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Sustainability and Renewable Energy: a Data Envelopment Analysis application

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Sustainability and Renewable Energy: a Data Envelopment Analysis application

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ATA DA DEFESA PÚBLICA DA DISSERTAÇÃO DE MESTRADO DE GEOVANNA BERNARDINO BELLO, DISCENTE DO PROGRAMA DE PÓS-GRADUAÇÃO EM ENGENHARIA DE PRODUÇÃO, DA FACULDADE DE ENGENHARIA - CÂMPUS DE BAURU.

Aos 26 dias do mês de março do ano de 2024, às 14:00 horas, por meio de Videoconferência, realizou-se a defesa de DISSERTAÇÃO DE MESTRADO de GEOVANNA BERNARDINO BELLO, intitulada **SUSTAINABILITY AND RENEWABLE ENERGY: A DATA ENVELOPMENT ANALYSIS APPLICATION**. A Comissão Examinadora foi constituida pelos seguintes membros: Prof. Dr. DIOGO FERRAZ (Orientador(a) - Participação Virtual) do(a) Departamento de Economia / Universidade Federal de Ouro Preto - UFOP, Prof.ª Dr.ª DAISY APARECIDA DO NASCIMENTO REBELATTO (Participação Virtual) do(a) Departamento de Engenharia de Produção / Escola de Engenharia de São Carlos - EESC/USP, Prof. Dr. ENZO BARBERIO MARIANO (Participação Virtual) do(a) Departamento de Engenharia de Produção / Faculdade de Engenharia de Bauru - FEB/UNESP. Após a exposição pela mestranda e arguição pelos membros da Comissão Examinadora que participaram do ato, de forma presencial e/ou virtual, a discente recebeu o conceito final: APROVADA. Nada mais havendo, foi lavrada a presente ata, que após lida e aprovada, foi assinada pelo(a) Presidente(a) da Comissão Examinadora.

Prof. Dr. DIOGO FERRAZ

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DEDICATION

To God, firstly;

To my lovely family;

To my supervisor Prof. Doctor Diogo Ferraz;

To the friends who supported me at this stage of my life.

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There is no demand for women engineers, as such, as there are for women doctors; but there's always a demand for anyone who can do a good piece of work.

Edith Clarke Quotes

ABSTRACT

The current global context presents the challenge of reducing the impact of production and consumption on the environment through the reuse of materials and energy. This dissertation aims to evaluate the performance of countries in this field. The research uses both quantitative and qualitative approaches, with two chapters: the first conducts a bibliometric review on sustainability and Data Envelopment Analysis (DEA), while the second focuses on constructing a renewable energy efficiency indicator through DEA. The results reveal variations in renewable energy efficiency between groups of countries, allowing for benchmarking and identification of nations with low efficiency in the use of renewable energy. The main contribution of this study is the creation of the Renewable Energy Index (REI), which highlights the potential for top 10 global performance in both developed countries (such as Sweden) and developing countries (such as Costa Rica and Sri Lanka). The study reveals that countries in central and northern Europe are among the most efficient, while those with political and economic instability remain among the lowest performers. Furthermore, nations with a predominant agricultural sector, such as Australia and Argentina, exhibited poorer REI performance due to significant methane emissions. This study also contributes to the mitigation of climate change and the advancement of the global sustainability agenda.

Keywords: Data Envelopment Analysis (DEA); Renewable energy efficiency; Indicators.

RESUMO

O contexto global atual apresenta o desafio de reduzir o impacto da produção e consumo no meio ambiente por meio da reutilização de materiais e energia. Esta dissertação tem como objetivo avaliar o desempenho dos países nesse campo. A pesquisa utiliza abordagens quantitativas e qualitativas, com dois capítulos: o primeiro realiza uma revisão bibliométrica sobre sustentabilidade e análise de envoltória de dados (DEA), enquanto o segundo foca na construção de um indicador de eficiência de energia renovável por meio de DEA. Os resultados revelam variações na eficiência de energia renovável entre grupos de países, permitindo a comparação e identificação de nações com baixa eficiência no uso de energia renovável. A principal contribuição deste estudo é a criação do indicador de energia renovável (REI), que destaca o potencial para as 10 melhores performances globais tanto em países desenvolvidos (como a Suécia) quanto em países em desenvolvimento (como Costa Rica e Sri Lanka). O estudo revela que países da Europa central e do norte estão entre os mais eficientes, enquanto aqueles com instabilidade política e econômica permanecem entre os mais baixos. Além disso, nações com um setor agrícola predominante, como Austrália e Argentina, apresentaram desempenho pior no REI devido a emissões significativas de metano. Este estudo também contribui para a mitigação das mudanças climáticas e o avanço da agenda global de sustentabilidade.

Palavras-chave: Análise Envoltória de Dados (DEA); Eficiência de energia renovável; Indicadores.

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INTRODUCTION

Environmental awareness is being expanded by society, resulting in organizations, governments, and individuals to be pressured to strive for a balance between economic, environmental, and social performance to achieve sustainable development (Kaur; Garg, 2023). In this context, humanity faces the challenge of reusing materials, such as energy, so that production and consumption have a reduced impact on the environment (Cooper; Gutowski, 2017). Considering this perspective, emerging topics in debates and academia include air pollution, renewable energy, and energy efficiency, as well as solutions to mitigate damage and promote sustainability (Dogan; Seker, 2016; Bilgili; Koçak; Bulut, 2016; Koengkan, *et al*., 2022). International literature highlights the direct relationship between air pollution and renewable energy (Novan, 2015; Alvarez-Herranz *et al*., 2017; Koengkan *et al*., 2022). Therefore, the need for government incentives to expand the use of renewable energy and reduce harmful environmental impacts is emphasized (Yousefi *et al*., 2018; Shah *et al*., 2022).

Situated within the current global challenges, this dissertation stands as a noteworthy contribution to the landscape of sustainability and renewable energy. Given the imperative of fostering sustainable practices in the face of a demanding global context, where mitigating the environmental impact of energy production and consumption is crucial, this research addresses pertinent themes with implications for academia, government policies, and societal concerns. The exploration encompasses the escalating significance of renewable energy, environmental efficiency, and the imperative to address air pollution concerns. In this sense, the renewable energy efficiency analyzed by this dissertation means the performance of countries in increasing renewable energy and electricity access, as well as decreasing pollutant emissions.

In light of these considerations, this dissertation seeks to proffer a solution to environmental issues by advocating for the promotion of sustainable development. This involves not only augmenting renewable energy and expanding electricity access but also concurrently decreasing pollutant emissions, encompassing CO_2 and methane, in both developed and developing nations. Consequently, the aim of this dissertation is to conduct a comprehensive analysis of renewable energy efficiency worldwide through data envelopment analyses. To achieve this aim, we have proposed several secondary objectives, which include conducting a bibliometric study to identify clusters of the international literature review, applying non-parametric tests on a worldwide database to examine different categories of countries, analyzing the descriptive statistics of renewable energy efficiency worldwide, and creating a DEA indicator named Renewable Energy Index (REI).

The methodological approach utilizes a comprehensive bibliometric review on sustainability and DEA, providing an analysis of the development of these fields over time. This bibliometric approach offers a deeper understanding of the research landscape in sustainability and DEA, enriching the study with valuable insights. Subsequently, the focus of the dissertation shifts towards constructing an renewable energy efficiency indicator for analyzing the use of renewable energy on a national scale. To achieve this objective, the DEA uses a non-parametric approach that evaluates the relative efficiency of decision units, in this case, countries. This method allows for a comprehensive assessment of countries' performance in using renewable energy, culminating in the creation of an renewable energy efficiency index.

This document is structured into two chapters, each composed of independent but interrelated scientific articles. The first chapter, entitled "Sustainability and Data Envelopment Analysis: A Bibliometric Review", provides an overview of the research community on DEA applied to sustainable issues. This article is relevant as it seeks to promote a comprehensive understanding of the state of research in this field. The first chapter provides a detailed overview of the development of the topics over time, identifying current trends such as innovation, empirical evidence, and urbanization. It addresses the challenge of promoting economic growth without harming the environment, a theme discussed in various articles and international meetings (Klewitz; Hansen, 2014; Govindan *et al.*, 2013; Geissdoerfer *et al.*, 2017; Hahn; Kühnen, 2013). Despite the existence of numerous indicators in this area, there is a gap in the organization of literature. This study addresses this gap through bibliometric analysis, providing a mapping of sources, documents, authors, and publication growth. Additionally, the research identifies trends, research clusters, and DEA models used. It is important to note that this investigation contributes significantly to academia, presenting co-cited clusters that comprehensively organize the literature on DEA and sustainability. It distinguishes itself from other studies that focus on specific aspects, such as the application of DEA models in environmental economics and energy, or literature reviews with citation-based approaches (Mardani *et al.*, 2018; Yu; He, 2020; Zhou *et al.*, 2021). In this sense, the bibliometric study highlighted a significant gap in the literature with regard to the absence of indicators for energy efficiency, particularly in the domain of renewable energy efficiency. In light of this, we developed a second paper, which is presented in the second chapter.

The second chapter, titled "Renewable Energy Efficiency at the National Level: A Data Envelopment Analysis Index", creates an indicator for evaluating the renewable energy efficiency at the national level. Our indicator aims to address this issue by incorporating consumption and production energy, methane emissions, and PM2.5 air pollution, thereby providing a more comprehensive evaluation of renewable energy efficiency. In this sense, the second chapter aims to meet the need for a comprehensive indicator that measures the renewable energy efficiency use at the national level. Based on existing research (Woo *et al*., 2015; Ji *et al*., 2022), the study focuses on three groups: countries with developed markets, developing markets, and the global scale. The relevance of the study lies in rigorous statistical tests that identify variations in renewable energy efficiency between groups of countries, allowing for benchmarking of nations with low efficiency. This data is essential for policymakers, empowering them to create effective interventions and promote the adoption of sustainable energy sources. By identifying factors that contribute to inefficiency, targeted strategies can be developed to improve efficiency and encourage sustainable energy practices. The findings inform best practices adapted to diverse national and regional needs, driving the transition to sustainable energy. Despite existing research on environmental efficiency, this chapter introduces a new index to precisely measure the renewable energy efficiency, contributing to the evolution of sustainable energy systems.

Both chapters seek to contribute to research on sustainable development and the increasing adoption of renewable energy. In summary, the dissertation not only expands on the knowledge of the application of data envelopment analysis for sustainability and renewable energy issues but also offers necessary observations for evaluating renewable energy efficiency in different national and global contexts. In addition to the separation by groups, another distinguishing factor lies in the specific variables, such as the consumption and production transition model, as well as methane emissions and PM2.5 air pollution. Furthermore, this dissertation also contributes by introducing a new index to measure the renewable energy efficiency, which contributes to the evolution of sustainable energy systems. The findings inform the best practices adapted to diverse national and regional needs, driving the transition to sustainable energy.

CONCLUSION

This chapter has undertaken a comprehensive analysis of countries' performance in the reduction of pollutant emissions, encompassing agricultural methane emissions, CO_2 emissions, fossil fuel energy consumption, and PM2.5 air pollution. The overarching objective has been to evaluate the efficacy of efforts in increasing renewable energy utilization and improving electricity access. The findings underscore the imperative for enhanced development practices specifically designed to bolster the adoption of renewable energy. It is emphasized that such practices must be customized to address the unique needs and circumstances inherent in diverse countries and regions. The outcomes of this study are positioned as instrumental in informing targeted interventions, aiming to enhance the efficiency of renewable energy and facilitate the transition of nations toward more sustainable energy models.

In this context, the chapter introduced the Renewable Energy Index (REI), unveiling the potential for top-10 performance globally among both developed (i.e., Sweden) and developing countries (i.e., Costa Rica and Sri Lanka). Notably, countries in Central and North Europe emerged as among the most efficient, while those grappling with political and economic instability persisted among the lowest performers. Additionally, nations characterized by a predominant agricultural sector, such as Australia and Argentina, exhibited poorer REI performance due to substantial methane emissions.

The comparative analysis of indicators between developed and developing markets brought to light significant disparities in the Renewable Energy Index (REI). These disparities emphasize the necessity to comprehend the distinct socioeconomic dynamics between these two categories of countries, offering essential insights for the formulation of effective policies and strategies. The examination of the interplay between agricultural methane emissions, CO_2 emissions, fossil fuel energy consumption, and PM2.5 air pollution with renewable energy consumption and access to electricity underscores the critical importance of balanced public policies. These policies should not only promote the use of renewable energy but also address the adverse effects of pollution. Existing literature underscores the direct connection between renewable energy, air pollution, and energy efficiency, emphasizing the role of government incentives in steering the transition towards more sustainable energy sources.

Furthermore, the comparative analysis of indicators across high, middle, and low-income countries revealed distinct patterns, providing guidance for the formulation of specific strategies tailored to each income group. However, it is acknowledged that this chapter has limitations. Firstly, the Renewable Energy Index (REI) lacks a temporal analysis, and future studies are urged to incorporate the evolution of renewable energy over time. Secondly, the REI does not account for Gross Domestic Product as an input, potentially affecting ranking positions concerning available wealth. Thirdly, to offer more robust policy recommendations, future studies may consider different methodological strategies, such as evaluating DEA benchmarks among countries and determining REI determinants through a second-stage DEA, integrating econometrics. Fourth, our DEA model did not consider the education as an input. Note that some authors argument that human capital is an essential capability to provide better conditions for countries to increase sustainability.

In conclusion, this chapter advocates for personalized approaches and tailored strategies to promote the renewable energy efficiency across diverse contexts. The overarching goal is to facilitate a transition towards more sustainable energy models and mitigate the adverse environmental impacts associated with conventional energy sources.

CHAPTER 3: CONCLUSION

This dissertation addressed the growing environmental awareness and the need to balance economic, environmental, and social performance in order to achieve sustainable development. The initial chapter systematically reviewed literature concerning the application of Data Envelopment Analysis (DEA) to sustainability, aiming to identify research gaps and establish a theoretical foundation for the subsequent chapter. Building upon the insights derived from this comprehensive literature review, the second chapter introduced a novel metric termed the Renewable Energy Index (REI). This index serves as a quantifiable measure of the renewable energy efficiency associated with national-level renewable energy utilization. The aim was to contribute to mitigating the adverse effects of climate change by promoting the increasing adoption of renewable energies.

The first chapter presented a bibliometric study that mapped the development of sustainability and Data Envelopment Analysis themes since 1984, with emphasis from 2009 onwards. It identified current trends, such as "innovation," "empirical evidence," and "urbanization" which have been timeless over the last four years. Despite the contributions, the research in the first chapter has limitations, such as searching only in the WOS database and the possibility of relevant articles not using specific terms. The chapter, in this sense, is considered a starting point, suggesting the need for further in-depth analysis.

The second chapter addressed gaps identified in the first, focusing on the renewable energy efficiency use on a global level. While the previous chapter highlighted the importance of bibliometric review to understand the research landscape in sustainability, the second chapter responds to a specific gap by constructing a non-parametric DEA indicator. This indicator aims to measure the renewable energy efficiency use at the national level, segmenting into countries with developed economies, developing economies, and globally.

By addressing the lack of indicators focused on the efficiency of worldwide renewable energy use, the research conducted rigorous statistical tests to identify variations in efficiency in different groups of countries, allowing the identification and benchmarking of nations with low efficiency in renewable energy use. Compared to the previous bibliometric study, this chapter directly addresses the gap in measuring environmental efficiency, offering a valuable contribution to a more in-depth understanding of the role of renewable energy in global sustainability.

Therefore, the main objective of the second chapter is to analyze the renewable energy efficiency at the national level, using data envelopment analysis to create a performance index.

Considering variables such as agricultural methane emissions, and air pollution by PM2.5, the study explored the relationship between renewable energy use and environmental efficiency. In this scenario, the importance of energy efficiency in promoting sustainable practices was highlighted. The main contribution was the environmental efficiency index, making it possible to evaluate the performance of countries in renewable energy, considering relevant variables.

The research developed, therefore, globally assists in analyzing the environmental efficiency of renewable energy, offering valuable insights for policymakers and promoting sustainable energy practices. In developing economies, variations in renewable energy efficiency were identified, allowing benchmarking of nations with low efficiency and encouraging the adoption of more sustainable practices. For countries with developed economies, the importance of energy efficiency was highlighted, providing a renewable energy efficiency index. The study presented an indicator that considers variables such as fossil energy consumption, and air pollution, cooperating to understand distinct socioeconomic dynamics and guiding strategies to improve efficiency and promote sustainable practices.

In this context, this dissertation has a significant impact on the area of sustainability and renewable energy, contributing to mitigating the adverse effects of climate change by fostering the increasing adoption of renewable energies and balancing economic, environmental, and social performance to achieve sustainable development. Despite the relevance, this study presents several limitations. First, future studies must analyze the bibliometric analysis using a systematic literature review. Second, the bibliometric and systematic literature review might use other languages (i.e., Spanish and Portuguese) to evaluate the non-English speaker research communities. Third, this research focused on the WoS database, and other databases may yield different results (i.e., Scopus). Fourth, the Data Envelopment Analysis indicator used a database from 2016. In this sense, future studies must use more recent time series. Fifth, the DEA technique evaluated the renewable energy performance using traditional DEA models (i.e., BCC). We encourage future studies to analyze this research problem using more advanced DEA models (i.e., Slack Based Model), temporal analysis (i.e., Windows Analysis) and the DEA-Second Stage (i.e., using linear regressions).

In terms of relevance, the research contributes to mitigating the effects of climate change by promoting the adoption of renewable energies. Seeking balance between economic, environmental, and social performance, it aims at sustainable development. Insights for policymakers and researchers assist in strategic decisions to improve efficiency and promote sustainable practices. Highlighting the importance of renewable energy efficiency helps raise awareness and implement sustainable measures on a national and global level. In summary, the research covered several crucial contributions, from practical tools to impacts on the global renewable energy and sustainability landscape.

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APPENDIX

Table 18. Selected Categories

WoS Selected Categories	
Agricultural economics policy	Horticulture
Agricultural engineering	Hospitality leisure sport tourism
Agriculture dairy animal science	Humanities multidisciplinary
Agriculture multidisciplinary	International Relations
Agronomy	Management
Biodiversity & Conservation	Marine & Freshwater Biology
Biology	Materials science textiles
Biophysics	Materials science biomaterials
Biotechnology & Applied Microbiology	Materials science ceramics
Business	Materials science coatings films
Business finance	Materials science composites
Demography	Materials science paper wood
Development Studies	Materials sciencie characterization
Ecology	Mathematical & Computational Biology
Economics	Mathematics
Education & Educational Research	Mathematics applied
Education scientific disciplines	Mathematics interdisciplinary
Energy & Fuels	Mechanics
Engineering aerospace	Metallurgy & Metallurgical Engineering
Engineering biomedical	Microbiology
Engineering chemical	Mining & Mineral Processing
Engineering civil	Multidisciplinary sciences
Engineering electrical electronic	Oceanography
Engineering environmental	Operations Research & Management Science
Engineering geological	Physics applied
Engineering industrial	Physics mathematical
Engineering manufactural	Physics multidisciplinary
Engineering marine	political science
Engineering mechanical	Public Administration
Engineering multidisciplinary	Public environmental occupation
Engineering ocean	Regional urban planning
Engineering petroleum	Reproductive biology
Environmental Sciences	Social Issues
Environmental studies	Social sciences interdisciplinary
Ethics	Social sciences mathematical
Evolutionary biology	Soil science
Fisheries	Statistics probability
Food Science & Technology	Thermodynamics
Forestry	Transportation
Geography	Transportation science technology

Geography physical	Urban Studies
Geosciences multidisciplinary	Water Resources
Green sustainable science	

Source: The authors.