-intensive countries and regions are committed to reducing their carbon footprint and preserving the environment. Sustaining energy productivity increases a country's competitiveness, assists consumers in managing their energy expenses, and contributes to reducing greenhouse gas emissions. It is a global challenge for countries and regions to reduce emissions throughout the value chain and assure high efficiency through sophisticated technologies, processes, and equipment while constantly upgrading and expanding their energy-transforming facilities. Energy efficiency reduces the amount of fuel used to generate electricity and the number of greenhouse gases and other pollutants released into the atmosphere (Vance et al. 2015). An economic transition away from energy-intensive growth and toward innovation-oriented development is often signaled by increases in energy productivity, which can be the consequence of using less energy to produce the same amount of output or utilizing the same amount of energy to produce more output (Jin and Zhang 2014). Using regional-level data from China from 1995 to 2012 and a dynamic panel data model, researchers examined the connection between energy output, consumption, and technological innovation Jin et al. 2018. Unlike previous research, it looks at the short-term and long-term relationships between technological innovation, energy productivity, and energy consumption. The results show that new technologies increase energy use in the short term but that energy use has no effect on new technologies.

On the other hand, energy use and technological progress are linked positively in the long run. These results show that new technologies do not directly lead to less energy use and fewer greenhouse gas emissions. Zhu et al. (2019) explore that technological progress is essential for increasing energy efficiency and growth in productivity. Huo et al. (2018) used the total-factor energy productivity change index (TFEPCH) to examine how China's construction industry used energy from 2006 to 2015. They researched 30 Chinese provinces. Also, TFEPCH was split into two parts: a change in how energy is used and a change in how technology is used. First, the results show that China's construction industry lost 7.1% of its energy productivity from 2006 to 2015. The overall drop in energy productivity was caused by energy technical regress in China's construction industry, not by technical energy efficiency. Since 2006, this has caused China's central region to lose 77.1% of its energy productivity, while the eastern and western regions have lost 54.3 and 65.3%,

respectively. Only Hebei and Shandong, out of the thirty provinces that were looked at, saw an increase in how much energy they used between 2006 and 2015. This study greatly affected how energy and resources were used in the Chinese construction industry.

Chang and Hu (2010) measured China's energy productivity and found that it went down by 1.4% per year from 2000 to 2004. Total-factor energy efficiency goes up by an average of 0.6% per year, while total-factor energy technical change goes down by 2% per year. The following things also affect TFEPI: The TFEPI performance of a region will be better if it is more developed and uses more electricity. In contrast, a region's TFEPI performance will worsen if the secondary industry's GDP goes up. Moreover, many studies measure energy productivity in different areas and countries globally to find the impact of technological advancement on energy productivity change Rath et al. 2019; Honma & Hu 2009; Liu et al. 2018; Malanima 2021. Zeshan and Ahmed 2013 concluded in their study that South Asia is a major energy consumer and carbon emitter. Literature advocates that although SA countries have implemented policies for technological improvement and energy productivity growth, the level of success in this mission is still not explored.

Methodology

DEA is a well-established mathematical linear programming technique to compare the efficiency of similar DMUs. Charnes et al. 1978 proposed the DEA basic model with the constant return to scale (CSR) assumption; Banker et al. 1984 amended the model to allow for a variable return to scale (VSR). Undesirable outputs are not accounted for in the standard DEA model, so Karou Tone 2003 presented the slack-based measure (SBM) with undesired results based on his first investigations Tone 2001.

SBM-DEA with undesirable output

We suppose that there are n total DMUs. Input, good outputs, and bad outputs are all distinct elements designated by various vectors: $x \in R^m$, $y^g \in R^{s1}$ and $y^b \in R^{S2}$, respectively. In other terms, the set of production possibilities P is defined as follows:

$$P = \left\{ \left(x, y^g, y^b\right) \mid x \geq X\lambda, y^g \leq Y^g\lambda, y^b \geq Y^b\lambda, \lambda \geq 0 \right\}, \quad (1)$$

The definition is compatible with the "constant returns to scale assumption" when the intensity vector $\lambda \in R^n$ is used. Even if the model contains bad outputs, the efficiency of DMU $_0$ (x_0, y_0^g, y_0^b) can be obtained. SBM is defined as follows:

$$[SBM - Undesirable] \; p *= \min \frac{1 - \frac{1}{m} \sum_{i=1}^{m} \frac{s_i^-}{x_{i0}}}{1 + \frac{1}{s_1 + s_2} \left(\sum_{r=1}^{s_1} \frac{s_r^g}{y_{ro}} + \sum_{r=1}^{s_2} \frac{s_r^b}{y_{r0}^b} \right)} \tag{2}$$

Subject to

$$\boldsymbol{x}_0 = X\lambda + s^- \tag{3}$$

$$y_0^g = Y^g\lambda - s^g \tag{4}$$

$$y_0^b = Y^b\lambda + s^b \tag{5}$$

$$s^- \geq 0, s^g \geq 0, s^b \geq 0, \lambda \geq 0 \tag{6}$$

Excessive input is represented by $s^- \in R^m$, and bad output is represented by $s^b \in R^{s_2}$, while a shortage of good outputs is shown by $s^g \in R^{s_1}$. The best solution for this program is $\left(\lambda^*, s^{-*}, s^{g*}, s^{b*}\right)$.

The following restriction can be placed on the [SBM-Undesirable] to allow for the inclusion of RTS features. Hence, production possibility can be defined as:

$$L \leq e\lambda \leq U \tag{7}$$

To estimate the EE for SA countries for each year, we used SBM-DEA in the initial stage of the empirical analysis (2001–2019).

DEA-Malmquist Productivity Index

Malmquist Productivity Indexes at a DMU can monitor efficiency trends over time. This index assumes that a production function, which reflects technology status at any given time, exists. We employ DEA models to locate this boundary. According to Färe et al. 1992, the variation in output between periods t and $t+1$ characterizes a given DMU (DMU_0).

$$M_0 = \frac{D_0^{t+1}\left(x_0^{t+1}, y_0^{t+1}\right)}{D_0^t\left(x_0^t y_0^t\right)} \left[\frac{D_0^t\left(x_0^{t+1}, y_0^{t+1}\right)}{D_0^t\left(x_0^t, y_0^t\right)} \frac{D_0^{t+1}\left(x_0^{t+1}, y_0^{t+1}\right)}{D_0^{t+1}\left(x_0^t y_0^t\right)} \right]^{1/2} \tag{8}$$

- where $D_0^t\left(x_0^t, y_0^t\right)$ represents the technical efficiency measurement of the DMU_0 in time period t.
- $D_0^{t+1}\left(x_0^{t+1}, y_0^{t+1}\right)$ is the technical efficiency measurement for the DMU_0 in time period t+1.
- $D_0^t\left(x_0^{t+1}, y_0^{t+1}\right)$ represents the shift from t to t + 1 in technical efficiency.
- $D_0^{t+1}\left(x_0^t, y_0^t\right)$ refers to the technical efficiency of a certain DMU 0 as measured by substituting its data from period t with those from period $t+1$.

The change in DMU 0's technical efficiency between periods t and $t+1$ is shown by the first term of Eq. (8), which does not have any parentheses. The second term between square brackets in Eq. (8) shows how the technological boundary of the same DMU has changed. If the index is more than 1, DMU 0 has been more productive than the first period. One of the two possible reasons for a rise in production is that the DMU changed its ways to make them more efficient (technological change). We used the DEA Malmquist Index to figure out how technological progress affected a drop in emissions and a rise in EE in SA countries from 2001 to 2019.

Mann Whitney U and Kruskal–Wallis test

The Mann–Whitney U test, first developed by Wilcoxon 1945 and later refined by Mann and Whitney 1947, is a well-known non-parametric method for comparing the results of two assumed groups completely different. The Mann–Whitney U test (also known as the Mann–Whitney Wilcoxon Test or the Wilcoxon Rank Sum Test) determines whether or not two samples come from the same population (i.e., the two populations have the same shape). This analysis contrasts the middle values (medians) of the two groups. The (H_0: 1 = 2) hypothesis test compares the means of two sets of unrelated individuals, while the (H_1: 1 = 2) hypothesis test compares the means of two sets of unrelated individuals. However, if there are more than two independent groups, the Kruskal–Wallis test can be used to determine whether or not the differences between them are statistically significant Theodorsson-Norheim, 1986. We compared the average energy efficiency ratings for 2001–2010 with those for 2011–2019 using the Mann–Whitney U test. As a result, we will use the following as our base case for the Mann–Whitney Wilcoxon test:

H_{01}: The distribution of Avg EE is identical between the two time periods.
H_{02}: The average Malmquist Index (MI) distribution is the same for both periods.
H_{03}: The distribution of average technology change across two distinct periods is identical.
H_{04}: The distribution of average efficiency change across the periods is the same.

The Kruskal–Wallis test was used to compare the EE across the six SA countries to see if there were any discernible differences. For the Kruskal–Wallis test, we use the following null hypothesis:

H_{11}: The distribution of Avg.EE is identical in six distinct SA countries.

Table 1 Input–output variables utilized for estimating EE and productivity

Inputs	Outputs
Labor: Labor force, total	Desirable output GDP (constant 2015 US$)
Capital: Gross capital formation (constant 2015 US$)	Undesired output CO_2 emissions (kt)
Energy: Total energy consumption annual, quadrillion Btu	

H_{12}: The average Malmquist Index (MI) change distribution is the same across all six SA countries.

H_{13}: The distribution of average technology change is identical across all six SA countries.

H_{14}: The distribution of average efficiency change is similar across all six SA countries.

Data sources

Researchers have used numerous input–output indicators to measure energy efficiency and productivity Li & Lin 2015; Zhang & Choi 2013; Wang et al. 2012. The following input and output variables are selected based on prior study expertise and data availability (Table 1). World Bank indicators were used to obtain data on all inputs and outputs except energy consumption from 2001 to 2019 World Bank 2021. The US Energy Information Administration was tapped for its database on annual energy consumption ((Eia), U. E. information administratin (2020).

Results and discussion

This study used SMB-DEA to analyze energy efficiency for 6 SA countries and account for undesirable output. Furthermore, Malmquist Productivity Index with undesirable output is employed to explore the total factor productivity change over the study period. To encounter a problem regarding the insufficient DMUs, we used KAM model by Khezrimotlagh 2015 and got the results to check the robustness of estimation. No significant difference was found in the rank or efficiency scores of DMUs. Given one of the inputs (energy consumption), this study measures technical efficiency, also known as energy efficiency. On the other hand, pure energy efficiency is usually measured in terms of energy intensity. Moreover, numerous factors, including energy efficiency, could cause changes in technical efficiency.

Energy efficiency results

Generating the desired output (GDP) using a variety of energy and economic inputs while disposing of the undesirable output (CO2), the EE scores are shown in Table 2. The average EE score of all 6 SA countries for 2001–2019 is 0.7278. This score indicates that SA countries still have the potential of 27.22% to improve their energy efficiency to minimize the inputs to get the optimum output level with the least emissions. Pakistan and Sri Lanka achieved an overall energy efficiency score of 1 during the study period. Nepal also scored unity from 2001 to 2015 until it tilted towards a decline in EE score for the rest of the study years. In other words, these countries use less energy and produce more GDP while emitting less CO2 than the rest of the South Asian countries, implying that they are more energy-efficient. After India (0.4008) and Bangladesh (0.6758), Bhutan is the least efficient country (0.3968). In addition, the efficiency score of 0.6401 for the entire South Asia sample is the lowest in 2019. From 2011 to 2010, the average efficiency scores of the six countries fluctuated but mainly on an increasing trend with an average score of 0.7469, while a decline was noticed from 2011 to 2019 with an average score of 0.7065. The decline in GDP, coupled with an increase in emissions, is the most likely explanation. It is clear from the EE results that the lowest average efficiency score was noticed in 2019. South Asian countries like Bhutan, India, and Bangladesh were the least efficient in the study period 2001–2019. In other words, these SA countries are less efficient at converting their inputs into outputs than they should be. It suggests that these countries should efficiently use their energy resources and reduce carbon emissions while simultaneously increasing GDP to reach the efficient frontier. Figure 5 shows the average EE score distribution for 2001–2019, indicating a gradual decline in EE scores.
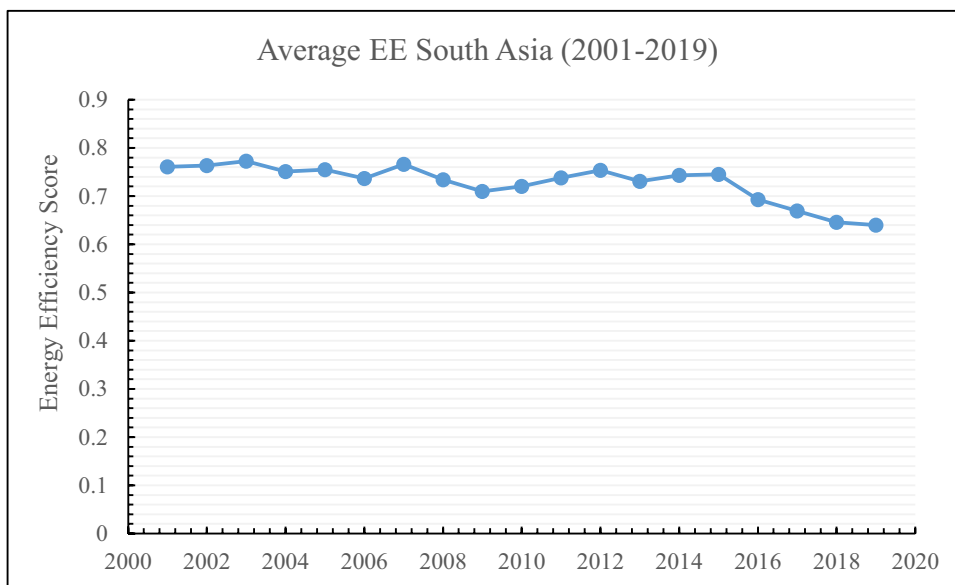
Energy productivity results

According to Table 3, the average growth rate of energy productivity is 1.0743, implying an average increase of 7.43%. From an annual results standpoint, the changes in energy productivity demonstrated various characteristics. According to the findings, the primary determinant of energy productivity growth was a technological change, with an average technological change score of 1.0812 (2001–2019), indicating an 8.12% increase in technology over the study period. Because the average efficiency change in South Asian countries is less than 1 during the study period, energy productivity increased or decreased as determined by technological changes (technical change is greater than one). Between 2001 and 2019, South Asia's energy productivity growth fluctuated. Thus, energy productivity increased from 1.0251 in 2001 to 1.0557 in 2008, a 3.06% increase, before it

Table 2 Energy efficiency of South Asian countries 2001–2019

DMUs	Energy efficiency scores						
	India	Pakistan	Bangladesh	Nepal	Sri Lanka	Bhutan	Avg
2001	0.4249	1	0.7809	1	1	0.3602	0.761
2002	0.4295	1	0.7485	1	1	0.4011	0.7632
2003	0.4303	1	0.7541	1	1	0.4503	0.7725
2004	0.3954	1	0.7358	1	1	0.3762	0.7512
2005	0.3884	1	0.7418	1	1	0.3982	0.7547
2006	0.3769	1	0.6707	1	1	0.3709	0.7364
2007	0.3573	1	0.6775	1	1	0.5601	0.7658
2008	0.3531	1	0.5786	1	1	0.473	0.7341
2009	0.3333	1	0.5384	1	1	0.3862	0.7097
2010	0.3492	1	0.6167	1	1	0.3561	0.7203
2011	0.3715	1	0.7168	1	1	0.3395	0.738
2012	0.3888	1	0.7825	1	1	0.3507	0.7537
2013	0.3855	1	0.6156	1	1	0.3832	0.7307
2014	0.4056	1	0.6703	1	1	0.3846	0.7434
2015	0.4286	1	0.6623	1	1	0.3786	0.7449
2016	0.4627	1	0.6725	0.6471	1	0.373	0.6926
2017	0.463	1	0.7036	0.456	1	0.3941	0.6695
2018	0.4438	1	0.6189	0.4226	1	0.3903	0.6459
2019	0.427	1	0.5541	0.4461	1	0.4132	0.6401
Avg. 2001–2019	0.4008	1	0.6758	0.8933	1	0.3968	0.7278

Fig. 5 Average EE in South Asia over the period 2001–2019

started to decline from 2009 to 2019 when it reached 0.9888. Between 2009 and 2019, energy productivity growth in SA countries remained less than one, indicating that energy productivity has declined since 2009. There were fluctuations in efficiency and technology change from 2001 to 2019; however, efficiency in most of the years is less than 1 while technological change is over 1, clearly indicating that growth in energy productivity is due to technological advancement.

Elaborating the energy productivity results for each SA country, different factors for different countries determine the change. Table 4 shows that the average efficiency change in India is 1.0013, while technological change is 1.0084, indicating that growth in energy productivity in India is mainly due to technology rise. Similar to India, Pakistan's rise in energy productivity is attributable to technological development, as shown by TECHCH and EFFCH values

Table 3 Energy productivity scores of South Asian countries over the period 2001–2019

Years	EFFCH	TECHCH	MPI
2001–2002	1.0138	1.0116	1.0251
2002–2003	1.022	0.9736	0.9937
2003–2004	0.955	1.0155	0.9687
2004–2005	1.0082	0.9888	0.9970
2005–2006	0.9677	1.0456	1.0101
2006–2007	1.078	1.0088	1.0851
2007–2008	0.9478	1.1263	1.0557
2008–2009	0.9485	1.0599	1.0007
2010–2011	1.0192	0.9356	0.9500
2011–2012	1.0299	0.9660	0.9906
2012–2013	1.0286	0.9686	0.9946
2013–2014	0.9785	1.1074	1.0758
2014–2015	1.0240	0.9207	0.9425
2015–2016	1.0049	1.0013	1.0063
2016–2017	0.9545	0.9894	0.9458
2017–2018	0.9680	0.9485	0.9257
2018–2019	0.9592	1.0311	0.9888
Avg. 2001–2019	0.9953	1.0812	1.0743

*EFFCH refers to technical efficiency change. *TECH refers to technological change. *MPI refers to the Malmquist Productivity Index

Table 4 Average energy productivity of South Asian countries

Country	EFFCH	TECHCH	MPI
India	1.0013	1.0084	1.0087
Pakistan	1	1.0153	1.0153
Bangladesh	0.986	0.9961	0.9708
Nepal	0.963	0.9629	0.9299
Sri Lanka	1	1.0156	1.0156
Bhutan	1.0174	1.0617	1.0698

of 1.0153 and 1, respectively, which raised the MPI to 1.0153 and showed that efficiency changes reduced the rise in energy productivity from 2001 to 2019. In Bangladesh, efficiency change was 0.986, explaining that, on average, a decline was noted from 2001 to 2019. Energy productivity score was 0.9708, while efficiency change hindered energy productivity growth in the study period as the technology change score was greater than efficiency change (0.9961 > 0.986). MPI scores in Nepal (0.9299) were the worst among all countries. Further elaborating the results, we found that the decline in energy productivity growth is due to efficiency change and technological change (0.963, 0.963) in the study period. On average (2001–2019), energy productivity growth in Sri Lanka was 1.0156 and mainly due to the rise in technological change (1.0156) as efficiency remained unchanged (1) during the sample period. Bhutan

was the most successful in all 6 South Asian countries as its productivity growth was risen by 6.98% in the study period. Results indicate that technological advancement (1.0617) was the primary determinant of energy productivity growth, as average energy efficiency was 1.01741 from 2001 to 2019.

Furthermore, Table 5 (Appendix) compares the average EE and MPI scores of all 6 countries for the study period (2001–2019). The average EE score of India is 0.4008, indicating that as compared to other SA countries, India still has 60% potential for improvement in energy efficiency. However, MPI score is over 1, which indicates the energy productivity growth during the study period. With EE score of 1, Pakistan is efficient among SA countries and improved its productivity growth by 1.53% during 2001–2019. Bangladesh and Nepal still have a potential of 32.42 and 10.67% in their EE, while both countries did not get energy productivity growth during 2001–2019. Sri Lanka is also efficient with an efficiency score of 1 and progresses with 1.56% in its energy productivity. Bhutan is the least efficient among all SA countries, with an average EE of 0.3968; however, it improves its energy productivity growth by 6.98% during the study period. These results indicate that Bhutan, India, Bangladesh, and Nepal still use extensive inputs (labor, capital and energy) to produce similar output (GDP). These countries could reduce the amount of inputs and improve their energy conversion process efficiency to get an efficient frontier. Energy productivity growth in Nepal and Bangladesh is on the decline, and primary determinants are both efficiency and technology, indicating that these countries need to improve both technological level and efficiency to achieve growth in energy productivity.

Mann Whitney U and Kruskal–Wallis test results

Table 6 shows the results of the Mann–Whitney U test. Table 3 indicates that SA countries' EE levels continuously declined after 2010; therefore, the first hypothesis tests whether there is a significant difference in average EE scores in two time periods, 2001–2010 and 2011–2019. The sig value is 0.035, which is less than 0.050. Therefore, we reject our null hypothesis "the distribution of average EE is the same across categories of two time periods" and conclude that the average EE scores after 2010 are significantly different from 2001 to 2010. It proves a significant decline in the energy efficiency level for SA countries after 2011. The possible and major causes are increased consumption of fossil fuels and carbon emissions which ultimately decrease EE levels in South Asia (Munir & Riaz, 2019). Similarly, energy productivity also decline after 2010 (see Table 3).

To test the significant difference among energy productivity scores before and after 2010, we divide the periods into two chunks and test them through the second hypothesis, which states, "The distribution of Avg. MI (Malmquist

Table 6 Mann–Whitney U table to indicate the significant statistical difference among EE and energy productivity results for two time periods (2001–2010 and 2011–2019)

Hypothesis test summary				
	Null hypothesis	Test	Sig	Decision
1	The distribution of avg.EE is the same across categories of two time periods	Independent-samples Mann–Whitney U Test	0.035[a]	Reject the null hypothesis
2	The distribution of avg. MI (Malmquist Index) is the same across categories of two time periods	Independent-samples Mann–Whitney U Test	0.297[a]	Retain the null hypothesis
3	The distribution of avg. technology change is the same across categories of two time periods	Independent-samples Mann–Whitney U Test	0.436[a]	Retain the null hypothesis
4	The distribution of avg. efficiency change is the same across categories of two time periods	Independent-samples Mann–Whitney U Test	0.730[a]	Retain the null hypothesis

Asymptotic significances are displayed. The significance level is 0.050

[a]Exact significance is displayed for this test

Index) is the same across categories of two time periods." The results show that the sig value is 0. 297; therefore, we retain our null hypothesis and conclude that although energy productivity gradually and continually declined after 2010, there is no significant difference found between the energy productivity score for the two time periods (2001–2010 and 2011–2019). Our results are aligned with the research of Jain and Goswami (2021), which shows that economic growth is the primary driver of energy use, and the shift toward sectors that use a lot of energy adds to this. But, except for Nepal and Bhutan, all South Asian countries use less energy because energy intensity is decreasing.

Further availability of energy resources, the production of renewable energy, the price of crude, the number of people living in a given area, and the GDP per person are all important factors that affect energy productivity and slow down its pace in South Asia for recent times. Table 3 explores that technology change is the primary determinant of energy productivity change instead of efficiency change over the period for SA countries. However, there are fluctuations in efficiency and technology changes over two periods. Therefore, to test the significant difference between the technology change and efficiency change for two time periods, we employed hypotheses 3 and 4. Results in Table 6 and Fig. 6 indicate that although there is no significant difference between technology change levels for two time periods, there is no significant change found in efficiency over the period and is not the primary determinant of productivity change. Therefore, we retain the third and fourth null hypotheses. This argument is sported by the research of Wijayatunga and Siyambalapitiya (2017), who state that the energy transformation process in south Asia is still inefficient and requires labor and capital efficiency achieved through a skilled workforce and continuous supply of funds for energy units. However, technology advancement level declined after 2010, a possible cause of energy productivity decline and carbon emission growth. Technology is a significant factor in energy

transformation for clean production and emission reductions (Fisher-Vanden et al. 2006).

Tables 2 and 4 show the different EE, MPI, EC, and TC levels for six different South Asian countries from 2001 to 2019. Therefore, it is critical to estimate that these differences are statistically significant. Table 7 and Fig. 7 show the Kruskal–Wallis test, which evaluates the significant difference in the average scores of EE, MPI, TC, and EC changes among six different South Asian countries. Hypothesis 1 concludes that the EE scores of all 6 SA countries are significantly different, and each country has a different EE level and is determined by its domestic factors. If we elaborate on the EE results for each country, the average EE scores of India, Bangladesh, and Bhutan are continually poor than Pakistan, Sri Lanka, and Nepal. The main cause of poor EE in these countries are extensive energy consumption, capital, labor, and inefficiency in the energy conversion process; otherwise, India and Bangladesh have dominant GDPs in SA Rahman et al. 2020. Null hypotheses 2, 3, and 4 proposed that productivity change, technology change, and efficiency change are the same across 6 SA countries, and there is no significant difference. The sig values of hypotheses 2, 3, and 4 are.005, 0.360, and 0.980; therefore, we reject our second null hypothesis and conclude that statistical difference exists among MI scores of 6 SA countries.

In contrast, we retain our third and fourth null hypotheses and conclude that there is no significant difference between technological change and efficiency change among SA countries. Our results are backed by the research by Arnold and Dewald (2012), who concluded that technology adoption in developing SA countries is similar and has equal access to modern technologies. However, energy productivity is on the decline due to efficiency change. For all SA countries, efficient utilization of labor, capital, and energy resources is the primary determinant of energy productivity growth in SA Hou et al., 2019. Efficient utilization of resources increases economic growth, leading to urbanization, another source of
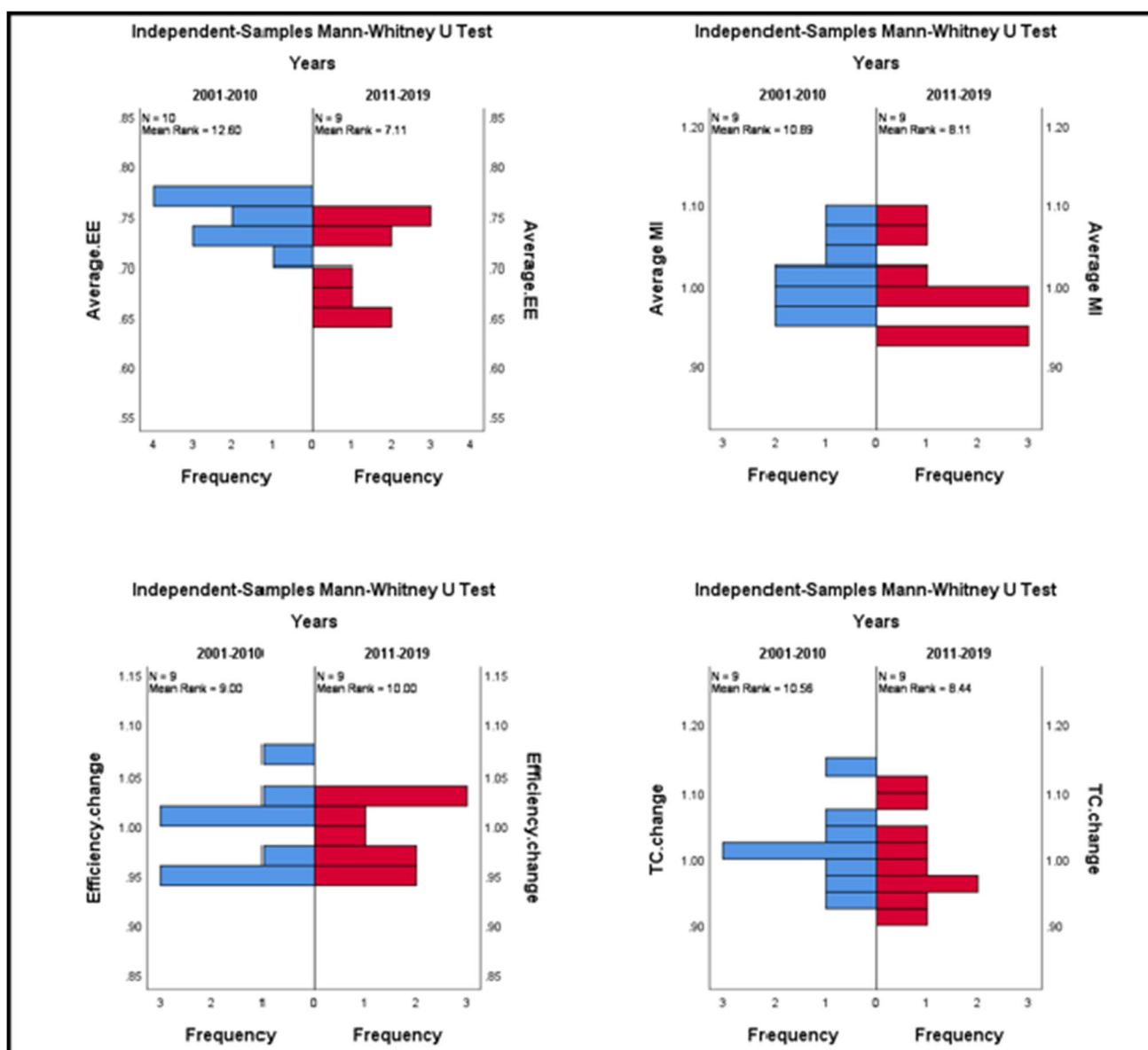
Fig. 6 Distribution of average EE, MI, EC and TC across different periods

Table 7 Kruskal–Wallis table indicates the significant statistical difference among EE and energy productivity results for six different SA countries

Hypothesis test summary				
	Null hypothesis	Test	Sig	Decision
1	The distribution of avg.EE is the same across six different SA countries	Independent-samples Kruskal–Wallis Test	0.000	Reject the null hypothesis
2	The distribution of avg. MI (Malmquist Index) change is the same across six different SA countries	Independent-samples Kruskal–Wallis Test	0.005	Reject the null hypothesis
3	The distribution of avg. technology change is the same across six different SA countries	Independent-samples Kruskal–Wallis Test	0.360	Retain the null hypothesis
4	The distribution of avg. efficiency change is the same across six different SA countries	Independent-samples Kruskal–Wallis Test	0.980	Retain the null hypothesis

Asymptotic significances are displayed. The significance level is 0.050
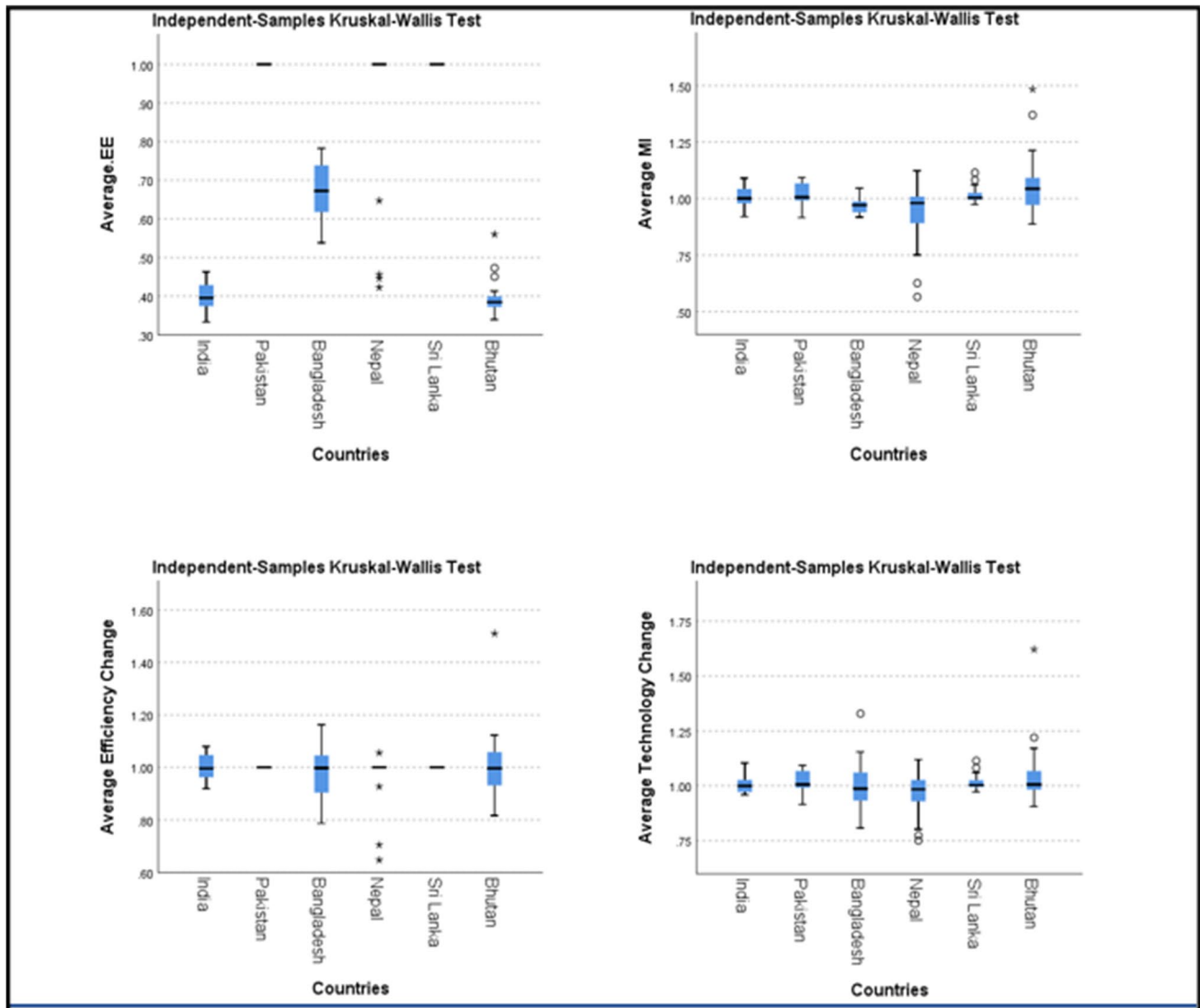
Fig. 7 Distribution of average EE, MI, EC, and TC across different SA countries

environmental degradation in SA countries (Azam & Khan 2016); therefore, with efficiency improvement, environmental regulation should be implemented strictly by SAARC countries to minimize the emissions of greenhouse gases.

Summarizing our empirical analysis, we conclude that the average EE score of all 6 SA countries for the study period 2001–2019 is 0.7278. This score shows that SA countries still have the potential of 27.22% to improve their energy efficiency to minimize the inputs to get the optimum output level with the least emissions. Compared to Sri Lanka, Pakistan, and Nepal, energy efficiency is comparatively low in India, Bangladesh, and Bhutan for the study period (2001–2019). Furthermore, a continuous and gradual decrease in EE levels was witnessed after 2010; results of the Mann–Whitney test proved a significant difference between the average EE level before and

after 2010. This situation advocates that carbon reduction, a possible reason is still on an increasing trend after 2010 and causing a diverse effect on the SA environment. Moreover, big economies like India, Pakistan, and Bangladesh are the main culprits of SA's environmental destruction; 15 out of 20 most polluted cities globally are located in these three countries, strengthening our argument for this bad environmental condition in SA Vanzo 2022; Lozano-Gracia & Soppelsa 2019. Possible solutions to improve the environmental conditions are to decrease the consumption of fossil fuels and shift to cleaner energy generations Panwar et al., 2011, moreover, establish policies and implement them with strict regulations to use the modern technologies in power generation units that can produce more power with fewer emissions (Guo et al., 2013) (Wu et al. 2020).

The average growth rate of energy productivity is 1.0743, implying an average increase of 7.43%. The primary determinant of energy productivity growth was a technological change, with an average technological change score of 1.0812 (2001–2019), indicating an 8.12% increase in technology over the study period. Efficiency did not change much during the study period. Therefore, it cannot be considered a major determinant in energy productivity growth. Thus, this study concludes that any change in productivity growth is due to technological advancement instead of efficiency increase. However, the results of the Mann–Whitney U test show that the decline in energy productivity growth after 2010 is not significant, and efficiency decline is the main culprit of this productivity deterioration. Moreover, technology growth in SA countries also decreases after 2010, another reason for productivity decline after 2010.

Poor technology is a big source of increased carbon emissions which ultimately slow the pace of energy productivity growth. Therefore our findings suggest the SA countries improve their production technologies and reduce emissions to foster energy productivity growth and improve environmental quality. Our results are backed by adequate literature and advocate that technological advancement plays an essential role in the energy transformation process and improves ecological quality Li et al. 2021; Cheng et al. 2021a, b. Further efficiency change plays a minor impact on the energy productivity growth of SA countries, which shows that more efficiency is required in the production process for optimum utilization of the input resources (labor, capital, and energy). The study by Miao et al. (2017) strengthens our argument that efficient resource utilization improves energy efficiency and productivity, leading to environmental upgradation. Therefore, this study recommends the SA authorities remove the hurdles in the supply of adequate capital, a skillful workforce, and energy stocks to improve power generation efficiency.

Furthermore, each country needs to improve technology or efficiency to improve its energy productivity growth. India needs to improve its efficiency to increase productivity growth and reduce carbon emissions because the technology level of India is the main determinant of energy productivity growth. Pakistan, Bangladesh, Sri Lanka, and Bhutan need to improve their efficiency in the production process as technology is better than efficiency in determining the energy productivity growth in these countries. Nepal lacks both technology and efficiency. Therefore, it needs to improve both factors to grow its energy productivity. Kruskal–Wallis test results explore that there is not much difference in technology or efficiency in all 6 SA countries, proving that modern technology access is equally available to all the countries. Therefore, all the countries lack modern technology and efficiency improvement, so this study's findings suggest that the administrative authorities improve these factors to foster energy productivity growth and environmental quality.

Conclusion and policy recommendations

In this study, six South Asian countries' energy efficiency, factors influencing the growth of energy productivity, and trends in EE and energy productivity are assessed over the study period (2001–2019). With three inputs (capital stock, labor, and energy consumption), one desirable output (gross domestic product), and one undesirable output variable (CO_2 emissions), we used SBM-DEA and the Malmquist Index to assess the growth of EE and energy productivity. The statistically significant difference between the mean energy efficiency and productivity scores for two distinct times and six countries was also investigated using the Mann–Whitney U and Kruskal–Wallis tests. First, we use SMB-DEA and MPI to evaluate energy productivity and efficient growth in 6 SA countries. We divide the study period into two segments to better understand how the energy policy of 2010 affected EE and changes in energy productivity: (2001–2010 and 2011–2019). Second, for two time periods and six nations, we apply the Mann–Whitney U and Kruskal Wallis tests to determine whether there is a statistically significant difference between the average EE, MPI, EC, and TC. Our findings and policy recommendations to improve EE and energy productivity growth for environmental enhancement are as follows: Firstly, results of EE reveal that once we employ inputs resources to produce desirable outputs, the production process automatically produces undesirable output (carbon emissions), which impact the environment and EE level in SA. On average, the EE score for the study period is 0.7278. This score shows that SA countries still have the potential of 27.22% to improve their energy efficiency to minimize the inputs to get the optimum output level with the least emissions (bad output). Results reveal that during the year 2001 to 2010, the EE level in SA increased; however, after 2010, a gradual and continued declining trend was noticed in the EE level. Mann–Whitney test results showed a significant difference among the EE levels during the two periods. To ensure the efficient usage of energy resources and emission reduction, SA countries need policies and programs that resolve established and unsustainable practices and permit individuals and energy consumers to make prudent energy decisions. India, Bangladesh, and Bhutan are less energy-efficient than their remaining 3 counterparts, and the core cause is extensive energy consumption and inefficient practices in the energy conversion process. To improve the EE and environmental conditions in these countries, they need to decrease the consumption of fossil fuels and shift to cleaner energy generations. They should also establish policies and implement them with strict regulations to use

the modern technologies in power generation units that can produce more power with fewer emissions. Furthermore, SA countries might adopt policy actions to better utilize energy and economic inputs to boost GDP growth.

Secondly, the Malmquist Productivity Index results explore that the average rate of energy productivity growth is 1.0743, which corresponds to an average increase of 7.43%. The average technological change score over the study period (2001–2019) was 1.0812, indicating an 8.12% increase in technology. During the study period, efficiency did not change much, so it cannot be considered a significant factor in energy productivity growth. Therefore, this.

growth is attributable to technological development rather than efficiency improvement. The decline in efficiency is the primary cause of this productivity decline.

Moreover, technology growth in SA countries decelerates after 2010, another reason for the decline in productivity after 2010. Based on our findings, SA countries should improve their production technologies and reduce emissions to speed up energy productivity growth and improve environmental quality. Changes in efficiency have a negligible effect on the growth of energy productivity in SA countries, which shows that production processes need to be more efficient to get the most out of the resources they use (labor, capital, and energy). So, this study suggests that the South Asian government remove barriers to getting enough money, skilled workers, and energy to improve power generation efficiency. Also, each country needs to improve its technology or efficiency for energy productivity growth. India needs to improve its efficiency to boost productivity and cut carbon emissions. India's efficiency level is the main factor determining energy productivity growth. Pakistan, Bangladesh, Sri Lanka, and Bhutan need to make their production processes more efficient because technology is a better way to measure energy productivity growth in these countries than efficiency. Nepal needs to improve its technology and efficiency to boost its energy productivity. The Kruskal–Wallis test shows that there are not many differences in technology or efficiency between the 6 SA countries. It shows that all the countries have the same access to modern technology. So, all countries do not have adequate modern technology and do not work as efficiently as they could. This study's results suggest that these things should be improved to boost energy productivity and environmental quality.

This research concluded that South Asia has tremendous potential for improving energy efficiency and productivity growth. Implementing appropriate policies and programs within the existing institutional structure can achieve these efficiency gains. The development calls for policies to improve efficiency and productivity growth (efficiency and technology). Proper and efficient use of resources (such as economic and energy expenditure) to stimulate GDP growth; proper and regulatory oversight of energy efficiency; and

climate financing tools to incentivize investments in technical improvement and fortify institutions that foster efficiency.

Appendix

Table 5 Average EE and MPI scores of 6 SA countries

Country	EE	MPI
India	0.4008	1.0087
Pakistan	1	1.0153
Bangladesh	0.6758	0.9708
Nepal	0.8933	0.9299
Sri Lanka	1	1.0156
Bhutan	0.3968	1.0698

Declarations

Ethics approval Not applicable.

Consent to participate Not applicable.

Consent to publish Not applicable.

Competing interests The authors declare no competing interests.

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