G20 COUNTRIES’ PROGRESS ON THE 7TH SDG UNDER CIRCULAR ECONOMY DEA MODEL

PROGRESSO DOS PAÍSES DO G20 NO 7º ODS SOB O MODELO DEA DE ECONOMIA CIRCULAR

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Abstract
The purpose of this paper was to analyze the performance of the G20 nations in terms of efficiency and productivity with respect to achieving the seventh Sustainable Development Goal (SDG 7) of providing affordable and clean energy between 2010 and 2019 under a circular economy framework. The diagnostic tools to measure included the output-oriented Data Envelopment Analysis (DEA, SBM) to determine efficiency and Malmquist Productivity Index (MPI) to measure productivity. In the DEA model, renewable energy is the primary energy source as input, and as outputs: total Greenhouse Gases [GHG] emissions, electricity consumption and renewable energy consumption. The results indicated that the efficiency and productivity of developed and emerging countries towards the 7th SDG targets were not homogeneous over the period of analysis. The results showed that among the G20 countries that ranked as efficient were emerging countries (South Africa, Brazil, India and China). Developed countries seem to have more to gain in efficiency by designing strategies with sustainable development and environmental policies consistent with CE actions than emerging countries. In addition, since productivity gains increased more due to efficiency changes than by technology gains, as indicated by the MPI analysis, it seems reasonable to infer that strengthening research and development of resource-efficient technologies could help to reach the 7th SDG faster by increasing productivity through adoption of new technologies. In the short run, all countries could benefit from a multilateral effort to reduce climate change and GHG emissions if developed countries provided technological support to emerging countries and the latter offered carbon credits to the former in exchange for measures to mitigate the emissions resulting from their rapid economic growth driven by capital investment.
Key words: G20 countries; Circular Economy, SDG 7 (affordable and clean energy), Data Envelopment Analysis (DEA), Malmquist Productivity Index (MPI)

Resumo
O objetivo deste artigo foi analisar o desempenho das nações do G20 em termos de eficiência e produtividade em relação ao alcance do 7º Objetivo de Desenvolvimento Sustentável (ODS) de fornecer energia acessível e limpa entre 2010 e 2019 sob uma estrutura de economia circular. As ferramentas de diagnóstico para medir incluíram a Análise Envoltória de Dados orientado ao *output* (DEA-SBM) para determinar a eficiência e o Índice de Produtividade Malmquist (MPI) para medir a produtividade. No modelo DEA, a energia renovável como fonte primária de energia foi utilizada como *input* e como *outputs*: emissões totais de Gases de Efeito Estufa [GEE], consumo de eletricidade e consumo de energia renovável total. Os resultados indicaram que a eficiência e a produtividade dos países desenvolvidos e em desenvolvimento em relação às metas do 7º ODS não foram homogêneas ao longo do período de análise. Os resultados mostraram que entre os países do G20 classificados como eficientes estavam os países em desenvolvimento (África do Sul, Brasil, Índia e China). Os países desenvolvidos parecem ter mais a ganhar em eficiência ao traçar estratégias com desenvolvimento sustentável e

políticas ambientais consistentes com as ações de CE do que os países em desenvolvimento. Além disso, uma vez que os ganhos de produtividade aumentaram mais devido a mudanças de eficiência do que a ganhos de tecnologia, conforme indicado pela análise do MPI, parece razoável inferir que o fortalecimento da pesquisa e desenvolvimento de tecnologias com uso eficiente de recursos poderia ajudar a atingir o 7º ODS mais rapidamente, aumentando a produtividade através da adoção de novas tecnologias. No curto prazo, todos os países poderiam se beneficiar de um esforço multilateral para reduzir as mudanças climáticas e as emissões de GEE se os países desenvolvidos dessem apoio tecnológico aos países em desenvolvimento e estes oferecessem créditos de carbono aos primeiros em troca de medidas para mitigar as emissões decorrentes de seu rápido crescimento econômico impulsionado pelo investimento de capital.
Palavras-chave: Países do G20; Economia Circular, 7º ODS (energia limpa e acessível), Data Envelopment Analysis (DEA), Malmquist Productivity Index (MPI)

1. Introduction

The equilibrium between using and replenishing natural resources has been disrupted due to the current socioeconomic model. Urgent action is needed to restore the equilibrium of the environment, such that sustainable development can be ensured. To address this issue, the concept of a more resource efficient and circular economy was developed. The circular economy approach focuses on the sustainable management of resources, in which material components are reused, shared, repaired, refurbished, remanufactured, and recycled to create a closed-loop system, as well as minimize the use of natural resources. The successful implementation of circular economy practices seems relevant for achieving progress on the United Nations Sustainable Development Goals (SDGs), particularly Goal7 (Clean and Affordable Energy). Without such access, economic and human development could be hindered. With this concern, this paper presents an analysis which ranks the performance of G20 countries with a DEA model set up to represent the achievement of goal 7 by adopting CE practices. The selection of variables for the DEA model analysis was based on a macroeconomic context explored by Schroeder et al. (2019) whom identified the relevance of CE practices to the achievement of the SDGs. These authors identified CE actions in consumption that were directly related to economic growth (Wang et al. 2022, Gyamfi, Bein & Bekun, 2020, Liu et al., 2022). The researchers determined that the Sustainable Development Goals most significantly affected by Circular Economy activities were the 7th (affordable and clean energy), 8th (decent work and economic growth), 12th (responsible consumption and production), 6th (clean water and sanitation) and 15th (life on earth), with particular emphasis in the first two from an economic perspective.

Pioneers in this matter, Meadows et al. (1972) introduced the concept that population growth and increased consumption require more efficient and sustainable natural resource management to meet the demand without damaging the environment. Later, the World Commission on Environment and Development (WCED) of the United Nations (UN) defined sustainable development as the capacity to satisfy the present generation's requirements without sacrificing the potential of future generations. This implies that the global economy should be able to eliminate hunger, secure basic standards of health care, hygiene, and education, without jeopardizing the future (UN, 1987).

Discussions on how to promote sustainable development have been gaining more attention through the last decades. In 2000, the United Nations Organization presented the Millennium Development Goals (MDGs) at the Millennium Summit. These were updated in 2015 and became the 17 Sustainable Development Goals (SDGs). The SDGs are expected to be accomplished by 2030 and include various objectives such as: no poverty, zero hunger, good health and wellbeing, quality education, gender equality, clean water and sanitation, affordable and clean energy, decent work and economic growth, industry, innovation, and infrastructure, reduced inequality, sustainable cities and communities, responsible consumption and production, climate action, life below water, life on land, peace and justice strong institutions, and partnerships to achieve the goal.

To promote sustainable development in line with the SDGs, the restructuring of the linear economic activities into a circular economy (CE) has been strongly supported in the literature (ELLEN MACARTHUR FOUNDATION, 2022). The study adds that to stimulate circularity of the economies, governments must create an enable appropriate environment for the development of circular business models and the adoption of a new way of consumption. This requires the implementation of regulatory, economic, and social instruments that incentivize and encourage companies to adopt circular business models. In addition, it is also important to increase public awareness and education on the opportunities, benefits, and strategies of CE, to ensure that the public is engaged and empowered to participate in the transition towards a circular economy. One of the key components to success is the development of a long-term vision that includes the integration of circular economy principles into the mainstream economy. Companies should start by assessing their current business model and identify opportunities for improvement, such as the reduction of waste, the adoption of new technologies, and the development of innovative business models. Furthermore, they should collaborate with other stakeholders to create a shared vision and design policies that incentivize the adoption of circular business models. The transition to a circular economy therefore requires a significant effort by all stakeholders involved, including governments, businesses, and civil society. For its large-scale implementation, the cooperation of all stakeholders is also necessary (Lieder e Rashid, 2016).

Wegge (2020) argues that the implementation of a CE could make production models more resilient to global supply disruptions – as in the scenario of the COVID-19 pandemic – and would help to achieve the SDGs. The transition to a circular economy can create 700,000 jobs by 2040, reduce greenhouse gas emissions by 25% and save US$ 200 billion per year (ELLEN MACARTHUR FOUNDATION, 2020).

Agbulut and Sarıdemir (2021) claim that fossil fuels are the most used energy source today, despite their environmental impact. By generating polluting gases that cause climate change and threatens the ecosystem, these have caused social turmoil and economic instability which cannot be ignored. They defended the urge in making the transition to energy sources that are low in emissions and have minimal environmental impact in order to sustain the progress of the past few centuries and meet most of the Sustainable Development Goals. (Bose, 2010; Clark & York, 2005; Erda, 2005; Lugus, 2017).

Biofuel or bioenergy is viewed as a potential means of reducing over-reliance on fossil fuels and encouraging efficient utilization of resources/waste to reach the SDGs, as well as in promoting a circular economy (Brandão, Gonçalves & Santos, 2021).

The G20 economies, comprising the European Union, twelve emerging nations, and seven developed countries, are notable for high levels of output growth. The considerable success records of these countries in the growth process can arguably be attributed to their massive capital investments. The Group of 20 is an intergovernmental forum that works to address major issues related to the global economy, such as international financial stability, climate change mitigation, and sustainable development. It includes the largest economies in the world - Argentina, Australia, Brazil, Canada, China, France, Germany, India, Indonesia, Italy, Japan, South Korea, Russia, United States, Mexico, Saudi Arabia, South Africa, Turkey, United Kingdom - plus the European Union, which accounted for 95.03% of the World's Gross Domestic Product and 65.32% of the world's population in 2021 (World Bank, 2022a). As these countries have a substantial effect on resource consumption and waste production, they were considered as a good reference for other nations in terms of the potential effects of using Circular Economy to reach SDGs. This research sought to evaluate the efficiency and productivity of the G20 countries in the context of the Circular Economy to evolve towards the 7th Sustainable Development Goal (affordable and clean energy) over the period of 2010-2019. For that purpose, econometric modeling, the Data Envelopment Analysis (DEA) – Slack Based Measure (SBM), and the Malmquist Productivity Index (MPI) were used to rank the performance G20 group of countries.

This paper is organized into seven sections. Section 2 shows an economic background. Section 3 presents a contextualization and the relation between CE and SDGs, section 4 provides literature review about G20 and sustainable development. The method description and econometric analysis are shown in Section 5. The results and discussions followed by efficiency and productivity analysis are presented in Section 6. Finally, section 7 summarizes the considerations of the paper.

2. Economic background

Resources have been subject to a higher pressure to meet the needed economic growth, given expected population growth in the following decades. There is a need to change consumption patterns to refrain negative impacts on the environment (Meadows et al., 1972) to assure sustainability. Lieder and Rashid (2016) argue that with the scenario of the increasing world population and the middle class, the demand for natural resources is expected to grow rapidly. Furthermore, it is not only the challenge to serve new consumers and combat environmental pollution that becomes critical, but also the scarcity of limited resources.

Regarding global challenges, as Weetman (2019) argues, the world population quadrupled in the 20th century. In addition, with the acceleration of industrial activities and changes in society, a significant portion of the population migrated from rural areas to cities. World trade accompanied this growth and globalization redesigned the business strategy in which industrial activities began to settle for emerging economies (Weetman, 2019).

It is estimated that in 2030, the world population will reach 8.5 billion inhabitants, and 9.7 billion in 2050 UN (2022). Expectations indicate that the world population will reach a peak in 2080, reaching 10.4 billion inhabitants, and remaining at this level until 2100 UN (2022).

In 2020, economic activity contracted in about 90% of countries, exceeding the number of countries that saw such declines during the two world wars, the great depression of the 1930s, the emerging economy debt crises of the 1980s, and 2007 to 2009 global financial crisis. After a sharp drop of 3.27% in 2020, due to the COVID-19 pandemic, world GDP growth projections for 2022 are 2.9%, and 3% for 2023 and 2024 (World Bank, 2022b). The effects culminated in a recession of approximately 3% of the world economy and global poverty increased for the first time in a generation. This scenario was compounded by a drop in demand, as the pandemic affected consumer behavior. Furthermore, it is suggested that the economic effects of the pandemic will be more persistent and more severe in emerging economies (World Bank (2022b).

After the collapse of per capita income worldwide, in 2020, 40% of the economies of high-income countries recovered and surpassed their 2019 level of production, already in 2021. The share of countries that achieved per capita income in 2021 higher than in 2019 is lower, however, for middle-income countries (27%), and even lower for low-income countries, at 21%, pointing to a slower recovery in emerging countries (World Bank, 2022b).

To complete the adverse scenario, in 2022 the developments of the War between Russia and Ukraine have caused inflation of commodity prices, causing food insecurity and poverty. The intensification of geopolitical tensions that extend to the energy sector, underscores the importance of a strong macroeconomic and structural policy response at the global and national levels (World Bank, 2022c).

Given this scenario, the short-term price increase resulting from the war between the two countries can serve as a warning about the importance of a long-term shift towards energy sustainability (Korosteleva, 2022, Tollefson, 2022). The results of the study by Zhou et al. (2023) show that replacing fossil energy is an effective way of dealing with the risk of war between Russia and Ukraine, as the more diverse the energy sources developed, the greater the capacity for autonomy, ensuring survival in situations of crisis.

Zhou et al. (2023) states that the war between Russia and Ukraine might induce a global energy and food security crisis for all countries. However, developed countries would face a relative crisis of reduced energy and food supply while in emerging countries the consequences would be even more severe. Therefore, for sustainable economic development, the existing international energy and food security organizations should try to balance the demand for global security between developed countries and emerging countries to prevent developed countries from importing and storing too much energy and food compromising supply for the underdeveloped countries (Zhou et al., 2023).

Therefore, policymakers must limit the economic speculation of some big players that base their interests on the misuse of natural resources, resulting in damage and global social impoverishment, while simultaneously providing energy to those who do not have it. creation of new markets and dissemination of well-being (Ayyildiz, 2022; D`Adamo, Gastaldi, Marone, 2022). Constantini et al. (2022) completes by stating that introducing practices that help to achieve the replacement of fossil fuels by renewable energies and reduction of general energy demand would favor social inclusion and equitable distribution of essential needs.

3. Circular Economy (CE) and Sustainable Development Goals (SDG)

Since the Second Industrial Revolution (1850), with the development of a linear production model oriented to extract resources from nature to produce and disposal, the planet has been in a situation of ecological overload (MEA, 2005). At this rate, 60% of Earth's ecosystems were affected or ceased to exist, while the world's population consumes 1.5 planets per year, restricting the planet's ability to replenish resources and absorb waste (MEA, 2005).

Evidence that the world is facing an unprecedented loss of ecosystem services due to industrialization and human activities is progressively higher. This is having a severe impact on the environment, economies, and public health, as well as our ability to meet the Millennium Development Goals. The full costs of these losses and degradation are not yet known, but there is a clear need to take urgent action to reverse the trend (MEA, 2005).

Economists have been studying ways to transition to a circular economy in which resources are continuously reused and recycled instead of being extracted and disposed of (Ellen MacArthur Foundation, 2020). The circular economy is based on three main principles: design out waste and pollution, keep products and materials in use, and regenerate natural systems (Ellen MacArthur Foundation, 2020). This transition is expected to create economic opportunities, such as job creation and new business models, while reducing environmental impacts (Ellen MacArthur Foundation, 2020).

Countries have been developing strategies consistent with sustainable development through partnerships and global cooperation, such as the Millennium Sustainable Development Goals (SDGs), and more recently, such as the concept of circular economy (CE) (UN, 2015; ELLEN MACARTHUR FOUNDATION, 2022).

Recently, a new report by the World Bank and the United Nations has highlighted the importance of the circular economy in achieving global sustainability goals. The report argues that circular economy can help countries reduce their reliance on finite resources and move towards a more resilient and sustainable economic system. The report identifies key areas where circular economy can be applied and provides a framework to help countries implement the principles of circular economy. The report suggests that countries should focus on three main areas: waste management, renewable resource use, and product design. In particular, the report emphasizes the need for countries to develop waste management strategies that move away from traditional linear approaches and instead focus on the reuse and recycling of resources. In terms of renewable resource use, the report encourages countries to develop strategies that maximize the use of renewable resources and minimize the use of finite resources. Finally, the report recommends that countries focus on product design that encourages the reuse and recycling of materials. The report also highlights the importance of global cooperation and partnerships in order to achieve the goals of sustainable development. The authors argue that countries must work together to create an effective framework that facilitates the implementation of circular economy principles. Overall, the report presents a comprehensive approach to achieving global sustainability goals and highlights the importance of the circular economy in achieving these objectives. Countries must work together to create a global framework that encourages the use of circular economy principles, and that this is an essential part of achieving sustainable development.

One of the most current definitions of CE presented by Korhonen et al. (2018), identifies it as a sustainable development initiative that aims to reduce the linearity of production-consumption systems and reduce the flow of materials and energy used in the manufacture of products. This means that instead of carrying out production in a linear fashion, CE promotes an adequate use of material cycles, together with traditional recycling and the development of cooperation systems between producers, consumers, and other social actors. There is already empirical evidence that this contributes to promoting sustainable development.

CE fits as a set of guidelines towards sustainability, as it can act as a tool that directs stakeholders to implement the principles of sustainable development (Kirchherr et al., 2017). According to Merli et al. (2018), despite the conceptualization, few CE studies involve social issues and sustainable development, failing to recognize, in broader terms, the social implications of a circular system.

Sánchez-Ortiz et al. (2020) argue that the main objective of CE is that the natural resources consumed in production have an unlimited life through the reuse of waste generated by the production process itself and the products since these become waste. This dynamic could partly solve the growing demand for increasingly scarce natural resources and promote the development of policies with global scope (Sánchez-Ortiz et al., 2020).

CE has been identified as a viable solution to the effects of the COVID-19 pandemic, which can be leveraged to direct activities that result in a better and more resilient low-carbon economy (Ibn-Mohammed et al., 2021). The pandemic crisis destroyed the main pillars of modern world economies, as global trade and cooperation succumbed to a nationalist focus and competition for scarce supplies, leading to the reshaping of supply chains and sectoral activities (Ibn-Mohammed et al., 2021).

In the pre-pandemic period, the progress towards the SDGs was slow, but the implementation of the SDGs was showing progress in important areas such as reducing poverty, improving maternal and child health, increasing access to electricity, and promoting gender equality. However, due to the pandemic unfolding, expectations suggest that about two-thirds of the 169 targets will not be met by 2030 (Naidoo; Fisher, 2020; UN, 2021)

Since 2020, the pace of progress on the SDGs has slowed even more and in some cases reaching stagnation, or even showing setbacks (UN, 2021). COVID-19 has brought to light the fact that the SDGs, as previously designed, are not resilient to the shocks imposed by pandemics.

Steiner (2020) recognized the setback caused to the SDGs due to COVID-19 but highlighted the important role of the G20 as a stimulator to synergistically put the SDGs back on track, due to its enormous capacity for global economic growth and the need to face the challenges caused by the pandemic.

Schroeder et al. (2019) identified the relationship between the 7th SDG (affordable and clean energy) with circular economy practices. Moreover, considering such definitions, when seeking the optimization and efficiency of production systems related to the trade-off of economic growth versus sustainable development, methods for measuring efficiency and productivity have gained increasing prominence in the literature, such as DEA and the Malmquist Productivity Index (MPI), enabling the development of CE indicators presented in next section.

4. Sustainable development, G20 and DEA models

He (2012) assessed Low-Carbon Management Performance (LCMPI) in G20 countries, using Data Envelopment Analysis (DEA) – Slack-Based Measure (SBM). The results showed that Europe, North America, and Japan presented the highest low-carbon management performance, identifying a relationship between these findings with countries with the highest level of economic development. In contrast, China demonstrated the lowest low-carbon management performance scores in reason of its huge energy consumption and CO_2 emissions.

A CO_2 emissions performance index and potential CO_2 emissions reduction index was developed by Choi (2013) using DEA. The results demonstrate that developed countries, with a high level of economic development in Europe, North America, and Japan showed the best carbon performance in line with He (2012). Besides, the potential level of carbon emission reduction was estimated, using Tobit regression to identify factors determining their carbon performance.

Chiu et al. (2016) calculated and analyzed G20 countries' productivity efficiency based on fossil-fuel CO_2 emissions, throughout 1991-2007, using DEA and Malmquist Index. The inputs were industry and population and as outputs GDP and the amount of fossil-fuel CO_2 emissions. The findings showed that some countries spent efforts to reduce CO_2 emissions, in coherence with Kyoto Protocol, but with results lower in productivity than before.

An Undesirable-Hybrid-Fuzzy DEA (UHFDEA) model to evaluate energy efficiencies was proposed by Wang et al. (2017). They applied this model to G20 countries. The results showed that the model is not only significant for assessing energy efficiency on a national level but also serves as a reliable and applicable tool for relative efficiency evaluation in similar situations. Also, Wang and Saito (2016) proposed a similar DEA method for investigating the efficiencies of different models of cars in reducing pollutant emissions.

Wang et al. (2019) estimated the well-being performance of carbon emissions in the G20 countries, from 2000 to 2015. They constructed non-parametric evaluation and decomposition models using hybrid measures and meta-frontier techniques. The results showed that the worst performance is in the BRICS (Brazil, Russia, India, China, and South Africa), whereas the development of the G20 group shows positive trajectories of performance.

Guo et al. (2021) applied a DEA-BCC model followed by a Malmquist Productivity Index for investigating the impact of agricultural science, technology, and innovation on the efficiency of G20 countries. The BCC model was the second DEA model developed and the first model based on the assumption of Variable Return to Scale (VRS). The BCC model used by there authors requires the choice of orientation (either inputs' minimization or outputs' maximization), which is hard to justify in practical means. Therefore, since the additive models (such as SBM) do not require the choice of orientation, they are understood as more adequate for practical applications (Dyckhoff Harald and Souren, 2020).

Sadorsky (2021) calculated eco-efficiency of the G20, using DEA-SBM model, MPI and a business as usual (BAU) scenario, over the period 1997 to 2040. The findings showed that the leaders in eco-efficiency were Australia, Brazil, France, Germany, Great Britain, Italy, Japan, Russia and the United States. The lagging countries were Canada, China, India and Indonesia, with negative growth rates in eco-efficiency.

Concerning sustainable economic and social development, Wu et al. (2022) evaluated energy efficiency of G20 economies from 2010 to 2014, using super-SBM model. The inputs were capital, labor and energy consumption and for outputs, they considered CO_2 emission and GDP. The overall average energy efficiency was 0.653 and developed countries were more efficient than emerging countries in line with He (2012) and Choi (2013).

This review suggests that there are gaps in the literature regarding studies on CE about the G20 countries in recent periods. This paper contributes to fill this gap as it investigates (a) the relationship between renewable energy with environmental variables connected to CE and the 7th SDG based in Schroeder et al. (2019); (b) G20, an important group of countries as a reference for comparing sustainable development policies worldwide; and (c) a more recent period, 2010 to 2019, through output-oriented DEA-SBM model and MPI.

5. Methodology

5.1. Data Envelopment Analysis (DEA)

The DEA procedures is widely used to calculate the relative efficiency of a system and assist in decision-making processes. Characterized by being a non-parametric property method, DEA is based on Mathematical Programming, which allows minimizing or maximizing functions with or without restrictions for the selected sample (Cook et al.; 2014). It measures the relative efficiency of Decision-Making Units (DMUs), which are responsible for transforming inputs into outputs. The efficiency value is established between 0 and 1 and the closer it is to 1, the more efficient is the DMU. Those that use the minimum value of their inputs without changing the number of outputs are considered efficient (Cook et al.; 2014).

The DEA's first presentation was in 1978 by Charnes, Cooper, and Rhodes (CCR) with the CCR model that measures the efficiency with constant returns to scale. Subsequently, to verify gains in efficiency scale, Banker, Charnes, and Cooper (BCC) created the BCC model or variable returns to scale Banker et al. (1984).

Along with the evolution of DEA models, Tone (2001) developed the SBM model, which uses slacks to construct an efficiency index, representing efficiency as an average reduction of inputs and an average increase of outputs to reach the efficiency frontier (Tone; 2001). In addition, the SBM model can be divided into two components relative to inputs or outputs. Therefore, its overall efficiency is the multiplication of the two components. To determine the efficiency of a DMU (x_{j0},y_{j0}), the SBM model can be used under Variable Returns to Scale (VRS) as represented by equations (1) to (5), as in Tone (2001):

$$\text{Minimize } \tau = t - \left({}^{1}/_{m} \right) \sum_{i=1}^{m} {}^{S_i^-}/_{x_{i0}} \tag{1}$$

Subject to

$$t + \left({}^{1}/_{s} \right) \sum_{r=1}^{s} {}^{S_r^+}/_{y_{r0}} = 1 \tag{2}$$

$$\sum_{k=1}^{z} \Lambda_k \, x_{ik} + S_i^- - t x_{i0} = 0 \qquad i=1,2,\ldots,m \tag{3}$$

$$\sum_{k=1}^{z} \Lambda_k \, y_{rk} - S_r^+ - t y_{r0} = 0 \qquad r=1,2,\ldots,s \tag{4}$$

$$\Lambda_k \geq 0,\ S_i^- \geq 0,\ S_r^+ \geq 0, \text{ and } t > 0 \tag{5}$$

Where: τ = the efficiency, t = the model linearization variable, S_i^- = the slack of the input i, S_r^+ = the slack of the output r, Λ_k = the participation of DMU k in the goal of the DMU under analysis, x_{i0} = quantity of input i of the DMU under analysis, y_{r0} is the rth output of the DMU under analysis, x_{ik} = quantity of input i of the DMU k, y_{rk} = quantity of output i of the DMU k, z = number of analyzed units, m = the number of inputs, and s = the number of outputs.

As the VRS was assumed, a constraint such as represented by the equality (6), must be added to the model:

$$\sum_{k=1}^{z} \Lambda_k = t \tag{6}$$

In this paper, we applied a DEA-SBM model output-oriented with Variable Returns to Scale (VRS). To deal with the heterogeneity of G20 countries, we chose the model under VRS, accounting for the scale of the DMUs (countries). According to Cook; Seiford (2009), the DEA-VRS models allow to identify efficiency models when an increase or decrease in inputs or outputs does not result in a proportional change in the outputs or inputs respectively.

An important point to consider in efficiency models focused on environmental issues are the undesirable outputs, that is, they are the outputs, when represented as variables to be minimized in the model and not maximized (LIU et al. 2015; 2010). To deal with undesirable outputs Scheel (2001) suggests three procedures that can be applied: a) inverse additive, b) translated and c) inverse multiplicative.

According to the author, the inverse additive procedure corresponds to considering the values of the undesirable outputs as inputs $f(U) = -U$. This technique where the undesirable outputs being placed as inputs would be minimized in the DEA model and no longer maximized.

The translated method adds a scalar vector to the values of the undesirable outputs which transforms them into desirable outputs $f_i^k(U) = -u_i^k + \beta_i$ In this way, the values are converted into outputs, which are intended to be maximized.

An inverse multiplicative process can also be used, which is equivalent to inverting the values of the undesirable outputs $f_i^k(U) = 1/u_i^k$. Observe that the efficiency ranking is maintained when applying the inverse or multiplicative inverse technique. Therefore, if a DMU is classified as efficient using the inverse multiplicative procedure, this same DMU will also be efficient applying the inverse additive method. Chart 1 illustrates these alternatives and their respective mathematical transformations.

Chart 1. Procedures applied to undesirable outputs and their mathematical transformations

Procedure	Mathematical transformation
a) Reverse additive	$f(U) = -U$
b) Translated	$f_i^k(U) = -u_i^k + \beta_i$
c) Inverse multiplicative	$f_i^k(U) = 1/u_i^k$

Source: Adapted from Scheel (2001)

5.2. Malmquist Productivity Index (MPI)

To include the time factor – years from 2010 to 2019 -, we used the DEA-based Malmquist Productivity Index (MPI) proposed by Fare; Grosskopf (1992) and Fare et al. (1994), based on Malmquist (1953) and Caves et al. (1982). It is adequate to measure productivity change through time, considering the efficiency changes and technological progress (frontier changes) separately.

The intertemporal scores from the MPI can be calculated using the Super-efficiency model because it can assume values greater than 1. According to Tone; Tsutsui (2017), the non-oriented Super-SBM, even under VRS assumptions, does not incur an infeasibility problem. An equivalent Super-SBM model with a form similar to the linear standard SBM is as follows in Equations 15 to 19 Fang et al. (2013).

$$\text{Minimize } \tau^{super} = t + \frac{1}{m} \sum_{j=1}^{m} \frac{H_j^-}{x_{j0}} \tag{7}$$

Subject to

$$t - \frac{1}{n} \sum_{i=1}^{n} \frac{H_i^+}{y_{i0}} = 1 \, , \tag{8}$$

$$\sum_{k=1,k\neq 0}^{z} x_{jk} \cdot \Lambda_k - H_j^- - t \cdot x_{j0} \leq 0 \qquad j=1,2\ldots,m \tag{9}$$

$$\sum_{k=1,k\neq 0}^{z} y_{ik} \cdot \Lambda_k + H_i^+ - t \cdot y_{i0} \geq 0 \qquad i=1,2\ldots,n \tag{10}$$

$$H_i^+ \leq y_{i0}, H_i^+ \geq 0, H_j^- \geq 0, \Lambda_k \geq 0, t > 0 \, , \tag{11}$$

Where τ^{super} = the Super-efficiency, H_i^+ = the linearized input savings rate for the linear problem ($H_i^+ = th_i^+$), H_j^- = the linearized output surplus rate for the linear problem ($H_j^- = th_j^-$), h_i^+ = the input savings for the Super-efficiency model, h_j^- = the output surplus for the Super-efficiency model. The other parameters and variables are the same as in Equations 1 to 5. For the output-oriented super-SBM model, the H_i^+ linearized input savings rate for the linear problem of the model from Equations 15 to 19 is considered as zero.

As the VRS assumption was investigated, it was needed to add the constraint from Equation 6 in the Super-efficiency model (Equations 15 to 19).

The DEA-based MPI under the VRS assumption can be computed in a similar way as the MPI proposed by Färe et al. (1994), based on a comparison of efficiencies from two periods and two intertemporal scores using the DEA-VRS models. The MPI under VRS and its decompositions into technological changes – TC (or frontier shift) and efficiency changes – EC (or catch-up effect) are formulated as shown in Equations 20 to 22 Cooper et al. (2011).

$$TC_{VRS}=\sqrt{\frac{D^{t}_{VRS}\,(x^{t+1},\, y^{t+1})\cdot D^{t}_{VRS}\,(x^{t},\, y^{t})}{D^{t+1}_{VRS}\,(x^{t+1},\, y^{t+1})\cdot D^{t+1}_{VRS}\,(x^{t},\, y^{t})}} \quad (12)$$

$$EC_{VRS}=\frac{D^{t+1}_{VRS}\,(x^{t+1},\, y^{t+1})}{D^{t}_{VRS}\,(x^{t},\, y^{t})} \quad (13)$$

$$MPI_{VRS}=\sqrt{\frac{D^{t}_{CRS}\,(x^{t+1},\, y^{t+1})\cdot D^{t+1}_{CRS}\,(x^{t+1},\, y^{t+1})}{D^{t}_{CRS}\,(x^{t},\, y^{t})\cdot D^{t+1}_{CRS}\,(x^{t},\, y^{t})}}=TC_{VRS}\cdot EC_{VRS} \quad (14)$$

Where) $D^{t}_{VRS}\,(x^{t},\, y^{t})$ is the efficiency considering the scale of the DMU under analysis in period t in comparison to the frontier in period t, $D^{t+1}_{VRS}\,(x^{t+1},\, y^{t+1})$ is the efficiency considering the scale of the DMU under analysis in period t+1 in comparison to the frontier in period t+1, $D^{t}_{VRS}\left(x^{t+1},\, y^{t+1}\right)$ is the intertemporal score considering the scale of the DMU under analysis in period t+1 in comparison to the frontier in period t, $D^{t+1}_{VRS}\,(x^{t},\, y^{t})$ is the intertemporal score considering the scale of the DMU under analysis in period t in comparison to the frontier in period t+1. So, it is the MPI, but using the models under the VRS assumption.

5.3. Empirical methodological procedures

We organized the empirical methodological procedures of this article in the following stages) a) selection of variables; b) econometric analysis, c) DEA efficiency results, and d) MPI productivity results.

5.3.1. Selected variables

The variables selected for the 7th SDG (Clean and Affordable Energy) corresponded to energy supply and environmental variables related to the Circular Economy. Based on the Circular Economy concepts of Ellen McArthur Foundation (2022), to represent the linear model, the variables of gross capital formation (%) and workforce (number of workers) were considered.

The 7th SDG (Clean and Affordable Energy) takes place in the energy sector. Regarding the Circular Economy in the context of Renewable Flow Management, the variable renewable energy (primary source), in percentage value of total energy consumed, was selected as input along with other variables related to energy access such as percentage of population with access to fuels and clean technologies for cooking and energy and renewable consumption (in percentage value of total energy consumption. For the Inventory Management, we considered variables of electricity consumption (TWh) and population that has access to electricity (in percentage value of the total population) as outputs. As externalities of the 7th SDG (Clean and Affordable Energy), the variable total GHG emissions ($MtCO_2eq$) was considered as an undesirable output. Figure 1 illustrates the framework for selecting variables for this SDG.

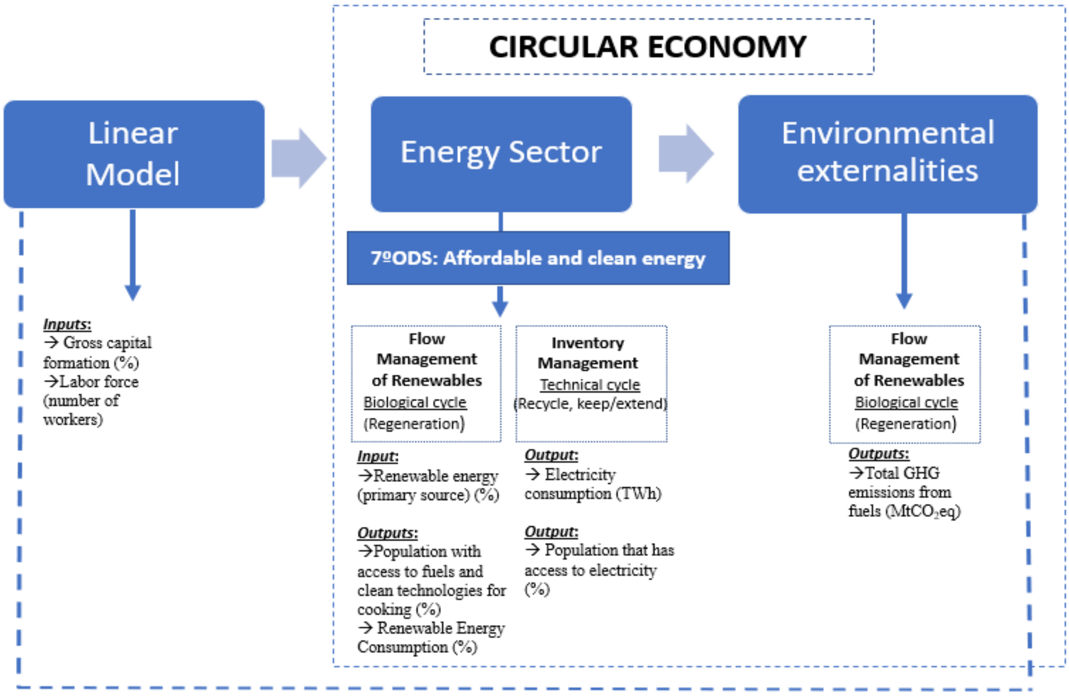

Figure 1. Framework for the selection of variables of the 7th SDG (Clean and Affordable Energy)
Source: Own elaboration based on Ellen McArthur Foundation (2022)

A database was created for eighteen of the G20 countries: Argentina, Australia, Brazil, Canada, China, France, Germany, India, Indonesia, Italy, Japan, Korea, Mexico, Russia, South Africa, Turkey, United Kingdom United States and United States. Saudi Arabia was excluded, since the country does not use renewable energy as a primary source of energy.

The analysis period was from 2010 to 2019, due to data availability and considering the most up-to-date periods with a standardized database.

As explained before, the purpose of the 7th SDG is to assure that each country can increase international cooperation to facilitate access to clean energy research and technologies, including renewable energy, energy efficiency and cleaner fossil fuel technologies, in addition to promoting investment in sustainable energy infrastructure (Rusydiana et al., 2021).

Renewable energy as a primary energy source, gross capital formation, access to electricity and access to clean fuels and cooking technologies, and renewable energy consumption are expressed in percentage terms of the total at each country. Electricity consumption is given in Terawatt-hours, workforce is given in number of workers, and total GHG emissions are given in millions of metric tons of carbon dioxide equivalent.

In the analyzed period (2010–2019), considering the eighteen G20 countries mentioned, renewable energy as a primary energy source grew by an average of 2.82%, registering the largest decrease in Indonesia (3.19%) and the highest rate of growth in the United Kingdom (12.54%). Gross capital formation presented an average reduction of 0.72%, with the most accentuated decrease in Brazil (4.11%) and the most significant increase in Japan (1.46%). The workforce grew by an average of 1.02%, being more expressive in Turkey (2.41%) and showing the biggest drop in Russia (0.25%).

Access to electricity increased by 0.25%, with the highest increase in India (3.13%). Access to clean fuels and cooking technologies grew by 0.99%, with the sharpest drop observed in Russia (1.11%) while Indonesia had the highest increase (7.28%). Electricity consumption increased by 1.48% on average, with the highest growth in China (6.38%) and the lowest in Japan (1.36%). GHG emissions increased by 0.17%, with the sharpest reduction in the United Kingdom (3.88%) and the largest increase in India (3.92%). And finally, the total consumption of renewable energy grew by 2.11%, registering the biggest expansion in the United Kingdom (12.32%) and the biggest decrease in Indonesia (7.21%). The descriptive analysis of the variables is shown in Table 1.

Table 1. Descriptive analysis of the variables for the 7th SDG (2010-2019 period)

Variable	**Obs.**	**Average**	**Standard Dev.**	**Min.**	**G20 countries (Min.)**	**Max**	**G20 countries (Max.)**
Renewable energy (primary source) (%)	180	12.22	9.9702	0.7	Korea	45.60	Brazil
Gross capital formation (%) (% GDP)	180	24.75	7.3449	14.21	Argentina	46.66	China
Labor force (number of workers)	180	116,599,629.98	119,784,863.50	116.611.96	Australia	795,572,880.00	China
Electricity consumption (TWh)	180	967.39	1441.96	114.7	Argentina	7154.60	China
Population that has access to electricity (% of total population?)	180	98.03	5.1664	67.6	India	100.00	Germany. Australia. Canada. Korea. United States. France. Italy. Japan. United Kingdom and Turkey
Population with access to fuels and clean technologies for cooking ((% of total population?))	180	90.43	15.7924	35.4	India	100.00	Germany. Australia. Canada. Korea. United States. France. Italy. Japan and United Kingdom
Total GHG emissions from fuels ($MtCO_2eq$)	180	1371.38	2210.99	164.2	Argentina	10,041.90	China
Renewable Energy Consumption (% of total energy consumed)	180	14.67	10.81	1.32	Korea	47.57	Brazil

Source: Own elaboration

5.3.2 Econometric validation

As a second stage, econometric models were set to validate the relation between intputs and each output. Since DEA is a non-parametric tool, it has been common to validate the relationship between outputs and inputs by estimating Linear Regression Analysis with these variables, describing the best linear fit of the data for prediction (Kazmier ; 2004).

To validate the efficiency model, the dependent variable is one of the model's outputs, while the set of independent of explanatory variables includes the inputs. For this research, estimations were useful to evaluate the degree of explanation between each output and potential set of inputs (Equation 23).

$$y^{Output}_{it}=\beta_0+\beta_1 INP1_{it}+\varepsilon_{it} \quad (15)$$

Where y^{Output} is the dependent variable (output); β_0 represents the intercept; β_1 is the explanatory variable coefficient; (*INP1*) is Input 1; *i* represents the i^{th} observation (DMUs); *t* is the t^{th} period and ε is the random error.

We transformed the variables into a logarithmic form such that the parameters can be interpreted as elasticities (Greene, 2019). We estimated panel data models which can result in estimates with heteroscedasticity, autocorrelation, and endogeneity problems (Greene, 2019; Wooldridge, 2019). To correct for these problems, we chose the Feasible Generalized Least Squares (FGLS) model, as presented in Moralles; Do Nascimento Rebelatto (2016) and Campoli et al. (2020).

6. Results and discussion

6.1. DEA analysis

To prepare the efficiency and productivity models for the 7th SDG (Clean and Affordable Energy), econometric validation was carried considering the 18 G20 countries from 2010 to 2019. Saudi Arabia is excluded, as the country does not consume renewable energy. The econometric equations applied to panel data to verify the relationship between the following models:

$$Ln\_y^{GEE}{}_{it} = \beta_0 + \beta_1 FC_{it} + \beta_2 Ln\_FT_{it} + \beta_3 Ln\_ER_{it} + \varepsilon_{it} \quad (16)$$

$$y^{EL}{}_{it} = \beta_0 + \beta_1 FC_{it} + \beta_2 Ln\_FT_{it} + \beta_3 Ln\_ER_{it} + \varepsilon_{it} \quad (17)$$

$$y^{TL}{}_{it} = \beta_0 + \beta_1 FC_{it} + \beta_2 Ln\_FT_{it} + \beta_3 Ln\_ER_{it} + \varepsilon_{it} \quad (18)$$

$$Ln\_y^{CEL}{}_{it} = \beta_0 + \beta_1 FC_{it} + \beta_2 Ln\_FT_{it} + \beta_3 Ln\_ER_{it} + \varepsilon_{it} \quad (19)$$

$$y^{CER}{}_{it} = \beta_0 + \beta_1 FC_{it} + \beta_2 Ln\_FT_{it} + \beta_3 Ln\_ER_{it} + \varepsilon_{it} \quad (20)$$

Where: β_n $(n = 0, \ldots, 3)$ are the estimated coefficients, y^{GEE} are total GEE emissions from fossil fuel, y^{EL} is the percentage of total population with access to energy, y^{TL} is the percentage of total population with access to fuel and clean technologies for cooking, y^{CEL} is the electricity consumption, y^{CER} is the percentage represented by renewable energy from total energy consumed, FC is the percentage of capital formation with respect to GDP; FT is the total labor force (expressed in number of workers); EP is the renewable energy as a primary source of energy and ε is the random error. The results of the regression analysis are summarized in Table 2.

Table 2. Econometric estimates of outputs in relation to inputs for the 7th SDG (Clean and Affordable Energy)

Inputs		*Outputs*				
		Total GHG emissions from fuels (in ln)	Population that has access to electricity (%)	Population with access to fuels and clean technologies for cooking (%)	Electricity consumption (in ln)	Renewable Energy Consumption (%)
Gross capital formation (%)	*Coef.*	-0.00198	-0.00380	-0.0379	-0.00182	0.0126
	p-value	0.3960	0.8220	0.4000	0.2880	0.4740
	Std. Errors	(0.00233)	(0.0169)	(0.0450)	(0.00172)	(0.0176)
Labor force (number of workers) (in ln)	*Coef.*	0.836***	0.00715	-2.808***	0.726***	0.187
	p-value	0.0000	0.9670	0.0030	0.0000	0.4850
	Std. Errors	(0.0314)	(0.170)	(0.930)	(0.0595)	(0.268)
Renewable energy (primary source) (%)	*Coef.*	-0.0361***	-0.0162	-0.0155	-0.0166***	1.056***
	p-value	0.0000	0.4050	0.8070	0.0000	0.0000
	Std. Errors	(0.00188)	(0.0195)	(0.0633)	(0.00204)	(0.0247)
Constant	*Coef.*	-7.805***	100.0***	147.5***	-6.295***	-2.200
	p-value	0.0000	0.0000	0.0000	0.0000	0.6410
	Std. Errors	(0.529)	(3.062)	(15.86)	(1.026)	(4.723)
Obs.		180	180	180	180	180
Number of DMUs		18	18	18	18	18

Statistical significance levels: ***: $p < 0.01$; **: $p < 0.05$: * $p < 0.1$

Source: Own elaboration

The regressions were set to evaluate the potential outputs as endogenous variables in the econometric models, including total GHG emissions from fossil fuels, population with access to electricity, population with access to fuels and clean technologies for cooking, electricity consumption and renewable energy consumption. The potential inputs, set as explanatory variables, includes gross capital formation, labor force and renewable energy as a primary source of energy.

Gross capital formation was not show statistically significant to explain potential output in all the regressions and was removed from the efficiency and productivity models.

The labor force showed positive statistical significance at the 1% level to explain the following potential outputs: total GHG emissions from fuels and electricity consumption. Furthermore, this labor force also showed negative significance at the 1% level to explain the size of population with access to fuels and clean technologies for cooking. In addition, the labor force was not significant to explain the potential outputs: population that has access to electricity and consumption of renewable energy. Since it does not show significance to explain renewable energy consumption, it was removed from the efficiency and productivity models.

Renewable energy as a primary source proved to be positively significant at the 1% level to explain total GHG emissions from fuels and electricity consumption. Furthermore, it presented positive significance at the 1% level with the consumption of renewable energy. After the econometric validation, the variables for the efficiency and productivity model were selected, as shown in Chart 2.

Chart 2. Efficiency and productivity model from the Circular Economy perspective for the 7th SDG: Clean and Affordable Energy

Efficiency and productivity model from a Circular Economy perspective for the 7th SDG	
Input	*Outputs*
a) Renewable energy as a primary energy source	1) Total GHG emissions from fossil fuels 2) Electricity consumption 3) Renewable energy consumption

Source: Own elaboration

To verify the efficiency of the G20 towards the 7th SDG (Clean and Affordable Energy) from the perspective of the Circular Economy, renewable energy production as the primary source of energy was used as input in the DEA model. As outputs, we used total GHG emissions from fossil fuels, electricity consumption and renewable energy consumption. In the context of the model, the first two variables are undesirable outputs. To deal with this issue, an inverse multiplicative procedure was used, as explained in section 5.1.

The average efficiency of the G20 was relatively constant through the period of analysis, with a slight reduction by less than one percent from 0.6304 in 2010 to 0.6246 in 2019. The only developed country that showed efficiency through the whole period was South Korea. France reached efficiency from 2013 onwards. Other efficient countries were all emerging countries, including South Africa, Argentina, Brazil and India. Indonesia went through an opposite path, starting on the efficiency frontier and becoming inefficient from 2016 onwards, with 0.7884 and decreasing even further until reaching 0.5179 in 2019.

The countries with efficiency below 50% in 2019 were: Mexico (49.84%), Russia (42.67%), Germany (36.63%), Japan (26.05), United States (5.6%) and China (5.54%), which is mostly explained by their use of fossil fuels and high rates of GHG emissions.

The countries with the highest increase in renewables in their energy matrix were: United Kingdom (70.49%), South Korea (65%) and France (24.53%) – a fact that contributed to this DMU reaching efficiency - Japan (41.27%), Germany (38%), United States (27.85%), Italy (30.39%) and Australia (27.40%).

It was observed that emerging countries increased their electricity consumption at a faster pace than others. The DMU with the highest consumption of electricity was China (44.96%), followed by Indonesia (43.25%), India (42.79%), Turkey (33.75%) and Mexico (24.49%). Developed countries that managed to reduce energy consumption were the United Kingdom (12.17%) and Japan (12.77%).

The DMUs that had the highest increase in GHG emissions were India (30.53%), Indonesia (29.71%), Turkey (26.45%) and China (20.89%), which are all emerging countries. On the other hand, those that managed to reduce emissions more significantly were all developed countries: United Kingdom (39.95%), Italy (26.48%), Germany (17.46%), France (15.51%) and the United States

(12.59%). These countries, as well as other G20 countries signed by "The Paris Agreement" against climate change (UNFCCC, 2015). The empirical results of the efficiency scores are shown in Table 3.

Table 3. Efficiency scores referring to the 7th SDG (Clean and Affordable Energy)

	Efficiency scores									
Countries	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**
Germany	0.2946	0.3226	0.3309	0.3345	0.3432	0.3558	0.3489	0.3466	0.3547	0.3663
Australia	0.8688	0.8659	0.8957	1.0000	0.8301	0.8927	0.7356	0.7272	0.7460	0.7248
Canada	0.4730	0.4880	0.5120	0.5120	0.5210	0.5570	0.5630	0.6090	0.5660	0.5710
South Korea	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
United States	0.0538	0.0566	0.0585	0.0604	0.0518	0.0592	0.0533	0.0569	0.0515	0.0560
France	0.5706	0.6000	0.6714	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
Italy	0.5058	0.5269	0.5760	0.6361	0.6671	0.6630	0.6540	0.6354	0.6358	0.6240
Japan	0.2673	0.2669	0.2695	0.2735	0.2769	0.2710	0.2740	0.2759	0.2743	0.2605
United Kingdom	0.6111	0.6059	0.5809	0.5541	0.5138	0.5230	0.5294	0.5347	0.5450	0.5519
Average developed countries	0.5161	0.5259	0.5439	0.5968	0.5782	0.5913	0.5731	0.5762	0.5748	0.5727
South Africa	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
Argentina	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
Brazil	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
China	0.0579	0.0520	0.0553	0.0580	0.0434	0.0479	0.0421	0.0463	0.0550	0.0554
India	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
Indonesia	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	0.7885	0.7124	0.5813	0.5179
Mexico	0.5251	0.5162	0.5172	0.5398	0.5446	0.5460	0.5329	0.5246	0.5099	0.4984
Russia	0.3159	0.3266	0.3313	0.3429	0.3881	0.4008	0.3827	0.4166	0.4416	0.4267
Turkey	0.8021	0.7579	0.7490	0.7751	0.6921	0.7154	0.6751	0.5901	0.5814	0.5905
Average emerging countries	0.7446	0.7392	0.7392	0.7462	0.7409	0.7456	0.7135	0.6989	0.6855	0.6766
Total average	0.6304	0.6325	0.6416	0.6715	0.6596	0.6684	0.6433	0.6375	0.6302	0.6246

Source: Own elaboration

The DMUs considered efficient such as? South Korea, South Africa, Argentina, Brazil and India, can be used as a reference for the others to achieve better performances. Except for South Korea, all other DMUs are emerging countries. It can be concluded that countries where the primary energy supply based on fossil fuels was higher than the supply based in renewable fuels were identified as inefficient by the DEA model.

Argentina and South Korea showed a similar tendency as both increased their primary supply of renewable as well as the total consumption of renewable energy what possibly led these DMUs to achieve efficiency. South Africa, in turn, managed to reduce its electricity consumption, which contributed to the country reaching the efficiency frontier. Although India has shown a drop in the supply and consumption of renewable energy, it is still a country with a significant supply of primary renewable energy (average of 23.32%) in terms of consumption of renewable energy (33.92%).

Brazil has made efforts to produce biofuels from sugarcane and corn, as well as second-generation biofuels, which reduces the pressure on the cultivated area. These are in line with the 15th SDG (Terrestrial Life) (KHANNA et al., 2021). Brazil has also been identified as the country with the highest percentage of primary energy based on renewables (average of 42.09%) and also highest consumption of renewable energy (44.85%). Therefore, the country can be considered as highly contributing to the mitigation of GHG emissions regarding these aspects.

The MPI showed that the average change in productivity of the G20 countries being evaluated was 0.8608 over 2010-2019, which indicates that the G20 countries suffered a loss of productivity.

For developed countries, the calculated MPI was 0.7183 suggesting productivity loss in the process of being able to reduce emissions and reach the 7th ODS under Circular Economy assumptions. Only Canada produced an MPI greater than one (1.0329), while Italy maintained an MPI=1 for the period. As for the emerging countries it was 1.0033, indicating a slight increase in productivity in the latter (MPI>1). The emerging countries with individual MPI ≥1 were South Africa (1.0400), India (1.4400) and Indonesia (1.0360).

It can be seen that for developed countries group, the loss of productivity (MPI) was more affected by efficiency loss (with AE equal to 0.8344) than by technology, since TA resulted in a higher value of 0.8647. Regarding the AE, the DMUs with the highest scores were South Korea and Italy, however both with AE=1, indicating stability instead of gains. Regarding the AT, Canada (1.1994) was the country that most benefited from the technological changes of the period and that affected all DMUs. Italy, in turn, only maintained productivity in the period with AT=1.

In emerging countries, there is an increase in productivity due to AE (1.2104) and loss due to fail in catching up with technology (TA = 0.9556). Countries with AE ≥1 were Russia (3.1655) and Mexico (1.0442). South Africa, Argentina, Brazil and India remained stable with AE=1. Regarding TA scores in emerging countries, the highest scores were in South Africa (1.0400), India (1.4400) and Indonesia (1.0360), which are also the only DMUs in this group that showed productivity gains due to technological changes. Individual results for productivity scores obtained by each country (DMU) are presented in Table 3.

Table 3. Productivity scores referring to the 7th SDG (Clean and Affordable Energy)

	Productivity scores		
Countries	**AE**	**AT**	**MPI**
Germany	0.9773	0.9471	0.9256
Australia	0.7513	0.8384	0.6299
Canada	0.8612	1.1994	1.0329
Korea	1.0000	0.4458	0.4458
United States	0.8601	0.8058	0.6931
France	0.7295	0.9809	0.7155
Italy	1.0000	1.0000	1.0000
Japan	0.8147	0.7178	0.5848
United Kingdom	0.5156	0.8475	0.4370
Average developed countries	0.8344	0.8647	0.7183
South Africa	1.0000	1.0400	1.0400
Argentina	1.0000	0.9086	0.9086
Brazil	1.0000	0.9961	0.9961
China	0.7622	0.9262	0.7060
India	1.0000	1.4400	1.4400
Indonesia	1.0000	1.0360	1.0360
Mexico	1.0442	0.9517	0.9938
Russia	3.1655	0.3159	1.0000
Turkey	0.9221	0.9862	0.9094
Average emerging countries	1.2104	0.9556	1.0033
Total average	1.0224	0.9102	0.8608

Source: Own elaboration

In the general context, an average AE (1.0224) greater than AT (0.9102) means that productivity gains were related to AE, suggesting that the countries improved their efficiencies in reaching the 7th ODS with circular economy and mostly with use of capacity to generate and use renewable energy. The average AT<1 means that the DMUs were unable to increase their optimal production weights suggesting that technological changes were not the factor responsible for Overall, the G20 countries showed a loss of productivity in the energy sector to advance the achievement of the 7th SDG.

7. Conclusion

It is intriguing to analyze the performance of the G20 countries in relation to the UN's Sustainable Development Goals (SDGs), as they make up a considerable proportion of the global economy, including both developed and emerging nations. Such an assessment provides a clear view of the existing status of the world in terms of fulfilling the SDGs and discerning the differences between countries which must be addressed if collective action is to be taken towards achieving this shared objective. In this paper we focused on the progress towards the 7th SDG (affordable and clean energy) with the adoption of circular economy related changes on a major component which is the change of primary energy sources from fossil to renewable energy sources with lower GHG emission capacity.

The results suggests that the efficiency and productivity of emerging and developed countries in relation to CE procedures to reach the 7th SDG targets were very heterogeneous over the period of analysis. A greater number of emerging countries (South Africa, Brazil, India and China) were efficient compared to developed countries. This might be explained not only by abundant non fossil fuels sources to produce energy, such as biomass, water and wind but also by real efficiency gains in changing the energy matrix profile away from fossil fuels. In Brazil, for example, ethanol and other biofuels programs have been advancing for decades.

Developed countries seem to have more to gain in efficiency to reach the 7^{th} SDG (affordable and clean energy) with the adoption of circular economy practices, which can be mostly explained by their use of fossil fuels and high rates of GHG emissions.

In addition, since productivity gains through the period of analysis increased more due to efficiency changes than by technology gains, as indicated by the MPI analysis, it seems reasonable to infer that strengthening research and development of resource-efficient technologies could help to reach the 7th SDG targets faster. If developed countries interact more with emerging countries in this matter, there could be mutual gains through technology transfer and adoption support from developed to emerging countries to build a multilateral effort for common interests in reaching SDGs. In the short run, all countries could benefit from a multilateral effort to reduce climate change and GHG emissions if developed countries provided technological support to emerging countries and the latter offered carbon credits to the former in exchange for measures to mitigate the emissions resulting from their rapid economic growth driven by capital investment.

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