

**UNIVERSIDADE ESTADUAL PAULISTA – UNESP
FACULDADE DE ENGENHARIA DE BAURU – FEB
PROGRAMA DE PÓS-GRADUAÇÃO EM ENGENHARIA DE PRODUÇÃO**

Geovanna Bernardino Bello

**Sustainability and Renewable Energy: a Data Envelopment Analysis
application**

Bauru
2024

Geovanna Bernardino Bello

**Sustainability and Renewable Energy: a Data Envelopment Analysis
application**

Master's dissertation presented to 'Programa de Pós-Graduação em Engenharia de Produção' at 'Faculdade de Engenharia de Bauru' of São Paulo State University "Júlio de Mesquita Filho" (UNESP) to obtain the degree of Master's in Production Engineering.

Supervisor: Prof. Dr. Diogo Ferraz

Bauru
2024

Bello, Geovanna Bernardino.
Sustainability and Renewable Energy : a Data
Envelopment Analysis application / Geovanna Bernardino
Bello. - Bauru, 2024
98 f. : il., tabs.

Dissertação (Mestrado)- Universidade Estadual
Paulista (Unesp), Faculdade de Engenharia, Bauru
Orientador: Diogo Ferraz

1. Data Envelopment Analysis (DEA). 2. Renewable
energy efficiency. 3. Indicators. I. Universidade
Estadual Paulista. Faculdade de Engenharia. II.
Título.

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 constituída 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

DIOGO

FERRAZ:37226

521890

Assinado de forma
digital por DIOGO

FERRAZ:37226521890

Dados: 2024.03.26

16:13:23 -03'00'

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.

ACKNOWLEDGMENTS

I shall begin by thanking my supervisor, Prof. Dr. Diogo Ferraz, for his supportive and encouraging assistance throughout my trajectory.

I gratefully thank Dra. Fernanda Pereira Sartori Falguera for agreeing to help with the first article.

I would like to thank the UNESP (São Paulo State University) – ‘Programa de Pós-Graduação em Engenharia de Produção’ at ‘Faculdade de Engenharia de Bauru’ for all support and infrastructure to develop this research.

I offer my thanks to my lovely husband Henrique, my parents Marinalva and Agnaldo, my brothers and sister and my family and friends for their love, support, and encouragement.

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.

LIST OF FIGURES

FIGURE 1: Bradford's Law.....	21
FIGURE 2: Top Authors' Productivity over the time.....	22
FIGURE 3: Most Local Cited Authors.....	25
FIGURE 4: Publication Growth.....	26
FIGURE 5: Most Local Cited Documents.....	27
FIGURE 6: DEA model analysis.....	29
FIGURE 7: Trend Topics.....	30
FIGURE 8: Citation Network.....	31
FIGURE 9: Flowchart of the DEA model.....	54
FIGURE 10: Correlation Matrix.....	61
FIGURE 11: Global distribution of the Renewable Energy Index (REI).....	62
FIGURE 12: REI and GDP per capita across different developmental groups.....	63

LIST OF TABLES

TABLE 1: Keywords.....	20
TABLE 2: Main contributions.....	24
TABLE 3: Most Local Cited Articles.....	28
TABLE 4: Inputs and outputs definition.....	53
TABLE 5: Main DEA radial models in the form of multipliers.....	55
TABLE 6: Top-10 countries on Renewable Energy Index (REI)	64
TABLE 7: Bottom-10 countries on Renewable Energy Index (REI).....	66
TABLE 8: Top-5 developed countries on Renewable Energy Index (REI).....	68
TABLE 9: Bottom-5 developed countries on Renewable Energy Index (REI).....	69
TABLE 10: Top-5 developing countries on Renewable Energy Index (REI).....	70
TABLE 11: Bottom-5 developing countries on Renewable Energy Index (REI).....	70
TABLE 12: Top-5 high income countries on Renewable Energy Index (REI).....	72
TABLE 13: Bottom-5 high income countries on Renewable Energy Index (REI).....	72
TABLE 14: Top-5 Middle income countries on Renewable Energy Index (REI).....	73
TABLE 15: Bottom-5 Middle income countries on Renewable Energy Index (REI).....	73
TABLE 16: Top-5 Low income countries on Renewable Energy Index (REI).....	74
TABLE 17: Bottom-5 Low income countries on Renewable Energy Index (REI).....	74
TABLE 18: Selected Categories.....	94

LIST OF EXPRESSIONS

EXPRESSION 1.....	56
EXPRESSION 2.....	58
EXPRESSION 3.....	58
EXPRESSION 4.....	59

TABLE OF CONTENTS

INTRODUCTION	12
 CHAPTER 1: SUSTAINABILITY AND DATA ENVELOPMENT ANALYSIS: A BIBLIOMETRIC REVIEW	 15
1.1 Introduction.....	15
1.2 Literature review	16
1.2.1 Sustainability	16
1.2.2 Data Envelopment Analysis (DEA) and the Environmental Issues	17
1.3 Method	19
1.4 Results	21
1.4.1 Most Relevant Sources	21
1.4.2 Authors Production.....	22
1.4.3 Most Relevant Documents.....	25
1.4.4 Citation network	30
CONCLUSION.....	42
 CHAPTER 2: RENEWABLE ENERGY EFFICIENCY AT THE NATIONAL LEVEL: A DATA ENVELOPMENT ANALYSIS INDEX	 45
2.1 Introduction.....	45
2.2 Literature review	47
2.2.1 Renewable energy efficiency.....	47
2.2.2 Renewable energy and air pollution	48
2.3 Method	52
2.3.1 Inputs and Outputs Variables	52
2.3.2 Data Envelopment Analysis	54
2.3.3 Inverted Frontier	56
2.3.4 Development and Income Group tests	57
2.4 Results.....	60
2.4.1 World Analysis	60
2.4.2 Group Development Analysis	67
2.4.3 Income Group Analysis	71
CONCLUSION	75
 CHAPTER 3: CONCLUSION	 77

REFERENCES 80

APPENDIX 94

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 CO₂ 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 a 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 a 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.

CHAPTER 1: SUSTAINABILITY AND DATA ENVELOPMENT ANALYSIS: A BIBLIOMETRIC REVIEW

1.1 Introduction

One of the challenges countries faces is to promote economic growth without environmental damage. In this regard, the topic of sustainability has been discussed in several articles (Klewitz and Hansen, 2014; Govindan *et al.*, 2013; Geissdoerfer *et al.*, 2017; Hahn and Kühnen, 2013; Parlasca and Qaim, 2022; Bibri *et al.*, 2024), being also the main topic in meetings between policymakers of several countries and multilateral organizations (United Nations - UN, World Bank, etc.). Paris Agreement is one of the most recent examples, in which countries declared Intended Nationally Determined Contributions (INDCs) outlining their post-2020 climate actions to limit global warming to 1.5 degrees Celsius (UNFCCC, 2015).

Countries can use an accounting approach of their choice in their INDCs, such as the inclusion of emissions and removals of CO₂ related to land use or any other sector, as used by Brazil and the United States of America (USA) (Rogelj *et al.*, 2016). The relevance of this theme can also be seen in the Sustainable Development Goals (SDGs), formulated by the United Nations Rio+20 Summit in Brazil in 2012 (UN, 2012). This approach increases public and political support and channels funds effectively to urgent global issues (Griggs *et al.*, 2013).

There are many indicators on the subject that have already been created, but there is no organization of this literature to know which communities treat these indicators, so this research shows and explains these clusters as a contribution to the academy, in addition to describing bibliometrics. The present article relied on a bibliometric analysis through the Web of Science (WoS) database contributing to the following aspects: map the main sources, documents, authors and the publication growth by year, as well as the trend topics, the research clusters and the DEA models used in the studies.

There are some articles that have been published previously to organize the literature in the area of DEA and sustainability, note that Mardani *et al.* (2018) shows an overview of the application of DEA models in the fields of environmental and energy economics, Yu and He (2020) introduces an overview of all publications published until 2018 about energy efficiency based on DEA and Zhou *et al.* (2021) review the literature on DEA applications in sustainability using citation-based approaches, this article distances itself from the previous ones because carries out a bibliometric analysis of sustainability in general and describes ten co-citation clusters.

1.2 Literature review

1.2.1 Sustainability

The significance of sustainability arises from the depletion of natural resources, concerns about wealth inequality, and the pressure for corporate social responsibility (Bocken *et al.*, 2014). Thus, the comprehensive definition of sustainability ensures that the utilization of natural resources and the human cycle does not compromise the quality of life of present and future generations (Govindan *et al.*, 2013). However, defining sustainability can be challenging due to its ambiguity, which stems from the complexity and breadth of the theme, including environmental and social aspects (Ahi and Searcy, 2013).

At the institutional level, sustainability refers to the management actions of organizations seeking to balance environmental, social, and economic objectives (Dyllick and Hockerts, 2002). Such balance would reduce environmental damage without compromising the economic benefits for society. The economic growth of countries has led to socio-environmental impacts that have generated concerns in society, emphasizing the need for responsible human actions (Santana *et al.*, 2017). In the current globalized world, collaboration between organizations and all their stakeholders is essential to achieve sustainability (Bocken *et al.*, 2014). From a governmental perspective, sustainability is a critical issue for policymakers and researchers to ensure sustainable performance (Čuček *et al.*, 2012).

Linked to the sustainability concept, the rise of the theme of sustainable development can be observed. The concept is interdisciplinary, as is sustainability, and is based on the balance between ecological, economic, and social values (Boons and Lüdeke-Freund, 2013). This nomenclature was registered for the first time at the United Nations Conference on the Human Environment in 1972 (Hall *et al.*, 2010). The definitions of sustainable development are diverse, however, they are usually similar to the definition given by the Brundtland Commission (1987): ‘development that meets the needs of the present generation without compromising the ability of future generations to meet their own needs’ (WCED, 1987, Ch. 2, p. 1). It is noteworthy that the political dimensions are a central part of the debate on sustainable development. Consequently, the theme has been receiving the attention of several governments (Glavič and Lukman, 2007). Due to such circumstances, there is a constant concern in actions developed by global institutions, such as the United Nations. Sustainability is a broad field of study that needs to be explored, considering its dimensions and interfaces with other themes. The importance of sustainability in the current context is considered the only way out for an acceptable society.

Another similarity between sustainability and sustainable development is the social, environmental, and economic dimensions called the Triple Bottom Line (TBL) (Govindan *et al.*, 2013). The triple bottom line term was coined by business consultant John Elkington in the mid-90s to show that organizations need to positively impact the environment and society, going beyond the search for economic performance. Therefore, the organization will be assuming its responsibility concerning economic prosperity, environmental quality, and social justice (Bai and Sarkis, 2010; Furlan and Mariano, 2022). Schulz and Flanigan (2016) recognized that is difficult accurately quantify and evaluate all three dimensions of TBL, specially the social and environmental dimensions.

The challenge present in the sustainability approach of transforming an interdisciplinary concept into quantitative measures has an important challenge that is how researchers might translate a complex concept into a single indicator, which must be straightforward and useful for policymakers. In most publications, the indicators are organized around the “triple bottom line” (Roca and Searcy, 2012). For example, Azapagic (2004) points out that sustainability indicators allow sustainable measures to be quantifiable, providing a path for organizations and governments to follow their strategies. The authors conclude that indicators developed for this area need to translate relevant sustainability issues into representative performance measures. Some researchers developed studies that aimed to analyze sustainability quantitatively. For example, Hák *et al.* (2007) analyze the sustainability indicators available in the literature and their challenges and approaches. Ness *et al.* (2007) assessed sustainability in indicators, product-related assessments, and integrated assessment tools.

1.2.2 Data Envelopment Analysis (DEA) and the Environmental Issues

The method called Data Envelopment Analysis (DEA) is based on mathematical procedures, such as linear programming, to analyze the weights that expand the efficiency of decision-making units (DMUs). This method allowed the application of several models and extensions, even in research on human development (Mariano *et al.*, 2015). The use of DEA allows the insertion of several inputs and outputs containing a single value. However, there is no need to transform them into a standard measure, and the type of scale return used will characterize the Constant Returns to Scale (CRS), and Variable Return to Scale (VRS) models (Cooper *et al.*, 2007).

Charnes *et al.* (1984) developed the model that was the first to analyze constant returns and variable returns to scale. This model allowed the advancement of other methodologies, such as the

Slack Based Measure (SBM), Russell Measure (RM), and even another model developed by Charnes *et al.* (1987), originating from a geometric combination between variables.

One of the uses of the DEA is the measurement of sustainable development, allowing the identification of multidimensional efficiency problems, direct interpretations in a single index, and winning the interest of decision-makers (Chaaban *et al.*, 2016). The choice for DEA is justified by allowing the weights to be chosen endogenously (Chaaban *et al.*, 2016).

According to the research carried out by Ferraz *et al.* (2020), several authors are using the DEA to measure social and environmental issues in their studies. The authors point out that the works of Mahlberg and Obersteiner (2001), Despotis (2005), Tofallis (2013), and Zhou *et al.* (2010) used the DEA to recalculate the HDI and analyze human and environmental development. Such repercussion is given by the DEA efficiency measures integrated with environmental technology, which have the property of measuring environmental performance (Zhou *et al.*, 2007).

Färe *et al.* (2004) discussed the environmental performance index which was calculated using DEA tools. The authors used distance functions to formulate the index, allowing them to only attach information on the input and output quantities. The method developed by the academics was applied to a sample of Organization for Economic Cooperation and Development (OECD) countries. Zaim (2004) aimed to develop a new definition of pollution intensity. According to the author, traditional indices do not consider pollution as a by-product of manufacturing activity. Therefore, the research provides a new index using the Malmquist quantity index modification. The index also allows for the comparison of pollution levels over time.

Zhou *et al.* (2007) claim that most studies use the DEA technique through radial efficiency models. Thus, the authors developed a non-radial DEA approach to measure environmental performance in their studies, filling a gap in the literature. The model developed by the authors allows for multilateral comparisons of environmental performance and provides a Malmquist environmental performance index. Research by Zhou *et al.* (2010) also introduces a non-radial DEA methodology and develops a Malmquist CO₂ emission performance index. These tools allow measuring changes in carbon emission performance over time.

1.3 Method

In order to map the intellectual territory concerning the use of DEA approach under the sustainability literature, we adopted a bibliometric analysis with quantitative synthesis. Such combination provides a large-scale set of scientific data in a knowledge domain, allowing researchers to establish intellectual connections in the searched field and indicate the main trends. Our articles selection involved only papers from peer-reviewed journals, aiming at a sample of publications with a higher academic impact.

The database used for the collection of bibliographic material was ISI Web of Knowledge, also called Web of Science (WoS), which is internationally recognized among researchers for having high-quality standards (Gaviria-Marin *et al.*, 2019) and indexing a large set of academic studies from highly respected journals all over the world (Gumus *et al.*, 2018). The WoS database has become one of the main tools for researching and evaluating different types of journals and publications (Gaviria-Marin *et al.*, 2019); being used by many notable bibliometric studies (Gonçalves, 2019; Lampe and Hilgers, 2015; Albort-Morant and Ribeiro-Soriano, 2016; Fetscherin and Heinrich, 2015). WoS indexes more than 15,000 journals and 50 million articles (Bonilla *et al.*, 2015). Furthermore, it includes a set of metadata (Gaviria-Marin *et al.*, 2019) to obtain information needed for analyses (Gumus *et al.*, 2018).

For research reproducibility, it should be noted that the data was collected during October 2021. The selection of keywords for the research was based on the preliminary readings of the most recent and cited articles on the subject and published in high-impact journals, we also selected terms linked to the main dimensions of indicators such as environmental performance and ecological footprint. The search terms resulted in the search phrase as shown in Table 1.

Table 1. Keywords

Group	Keywords
Group 1	"Data Envelopment Analysis" OR "DEA"
	AND
Group 2	sustainab* OR environmental* OR "air* qualit*" OR sanitation OR wastewater* OR water* OR freshwater OR "heavy metal*" OR "waste management" OR biodiversity OR habitat* OR "climate change" OR pollut* OR "greenhouse gas" OR agriculture OR biocapacit* OR natur* OR carbon* OR CO2 OR "land use" OR forest* OR pasture* OR fisheries OR energ* OR renewabl* OR emission* OR ecolog* OR "green growth" OR "green development" OR "green innovat*" OR "green product*" OR ecoefficiency OR eco-efficiency OR "eco efficiency"

Source: The authors.

Note that “*” replaces one or more characters of an expression, for instance, “sustainab” includes the expressions “sustainable” and “sustainability”.

Some terms were used in group 1 to exclude articles from other areas such as “desethylatrazine”, “diethylamine”, and “diethanolamine”. In WoS, this search was conducted in the title, abstract and keywords. The results of this search generated an initial set of documents. We excluded those that did not fit the criteria of articles written in English and selected the categories related to this research such as Engineering, Environmental studies, Political science, and Economics as shown in Table 18 (see Appendix).

Subsequently we conducted a quantitative analysis of the data. Aiming to find journals with the highest quantity of publications, authors with the most papers published, the evolution of the number of papers on the theme over the years, and the most cited papers discussing the research topic.

We also carried out an analysis of the citation network with the assistance of the VOS Viewer and Biblioshiny tools, which enabled the formation of a citation network, with the formation of clusters that group papers with more links. The citation analysis allowed a broader perspective of the field of the theme study by viewing works with greater affinity to each other, offering a classification of publications according to their themes. The trend topics analysis also contributes to map themes within the study field, since identifying terms are often used together in articles.

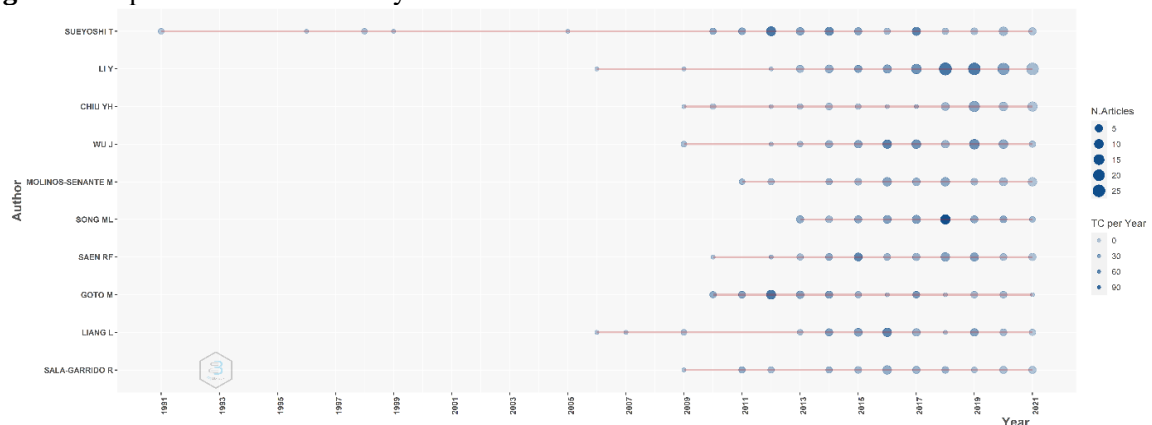
the theme and 15 years later, the Journal of Cleaner Production overcame the European Journal of Operational Research in number of publications.

Note that the Journal of Cleaner Production is a recognized scientific journal focused on cleaner production, environmental, and sustainability research and practice. It explores several subject areas, such as energy efficiency, climate change, pollution reduction, eco-efficiency, sustainability indicators. In this sense, our study reveals that studies published on the Journal of Cleaner Production has been using the Data Envelopment Analysis as one of the most significant methods to measure indicators for the sustainability issue, among others like Stochastic Frontier Analysis (SFA), life cycle assessment (LCA), multi-criteria decision analysis (MCDA), sustainable business model (SBM), circular economy (CE) model, delphi method, multi-attribute utility model.

1.4.2 Authors Production

We identified the authors with the more published studies over time from the sample based on the theme. This is important to map the main authors and the most renowned scientists that discuss the theme with their H index. Figure 2 illustrates the authors' production (in terms of the number of publications and total citations per year).

Figure 2. Top Authors' Productivity over the time



Source: The authors.

Toshiyuki Sueyoshi dedicates himself to studies on solid-state physics, spectroscopy, physical chemistry, and catalysis (Research Gate, 2022). He published 2 articles in 1991, which received 47 citations. After a five-year hiatus, he published again in 1996. Since then, 2012 has been the year he published the most, with 11 articles and 817 citations in total, putting his H

index at 38. His first publication, entitled ‘A literature study for DEA applied to energy and environment’ summarizes previous research efforts on DEA applied to energy and the environment, including concepts and methodologies on DEA environmental assessment.

Yi Li is a researcher at the University of California, Los Angeles, United States. His research focuses on materials science, chemistry, physics and astronomy, computer science, engineering, and mathematics. His research is of unique relevance to several studies, including research on the carbon-polymer nanotube bilayer electrode (SCOPUS, 2022). His works received numerous citations, constituting an H index of 19.

Yung Ho Chiu is a professor at Soochow University in Taiwan. He is dedicated to research in energy savings, quantitative social research, microeconomics, and industrial organization (Research Gate, 2022). The author has about 545 citations between 2009 and 2021 and an H index of 12.

Researcher Jie Wu is a management science and engineering professor at the University of Science and Technology in China. His research focuses on decision analysis and data envelopment analysis (Google Scholar, 2022). The author has been cited around 1,760 times since 2009, the number of citations being higher each year. His H-index is 23.

Maria Molinos Senante is a professor at the Pontifical Catholic University of Chile. Her studies are about data envelopment analysis, sewage system and Metaborder (Google Scholar, 2022), the author is cited about 1,157 times, with an H index of 20.

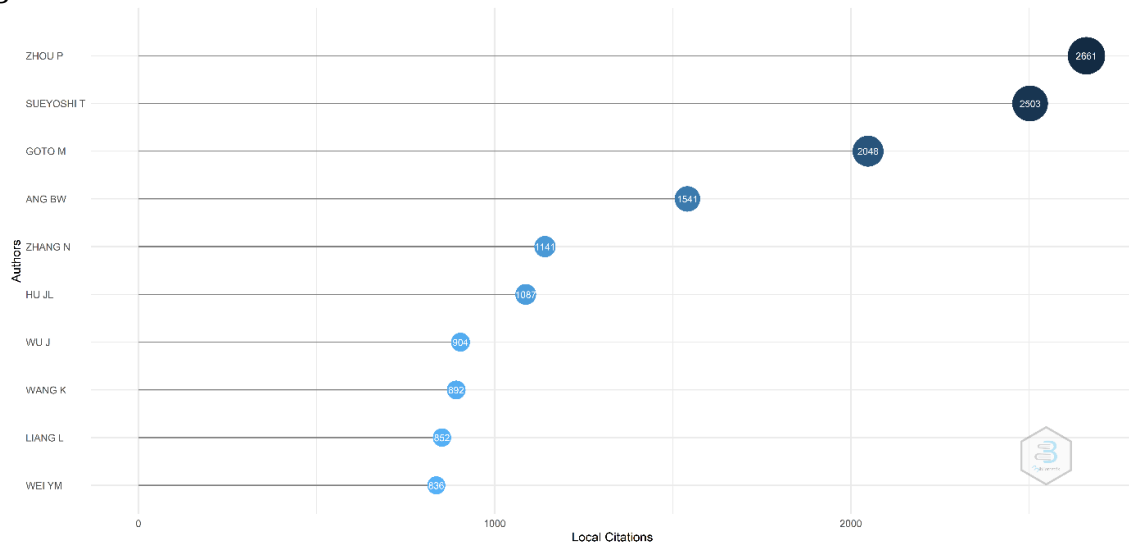
The Table 2 presents the most local cited article of these authors and its main contributions.

Table 2. Main contributions

Author	Document	Contribution to the research area
Toshiyuki Sueyoshi	SUEYOSHI T, 2017, ENERG ECON	To summarize studies on DEA applied to energy and environment in the last forty years and discusses three issues as future research tasks.
Yi Li	LI Y, 2013, ENERG POLICY	To model three internal factors (economic structure, energy consumption structure, and technological progress) to compare the impact of each factor on energy intensity, and then discuss the effects of technological progress using the DEA-Malmquist method.
Yung Ho Chiu	CHIU YH, 2015, ENERG SOURCE PART B-a	To find a comparatively fair and efficient allocation method, using a zero sum gains DEA model to explore the allocation of emission allowances.
Jie Wu	WU J, 2016, TRANSPORT RES D-TR E	Measure the energy and environment performance of transportation systems using DEA with the goal of sustainable development.
Maria Molinos Senante	MOLINOS-SENANTE M, 2014, CLEAN TECHNOL ENVIR	To estimate an efficiency scores for each input involved in the operation of WWTPs, a non-radial DEA model has been applied, identifying cost-saving opportunities.

Source: The authors.

The 10 most cited local authors are shown in Figure 3.

Figure 3. Most Local Cited Authors

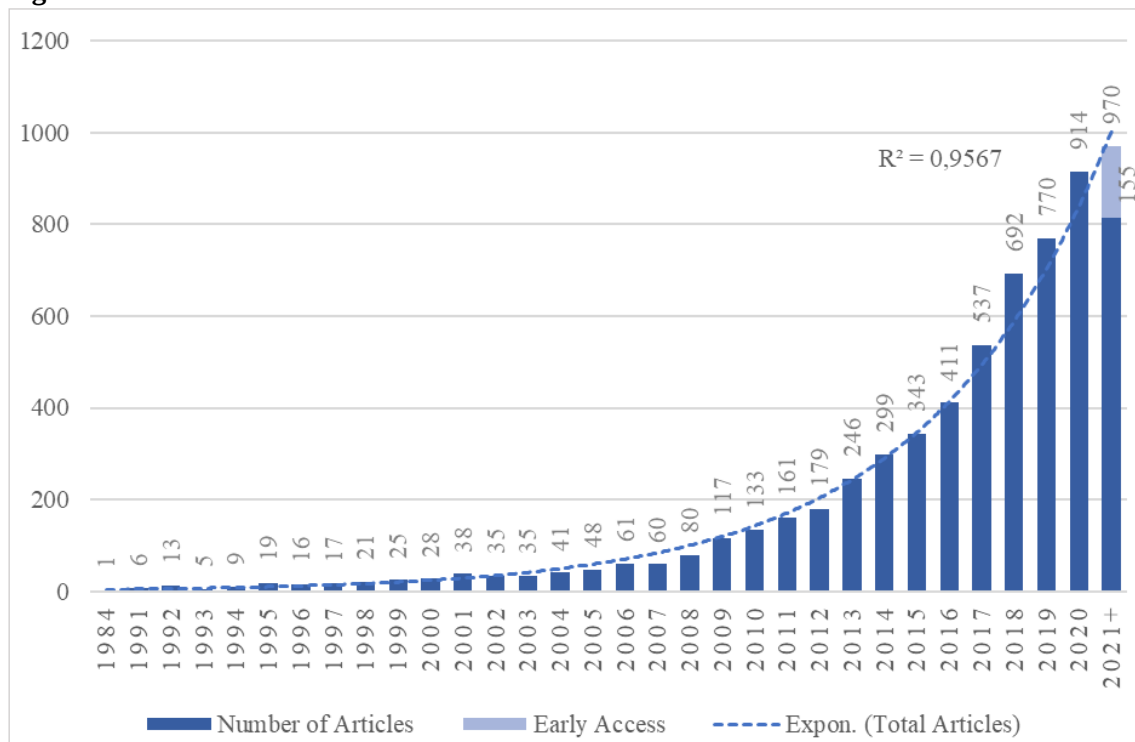
Source: The authors.

(1) Peng Zhou (2646), (2) Toshiyuki Sueyoshi (2466), Mika Goto (2018), Beng Wah Ang (1532), Ning Zhang (1134), Jin-Li Hu (1087), the rest did not pass of 898 citations. 11872 authors and 56,8% received 1 or 0 citations.

Peng Zhou contributes to the theme by studying non-radial function modeling energy and CO₂ emission performance (non-radial DEA approach to measuring environmental performance), Malmquist CO₂ emission performance index for measuring changes in total factor carbon emission performance over time, measuring the carbon emission performance, defining an energy index, decomposing the change of aggregate CO₂ emissions over time, DEA models for measuring economy-wide energy efficiency performance, index with higher discriminating power for modeling economic-environmental performance and estimating the impacts of environmental regulations.

1.4.3 Most Relevant Documents

Figure 4 presents the evolution of publications over time. The articles are dated between 1984 and 2021 (about 37 years) and show exponential growth over time (the adjustment to a natural exponential function has an R² of 96%). When analyzing the annual accumulated percentage, the last 10 years account for 87% of the sample. We can see that 155 articles are Document Type Early Access.

Figure 4. Publication Growth

Source: The authors.

The Publication Growth graph allows us to analyze the distribution of articles published over the years, in this way it is possible to observe the growing number of publications on the theme. Note the importance of observing the graph together with the events of society. In 1972, the Stockholm Conference was held, being the first world conference seeking environmental issues (Maus, 1972). The Vienna Conference was held in 1985 its established the principles for protecting the ozone layer (Slaper *et al.*, 1996). In 1987, the Brundtland report was published, being the first document that conceptualized the term sustainable development (Keeble, 1988). After this series of events, one can observe the emergence of the first studies on DEA and sustainability, illustrating the emerging need for environmental concerns. Later, in 1992, Rio-92 took place, with the launch of Agenda 21 (Sánchez and Croal, 2012). Then, in 1997, the Kyoto Protocol took place, such protocol established goals and deadlines for countries to reduce their greenhouse gas emissions (Freedman and Jaggi, 2005). At the beginning of the 21st century, in 2000, the United Nations Millennium Summit was organized, the event resulted in the launch of the Millennium Goals (Summit *et al.*, 2000). The compound annual growth rate from 1991 to 2008 is 16%, suggesting that all these events had a positive effect on boosting publications on the subject.

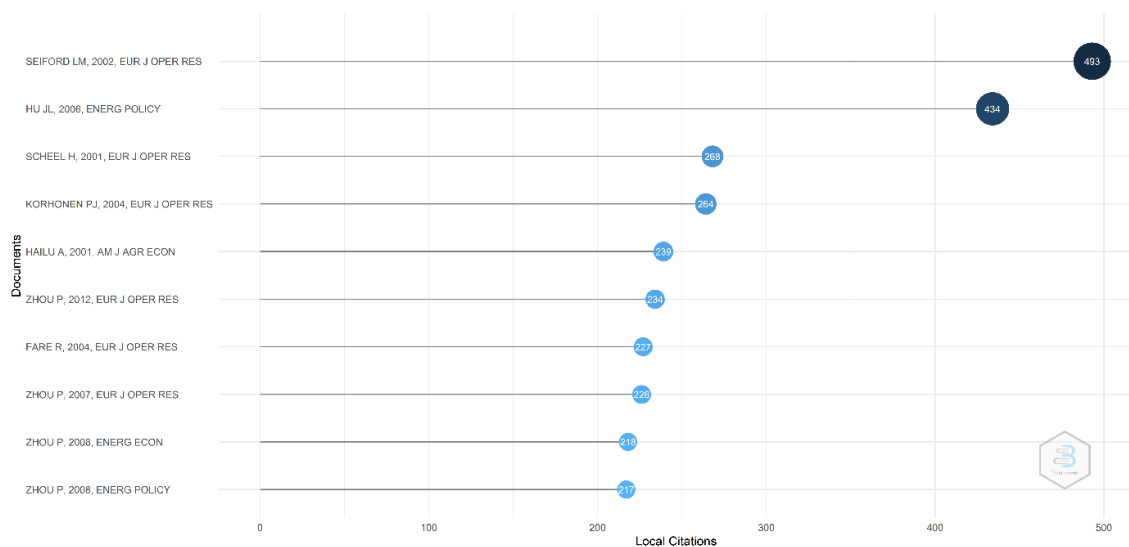
Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report, released in 2007, has its main activity to provide an assessment of the state of knowledge on

climate change based on peer-reviewed and published scientific/technical literature. From 2008 to 2009, the graph shows a change in the level of annual publications, with a 46% growth from one year to the next, showing that the topic has gained relevance for academia.

In 2013 we can observe a change of level being 37% more voluminous than the previous year, on the other hand, we observe the realization of Rio+20, in 2012, with the main focus on eradicating poverty (Mische, 2014). In 2015 two important moments stand out, the COP 21, whose main result was the Paris Agreement (Rhodes, 2016), and the 2030 Agenda and the Sustainable Development Goals (Liu *et al.*, 2016). Therefore, given the context of studies about environmental concern in society, it is justified, as shown in the figure 4, the growing increase in the analysis of DEA measurement and sustainability in this period.

In Figure 5 we can see the 10 articles most local cited.

Figure 5. Most Local Cited Documents



Source: The authors.

We analyzed the 25 most local cited articles, and we mapped the most used DEA models as seen in Figure 6 that presents that the majority research has an emphasis on quantitative modeling DEA methods. Table 3 shows these articles, using data from WoS citation count as shown.

Table 3. Most Local Cited Articles

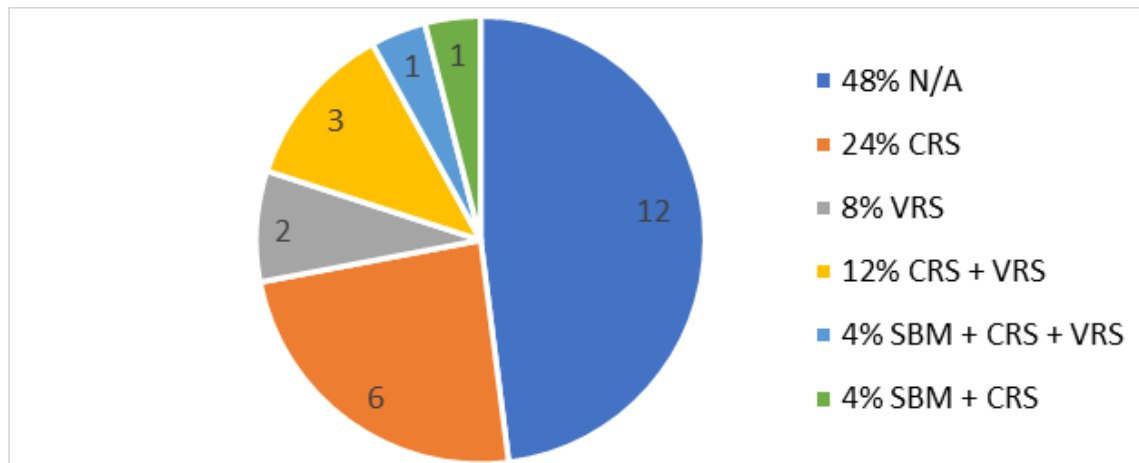
No	Document	Year	Local Citations	Global Citations	LC/GC Ratio (%)	Methodology	DEA Model
1	SEIFORD LM, 2002, EUR J OPER RES	2002	493	820	60,12	Quantitative	N/A
2	HU JL, 2006, ENERG POLICY	2006	434	773	56,14	Quantitative	CRS
3	SCHEEL H, 2001, EUR J OPER RES	2001	267	475	56,21	Quantitative	CRS
4	KORHONEN PJ, 2004, EUR J OPER RES	2004	264	380	69,47	Quantitative	VRS
5	HAILU A, 2001, AM J AGR ECON	2001	239	382	62,57	Quantitative	N/A
6	ZHOU P, 2012, EUR J OPER RES	2012	233	411	56,69	Quantitative	N/A
7	FARE R, 2004, EUR J OPER RES	2004	227	347	65,42	Quantitative	CRS
8	ZHOU P, 2007, EUR J OPER RES	2007	225	316	71,2	Quantitative	N/A
9	ZHOU P, 2008, ENERG ECON	2008	217	324	66,98	Quantitative	CRS + VRS
10	ZHOU P, 2008, ENERG POLICY	2008	216	317	68,14	Quantitative	CRS
11	ZHOU P, 2006, ECOL ECON	2006	209	283	73,85	Quantitative	N/A
12	ZHANG B, 2008, ECOL ECON	2008	209	300	69,67	Quantitative	CRS + VRS
13	ZHOU P, 2010, ENERG ECON	2010	194	366	53,01	Quantitative	N/A
14	SHI GM, 2010, ENERG POLICY	2010	194	276	70,29	Quantitative	CRS + VRS
15	DYCKHOFF H, 2001, EUR J OPER RES	2001	191	266	71,8	Quantitative	CRS
16	KUOSMANEN T, 2005, J IND ECOL	2005	189	304	62,17	Quantitative	N/A
17	CHOI Y, 2012, APPL ENERG	2012	171	353	48,44	Quantitative	SBM + CRS + VRS
18	REINHARD S, 2000, EUR J OPER RES	2000	170	316	53,8	Quantitative	N/A
19	CHANG YT, 2013, ENERG POLICY	2013	168	248	67,74	Quantitative	SBM + CRS
20	TYTECA D, 1996, J ENVIRON MANAGE	1996	165	326	50,61	Quantitative	N/A

21	HU JL, 2007, ENERG POLICY	2007	165	274	60,22	Quantitative	CRS
22	WANG K, 2013, MATH COMPUT MODEL	2013	164	235	69,79	Quantitative	VRS
23	KUOSMANEN T, 2005, AM J AGR ECON	2005	157	276	56,88	Quantitative	N/A
24	SUEYOSHI T, 2017, ENERG ECON	2017	157	198	79,29	Theoretical	N/A
25	FRIED HO, 2002, J PROD ANAL	2002	154	340	45,29	Quantitative	N/A

Source: The authors.

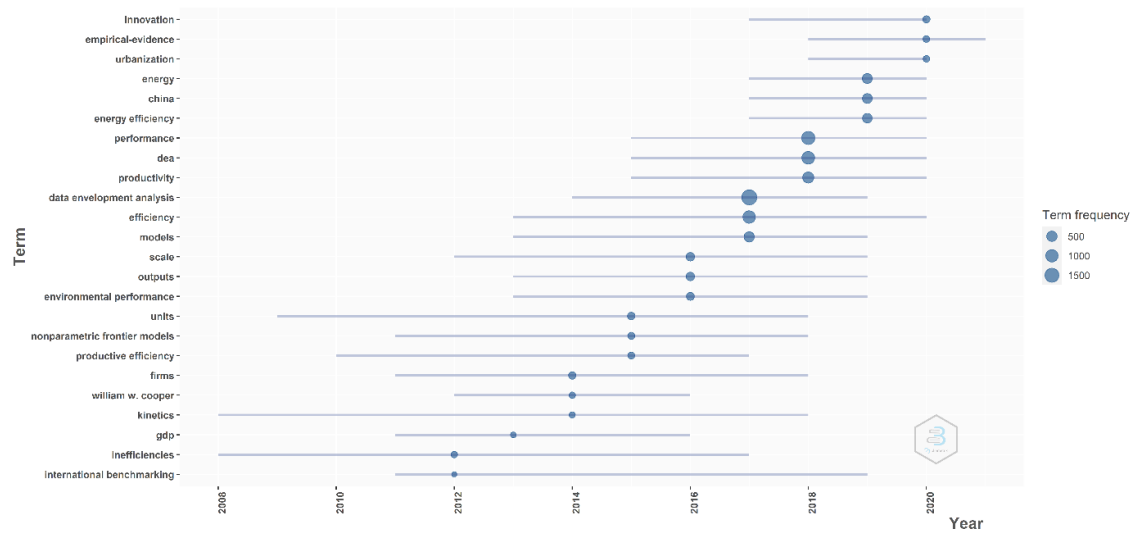
Column 5 shows the global citation (GC), which is the number of citations of a paper. Meanwhile, column 4 shows the local citation (LC) of each paper. While GC can be interpreted as the overall influence of the document across scientific disciplines, LC is the influence of a paper on the examined pool of documents, showing the overall influence of the paper on the literature on the theme. In Figure 6 we can see the DEA Model of these 25 selected articles.

Figure 6. DEA model analysis



Source: The authors.

In Figure 7 we can see the trend topics. This analysis shows that research related to “innovation” was more commonly performed since 2017, with the highest concentration being in 2020, and the term “data envelopment analysis” was more commonly performed since 2014 with the highest concentration in 2017.

Figure 7. Trend Topics

Source: The authors.

1.4.4 Citation network

To better understand how the studies published on the theme relate with each other, we carried out a citation network analysis using the VOSviewer software. The citations clusters achieved by those documents is shown in Figure 8. Waltman and Van Eck (2017) elucidate that the VOSviewer clustering technique determines the relatedness of publications based on direct citation relations. In this case, a citation link is a link between two items where one item cites the other. Publications are assigned to clusters by maximizing a quality function. In order to maximize the quality function, the VOSviewer clustering technique uses the smart local moving algorithm introduced by Waltman and Van Eck (2013).

by electricity generation, but energy supply is invaluable for economic growth (Zhou, 2012). Therefore, the efficiency of energy consumption must be simultaneously promoted so that redundant energy consumption is eliminated. There are various definitions of the term energy efficiency, among which “the ratio of energy services to energy input” is a popular one. A general definition given in the Directive 2006/32/EC of the European Council and the Parliament on energy efficiency and energy service is “a ratio between an output of performance, service, goods or energy, and an input of energy”. Indicators used to monitor changes in energy efficiency can yield very different results and policy implications (Zhou, 2008).

In this sense, the main article of this cluster, named “Total-factor energy efficiency of regions in China”, constructed a new index of energy efficiency defined as the ratio of the target energy input that the DEA suggests to the actual energy inputs in a region (Hu and Wang, 2006). Among the main articles, we can see “Linear programming models for measuring economy-wide energy efficiency performance” that developed three alternative energy efficiency performance indexes to evaluate energy efficiency within a joint production framework of both desirable and undesirable outputs (Zhou, 2008). One of the top articles, which created several performance indexes for measuring energy and CO₂ emission performance in electricity generation is titled “Energy and CO₂ emission performance in electricity generation: A non-radial directional distance function approach” (Zhou *et al.*, 2012).

Hu and Wang (2006) pointed out that a more detailed analysis can be conducted by referencing each region’s root causes at a deeper level, and that industrial structure, energy policies, energy consumption type, and treatments from local governments can be further incorporated together. Zhou *et al.* (2012) did their empirical study based only on data from 2005, but further research may be carried out using time-series data or the data from for a more recent year. They also pointed out that the proposed approach can be directly applied to measure energy and environmental performance of electricity generation at factory level if the needed data is available. In cases where there are more input and output variables, the proposed non-radial directional distance function approach can also be easily adapted.

In accordance with what has been exposed, the understanding that energy efficiency and pollution are relevant topics and, consequently, should be considered in this research is notorious. Still, it is necessary to emphasize the possible paths for this theme, as evidenced in the suggestions for a future research agenda by the authors Fenerich *et al.* (2017), who consider that a research agenda in energy efficiency can be the path to solutions aimed at reducing energy consumption in industries.

Cluster 2 - DEA and Economic Sectors Analysis (Color green)

The second cluster analyzes issues pertaining to “DEA analysis for economic sectors (agriculture, fisheries, and airports)”. There is a strong scientific consensus that climate change may affect both the quantity and quality of available water and energy resources. Wastewater treatment plants (WWTPs) are energy-intensive facilities contributing in some measure to climate change (Plósz *et al.*, 2009). This energy consumption is expected to grow considerably in the near future, due to a higher expected volume of water being treated, as well as the adoption of new technologies aimed at yielding higher quality effluents (Hernández *et al.*, 2011). This cluster defines environmental efficiency as the ratio of minimum feasible to observed use of multiple environmentally detrimental inputs, conditional on observed levels of output and the conventional inputs.

In this sense, the main article of this cluster, “A survey of DEA applications”, classifies a set of DEA papers into methodological and non-methodological works and then further segments the theoretical works based on real world problems that are discussed, tested, and validated within each work. Among the main articles, we found “Environmental efficiency with multiple environmentally detrimental variables; estimated with SFA and DEA” that revealed the strengths and weaknesses of the Stochastic Frontier Analysis and Data Envelopment Analysis methods for estimating environmental efficiency scores (Reinhard *et al.*, 2000). This article is important because it shows SFA and DEA based on its facility to incorporate their fulfilment of theoretical restrictions, the possibility of testing these restrictions, and the effects of statistical noise.

Moreover, the article titled “Energy efficiency in Spanish wastewater treatment plants: A non-radial DEA approach” is also among the top articles, which analyzes the efficiency behavior of a sample of WWTPs and identifies several variables that can explain differences between the energy plants. It also quantified the savings in CO₂ emissions and economic costs that could be obtained if plant efficiencies were improved (Hernández *et al.*, 2011).

Liu (2013) pointed out the following limitations of his study. First, the dataset is from the WoS database and does not include all DEA papers published in academic journals. Second, these papers are categorized manually by one of the authors; some errors in judgment may occur, but this should be reduced to a minimum. Third, application studies discussed herein include application-centered and theory-together-with-empirical-data papers; some of them may not be accurate. Furthermore, they may also be duplications of previous studies where the data is used to illustrate a new method as opposed to a new application. Fourth, the results of the main path analysis are subject to citation noise, which is a general limitation of the citation

analysis. Finally, each application area is treated as one broad research area. Some of the application areas may be heterogeneous in nature, such that certain development streams of the area are left out by the main path method. Reinhard *et al.* (2000) pointed out that the DEA is deterministic, and is unable to identify whether the environmentally detrimental variables suit the model. Liu (2013) suggested that theoreticians should attempt to make their models operational and available by providing standalone software or an add-in to existing commercial software such as DEA Frontier and DEA-Solver. This will attract practitioners to use the model, offer feedback on issues of the model, and eventually turn the development process into virtuous cycles.

After this brief contextualization of the literature on DEA and the analysis of economic sectors, it is noted, therefore, the significance of this field of study for this research. As evidenced in Liu *et al.* (2013) the DEA methodology evaluates the individual efficiency or performance of a decision-making unit, thus contributing to the analysis of economic sectors. Given this interface between the fields of study, the construction of this second cluster is justified.

Cluster 3 – DEA methodological issues (Color dark blue)

The third cluster analyzes “DEA issues (i.e., undesirable outputs and radial model)”. DEA has frequently used in environmental performance measurement because it can provide some standardized environmental performance index. Most studies mainly deal with the developments and applications of radial DEA-based models (Zhou *et al.*, 2007). Efficiency measurement is usually based on the assumption that inputs have to be minimized and outputs have to be maximized. In many applications, however, undesirable outputs are incorporated into the production model which have to be minimized (Scheel, 2001).

In this sense, the main article of this cluster, named “Modeling undesirable factors in efficiency evaluation”, develops an alternative approach to improve the performance via increasing the desirable outputs and decreasing the undesirable outputs in DEA (Seiford, 2002). Among the main articles, we can see “Undesirable outputs in efficiency valuations” that discussed several approaches for treating such outputs in the framework of DEA and the resulting efficient frontiers are compared, then, new radial measures are introduced which assume that any change of the output level will involve both undesirable and desirable outputs (Scheel, 2001). The article titled “A non-radial DEA approach to measuring environmental performance” is also among the top articles, it created a non-radial DEA approach to measuring

environmental performance and applied in a case study of OECD countries from 1995 to 1997 (Zhou *et al.*, 2007).

Seiford (2002) pointed out that the new approach can also be applied to situations when some inputs need to be increased to improve the performance. Scheel (2001) argued that the universally efficient DMUs which even cannot improve the “ratio” of desirable and undesirable outputs may be of special interest for benchmark selection, which is an important topic in management applications.

As shown, this cluster demonstrates an alternative to maximize performance, which is possible by increasing desirable inputs and decreasing undesirable outputs in the DEA methodology (Scheel, 2001; Seiford, 2002). Thus, it appears that this alternative is of significant importance for the DEA methodology and, consequently, for this research.

Cluster 4 – DEA for Eco-efficiency measures (Color yellow)

The fourth cluster analyzes “DEA for eco-efficiency measures” issues. Eco-efficiency is an instrument for analyzing sustainability, it represents the efficiency of economic activity in relation to nature's goods and services (Dyllick and Hockerts, 2002). Given its possible contribution to academia and society, the correct measurement of eco-efficiency can be obtained through the DEA, as analyzed in the articles found, therefore, it is essential to analyze the cluster of this theme.

Tyteca (1996) carried out a literary review on the measurement of the environmental performance of organizations. The study proposes a discussion about the nature and causes of environmental inefficiencies, analyzes the relationship between environmental performance and the global effect of industrial activities on health and the environment, in addition to considering the DEA method for measuring the environmental performance of organizations. Korhonen and Luptacik (2004) carried out the analysis of the eco-efficiency of power plants. According to the authors, the DEA can help in the measurement and evaluation if used as an efficiency measure. The authors applied their approaches in 24 European plants. Zhang *et al.* (2008) focused on the eco-efficiency analysis of the industrial system in China using DEA-based models. The study aims to illustrate the possibilities of measuring the eco-efficiency of a region by selecting appropriate indicators, in addition provides insights into the causes of eco-inefficiency.

As a topic for future research, the following suggestions can be inferred from this cluster: Korhonen and Luptacik (2004) advise introducing environmental standards in their models to assess the impact of environmental policy for the measurement of efficiency, in

addition to performing multilateral comparisons of productivity between organizations from all over the planet. Zhang *et al.* (2008) point out that future research involving the DEA should cover the integration of the non-linear structure, as the increase in of insights into the impacts of production will probably lead to a circular production model. They also consider that the following studies should acknowledge consider the relative weight restrictions, including them in the DEA model.

In this way, this cluster contributes to a satisfactory measure of eco-efficiency, given the importance of analyzing sustainability nowadays (Lu *et al.*, 2022). Once the synergy between the themes is identified, the construction of this fourth cluster is justified, in this way, the contributions of this research are relevant to society and literature.

Cluster 5 - DEA measures for Agriculture (Color lilac)

The fifth cluster analyzes “DEA measures for Agriculture” issues. The fifth cluster analyzed focuses on the issue of DEA measurement for agriculture, which is of considerable importance, given that agriculture represents a significant part of the global economy and is indispensable for life (Tilman *et al.*, 2011). The DEA method consists to compare the revealed efficiency with the benchmarks of decision making units (Cooper *et al.*, 2007).

When analyzing the main studies of this cluster, we found that the following statements as main results: Hailu and Veeman (2001) dedicated themselves to understanding the Canadian pulp and paper industry. The authors carried out studies to find the modifications of the nonparametric Varian–Banker–Maindiratta models extended by Chavas and Cox. The results show that researchers must recognize the limitations of the results of analyzes based only on DEA methods. Kuosmanen and Podinovski (2009) carried out a study in order to analyze how non-disposable technology can be modeled so that non-uniform reduction factors can be applied. The authors found a limitation in the literature regarding the conventional specification of disposability in the analysis of activity. Färe *et al.* (2004) constructed an environmental performance index based on distance functions. The index developed by the authors consists of a formal environmental performance index calculated through the DEA and allows for the measurement of how a company managed to simultaneously yield good production and account for reductions in bad productions.

The studies in this cluster illustrated some limitations regarding theme and research suggestions, such as: empirical estimates of efficiency ratings or productivity growth generated exclusively from analyses done by the DEA (internal limit) do not provide reliable data (Hailu and Veeman, 2001). Another limitation is pointed out in the conventional specification of

disposability in activity analysis, and the main drawbacks of this limitation are pointed out (Kuosmanen and Podinovski, 2009). Färe *et al.* (2004) suggest that the index built by them be explored in future studies. According to the authors, this would allow for finding more direct evidence on the relationship of the environmental Kuznets curve.

Thus, it is observed that the DEA contributes significantly and positively to agriculture, as pointed out by Hailu and Veeman (2001) and Tilman *et al.* (2011) DEA measurement for agriculture is of significant importance. Note that there are gaps in DEA measurement, such as the lack of studies that analyze empirical estimates of efficiency indices and about the conventional specification of disposability in the analysis of activities. Consequently, it is noted that, although the DEA measurement is considerable, it still has gaps in its literature, emphasizing the importance of studies in the area and the proper analysis of the interfaces with agriculture.

Cluster 6 - Power plant generation and Energy (Color light blue)

The sixth cluster analyzes “Power plant generation and Energy” issues. In this cluster DEA was important to apply power plant generation and, also, energy. Then, a use of DEA was proposed by many researchers in energy economics (Sueyoshi, 2017). Also, in performance measurement of power industry, DEA has gained much popularity (Bi *et al.*, 2014).

Yang and Pollitt (2009) built six DEA-based performance evaluation models, using a sample of coal-fired power plants located in China. This effort was a reflection of the lack of studies that, according to the authors, assess undesirable outputs and uncontrollable variables. The authors consider that the findings of this research have implications for both measurement methodology and policies from the power sector to Chinese coal. Bi *et al.* (2014) analyzed whether environmental regulation affects energy efficiency in China's thermal power generation. To fulfill the objective, the researchers analyzed the relationship between fossil fuel consumption and the environmental regulation of thermal energy generation. Among the research findings, three stand out: 1- Both energy and environmental efficiency were low, 2- Both efficiencies have considerable variations depending on the analyzed location, 3- The characteristics of both efficiencies can be defined on account of the geography. Sueyoshi *et al.* (2017) summarized the application of DEA measurement applied to energy and the environment. They concluded, therefore, that the use of the DEA maximizes the mitigation of problems due to climate change and environmental pollution.

When looking at this cluster, it is necessary to point out the following propositions for future research: the literature on the DEA should focus on three main issues, namely: technological heterogeneities and time lag, statistical inference, applications for China

(Sueyoshi *et al.*, 2017). Bi *et al.* (2014) consider that the literature should focus on the Malmquist productivity index, the use of the two-stage DEA approach to analyze the energy conservation and emission reduction performance of the Chinese government and measurement comparisons with other methodologies.

To end the construction of the sixth cluster, note the favorable relationship of the DEA measurement applied in the generation of power plants and energy, observing the popularity of the adoption of the DEA measurement in these cases. There are also gaps in the literature, such as the lack of studies on energy conservation performance and comparisons with other measurement methodologies. It appears that the themes have points in common and that the construction of this cluster is fundamental for the present research.

Cluster 7 - DEA and production systems (Color orange)

The seventh cluster analyzes “DEA and production systems” issues. This cluster analyzes how the DEA can favor the measurement of production systems. Production systems are understood as the process used in the production of products and services (Cassman, 1999).

The following most relevant results can be inferred: Fried *et al.* (2022) developed a technique to incorporate environmental effects and statistical noise into producer performance evaluation using the DEA. According to the study, when using the DEA through three stages, being: stage one based on conventional inputs and outputs, stage two based on regression and the third stage based on conventional outputs and adjusted inputs, it is possible to obtain a more accurate measurement. Kuo, Wang and Tien (2010) analyzed the integration of artificial neural networks and MADA methods for the selection of green suppliers. The authors conclude that the ANN-MADA hybrid method surpasses the ANN-DEA and ANP-DEA hybrid methods, it is also concluded that the ANN-MADA model stands out in discrimination and insensitivity to noise in the evaluation of the performance of green suppliers. Mavi, Saen and Goh (2019) focused on understanding the joint analysis of eco-efficiency and eco-innovation with common weights in the DEA two-stage network. The model proposed by the authors allows decision makers to fully classify the decision-making units. Therefore, the model becomes attractive to those who seek to objectively maximize the relationship between products and inputs.

Regarding the limitations of the subject, it is noteworthy to emphasize that the measurement by the DEA for production systems has limitations because it is deterministic and disregards environmental variables (Fried *et al.*, 2022). Therefore, we have studies such as those by Kuo, Wang and Tien (2010) and Mavi, Saen and Goh (2019) that allow mixed measurement

methods. However, it is noteworthy that the literature lacks studies in this field and that future research should delve deeper into the DEA linked to other methodologies.

As stated above, it can be understood that the DEA measurement has an interface with the production systems. It highlighted the possible contributions between the themes as punctuated by the authors Fried *et al.* (2022), Kuo, Wang and Tien (2010) and Mavi, Saen and Goh (2019) and the absence of studies that carry out this analysis jointly was emphasized. Therefore, the choice of this cluster is justified, given its importance for the literature and given its possible contribution to the measurement of production systems.

Cluster 8 - DEA and Manufacturing (Color brown)

The eighth cluster analyzes “DEA and Manufacturing” issues. Manufacturing problems encompass all events that negatively interfere with the design of the final product or service. Such events can be characterized by the failure of a certain item to function or even environmental damage caused by the production chain (Gill *et al.*, 2001). Therefore, the measurement of these problems in the manufacturing process is essential for prevention and for corrective measures, and the DEA, as justified by the articles in this cluster, is a way to accomplish this task.

Zaim (2004) focused on measuring the environmental performance of state-owned manufacturing through changes in the intensity of pollution using the DEA. According to Zaim, pollution is a by-product of manufacturing, and therefore a consequence of it. The index constructed by the author consists of a variant of the Malmquist quantity index, satisfying the established axiomatic properties. Sueyoshi and Goto (2012) made a comparison between the Japanese electricity industry and manufacturing industries. For this, the DEA environmental assessment was used to measure weak and strong disposability versus natural and managerial disposability. The study allows us to conclude that manufacturing companies outperform electric power companies under natural disposability, however, in managerial disposability, the opposite occurs. Another study by Sueyoshi and Goto (2012) focused on DEA for environmental assessment, comparing public and private ownership in the oil industry. The authors consider that the measurement by the DEA should classify the results of the productive system in desirable and undesirable products, for that the study is composed of three types of unification for environmental evaluation. The first being the decrease in the input vector with the decrease in the direction vector of undesirable outputs, the second consists of the decrease in an input vector with the decrease in the vector of undesirable outputs and the third considers an increase in the input vector but a decrease in the vector of undesirable outputs.

For future research, we found suggestions such as those of Sueyoshi and Goto (2012) who consider that for more robust results of the constructed index it is necessary to increase the sample of manufacturing companies and electric energy companies. The authors also point out that the natural and managerial disposability should be linked to game theory, in addition to considering that future studies should explore the economic and managerial characteristics of the RTS/DTS measurement.

This cluster contributes substantially to this research because, as listed in the development of the analyses, the DEA measurement is positively related to manufacturing. Important contributions can be found in this cluster, such as the DEA being used to measure the environmental performance of manufacturing as well as measuring its disposability (Zaim, 2004; Sueyoshi and Goto, 2012). Thus, the contribution of this cluster is of mutual importance between the fields of study, then justifies being part of the present research.

Cluster 9 - DEA and Energy efficiency (Color pink)

The ninth cluster analyzes “DEA and Energy efficiency” issues. Energy efficiency has, at its core, improved the use of energy sources, rather, it is concerned with efficiently using energy to carry out any industrial, agricultural or service activity (Greening *et al.*, 2000). Consequently, the DEA can favor the correct measurement for energy efficiency, providing real data on energy use. In this way, the cluster analyzed here is responsible for observing the interfaces between both themes.

Yu and He (2020) developed a bibliometric study for the DEA applied to energy efficiency to assess future trends and challenges. After analyzing the articles, the authors concluded that the DEA contributes positively to studies applied to energy efficiency, indicating an interface between the themes that must be analyzed more deeply. Chauhan, Mohapatra and Pandey (2006) used the DEA to improve energy productivity in rice field production through benchmarking. The study separated efficient from inefficient farmers, in addition to identifying unnecessary energy uses. As a result, about 11.6% of energy could be saved if farmers followed the model recommended by this study. Nassiri and Singh (2009) analyzed the energy use efficiency for rice cultivation with the DEA. The authors observed a strong correlation between the energy ratio and technical efficiency and identified a correlation coefficient between specific energy and inverse technical efficiency.

For future research in this field of study, we have the observations of Yu and He (2020), which point out that the DEA should be analyzed with other analytical tools, such as life cycle assessment analysis. The authors also advise research that analyzes the reversal phenomenon

in the assessment of energy efficiency. Chauhan, Mohapatra and Pandey (2006) suggest that for future research the sociocultural and economic aspects of the group of more efficient farmers are compared with those of relatively inefficient farmers, the analysis of agricultural practices and yields collected at different times and locations, and the use of the DEA to analyze energy input in various operations with time and duration. Nassiri and Singh (2009) recommend that future studies analyze the CCR and BCC models used to calculate technical efficiencies.

In accordance with what has been exposed, this cluster fulfills its objective by exploring the interfaces between DEA measurement and energy efficiency. In this way, the contributions between the fields of study are well known, in addition to the notes for future research. It is concluded, therefore, that cluster nine is essential for the development of this research and the current literature.

Cluster 10 - DEA and Fisheries efficiency (Color light red)

The tenth cluster analyzes “DEA and Fisheries efficiency” issues. The issue of fishing efficiency refers to operations that guarantee greater results in fishing activities. Therefore, the DEA methodology can help to measure this efficiency, such a conclusion can be obtained by reading the articles that make up this cluster and which are presented in the following paragraph.

Dupont *et al.* (2002) investigated measures of capacity utilization and overcapacity in privatized fisheries using the DEA. The results that were accounted for provide useful information for decision makers interested in using market-based approaches to improve their efficiency. Tingley, Pascoe and Cogan (2005) studied the factors that affect technical efficiency in fisheries using the DEA. Among the conclusions of the authors, we can highlight that the DEA can be used as an alternative to SPF (Stochastic Econometric Production Frontier) techniques. Yang and Fukuyama (2018) used the DEA to measure Chinese regional production potential. Through this study, the authors make some suggestions for Chinese policy makers, since the identification of excess capacity was identified in four provinces, namely: Tianjin, Liaoning, Shanghai and Zhejiang.

Regarding the interface presented by this cluster, we have as suggestions for future research the notes of Yang and Fukuyama (2018). The authors point out that spatial econometric studies should be considered and that they allow the formulation of public policy suggestions.

Note that, after the developed analyses, the DEA measurement can be related to fishing efficiency. Although studies are found that are based on this joint analysis, they are scarce, requiring the development of research that punctuate the two fields of studies synergistically. Consequently, the development of cluster ten is essential for this research to contribute to academia and society.

Upon examining the presented clusters, a gap was identified due to the absence of indicators for energy efficiency, particularly renewable energy efficiency. Furthermore, it was also noted that there is a lack of studies that take into account pollutant emissions other than CO₂ emissions, such as methane emissions and PM_{2.5} air pollution. Additionally, there is a dearth of research that analyzes the differences in energy efficiency concerning the development level of countries and income groups.

CONCLUSION

The bibliometric study presented in this article has revealed a rapidly expanding theme that has been addressed since 1984, with a notable surge in activity since 2009. These findings underscore the significance of conducting a literature review to enable researchers to map out the existing research and gain insights into the methodologies employed in prior studies. By understanding the historical evolution of a given research area and the ways in which it has been approached in the past, researchers can identify gaps in knowledge, develop new approaches, and build on the findings of previous studies. Therefore, this study highlights the value of conducting a bibliometric analysis in promoting a deeper understanding of a given research topic and informing future research directions.

There are two articles that stand out in terms of local citations. The article Seiford L.M., 2002, *European Journal of Operational Research* focused on emphasizing that to increasing the desirable outputs and decreasing the undesirable outputs the DEA model can be used and Hu J.L., 2006, *Energy Policy* titled “Total-factor energy efficiency of regions in China” are the top two and can be considered as mandatory references in their themes.

We verified the existence of several journals, however, the publications are concentrated on few relevant ones, such as: (1) *Journal of Cleaner Production* (with 7% of the articles); (2) *Sustainability* (6%); (3) *European Journal of Operational Research* (3%); (4) *Energy*; (2%) and (5) *Energy Policy* (2%). The same happened with the most relevant authors. When the great importance for the development of this research field is considered from the point of view of the volume of publications, author Sueyoshi T., Li Y., and Chiu YH. can be highlighted. From the point of view of the number of citations (local impact), author Zhou P., Sueyoshi T., Goto M. can be considered as main references in the field.

When analyzing the DEA models most used in 25 articles with the greatest local impact (local citations), the model CRS stands out, representing 24% of the sample, followed by CRS+VRS with 12%. As the most current trend topics, “innovation”, “empirical-evidence”, and “urbanization” appear as timeless themes, which over the last 4 years have always been approached. Although it is an extensive literature, we can see the formation of 10 research clusters and articles that can be considered pillars in each cluster.

Despite these contributions, we have pointed out the following limitations. The search for articles was limited to the WoS database, suggesting that material from other databases may offer different results. Although we cover a wide range of words related to sustainability, it is always possible that related articles have not used these terms in the title, abstract and keywords. Another limitation is the range of words related to sustainability not covering the entire academic production

on the matter. This bibliometric mapping is just a starting point, the deeper analysis of the clusters and the content of the most relevant articles are important continuities.

CHAPTER 2: RENEWABLE ENERGY EFFICIENCY AT THE NATIONAL LEVEL: A DATA ENVELOPMENT ANALYSIS INDEX

2.1 Introduction

Renewable energy has been identified as a key alternative means of enhancing environmental efficiency, as highlighted by policymakers and researchers. This recognition of renewable energy as a viable solution to environmental concerns has fueled significant research and development efforts aimed at promoting its adoption and maximizing its efficiency. The use of renewable energy sources, such as solar and wind power, represents a critical step towards reducing the negative impact of traditional energy sources on the environment and mitigating the harmful effects of climate change. Consequently, policymakers and researchers have called for continued investment in renewable energy technologies and initiatives that support their widespread adoption (Woo *et al.*, 2015).

In light of the importance of the discussed matter, it becomes imperative to ascertain the correlation between the escalating utilization of renewable energy sources and the consequent enhancement of energy efficiency, a relationship substantiated by prevailing international scholarly discourse. However, there is a lack of globally standardized indicators specifically focused on the renewable energy efficiency. In this chapter, renewable energy efficiency is understood as the ability to maximize the use of renewable energy sources to achieve a higher level of energy efficiency.

In this context, the research problem presented in this paper revolves around identifying the optimal national performance in converting pollutant emissions into renewable energy and achieving electricity access. For this reason, the main objective of this paper is to create a non-parametric DEA indicator that can measure the renewable energy efficiency at the national level worldwide. The proposed indicator will be segmented into three distinct groups: a global indicator, a developmental group (i.e., developed and developing countries) indicator, and an income group (i.e., high-, middle-, and low-income) indicator. This study's significance lies in its ability to conduct rigorous statistical tests that can help to identify variations in renewable energy efficiency in groups across different countries. This analysis will provide policymakers with crucial information for designing effective policies and interventions aimed at promoting the adoption of renewable energy sources. By identifying the factors that contribute to inefficiency in renewable energy use, policymakers can develop targeted strategies to improve efficiency and encourage the adoption of sustainable energy practices. The insights gleaned

from this analysis can inform the development of better practices for increasing the use of renewable energy, which can be tailored to meet the unique needs and circumstances of different countries and regions. The findings of this study can be used by multilateral organizations (i.e., United Nations) to design targeted interventions that can improve renewable energy efficiency and help countries transition towards more sustainable energy practices.

The expansion of the renewable energy sector underscores the need for comprehensive exploration into methodologies focused on increasing energy efficiency (Ji *et al.*, 2022). Despite some research endeavors that have focused on the evaluation of the renewable energy efficiency, a comprehensive understanding of this phenomena is crucial for achieving sustainable energy systems (Woo *et al.*, 2015). Woo *et al.* (2015) examines the renewable energy efficiency in 31 OECD countries using labor, capital, and renewable energy supply as the three inputs, while GDP is the desirable output and carbon emissions are the undesirable output applying the Malmquist productivity index to estimate the average efficiency change from 2004 to 2011. Hou *et al.* (2019) creates a set of indicators, including an energy self-sufficiency ratio, energy production over consumption ratio, energy imports, diversification index of energy imports, energy reserve ratio, GDP productivity, energy intensity, per capita energy consumption index, carbon emission index, carbon emission index per unit of energy consumption and share of renewable energy in order to develop an energy efficiency and environmental performance index. Ji *et al.* (2022) used the DEA game cross-efficiency model to calculate the clean energy efficiency (CEE) and fossil energy efficiency (FEE) of China at the provincial level. Li, Ji and Dong (2022) consider five types of installation capacity of renewable energy as input indicators and renewable energy power generation as an output indicator using the Malmquist index and a random forest regression model to evaluate the influencing factors of renewable energy PGE in each country. Chien and Hu (2007) analyze the effects of renewable energy on the technical efficiency of 45 economies during the 2001–2002 period through the DEA model using labor, capital stock, and energy consumption as the three inputs and real GDP as the single output. Menegaki (2013) conducts DEA for the purpose of calculating inefficiencies in the European countries' growth using the variables typically used in the growth-energy literature nexus such as energy consumption, carbon emissions, employment and capital as the main inputs, but also with a particular focus on the consumption of renewable energy sources (RES). But none of this research has created an index to measure renewable energy efficiency.

2.2 Literature review

This section provides an elucidation of the literature review and theoretical framework that underpins the utilization of the Data Envelopment Analysis (DEA) indicator in scrutinizing the renewable energy efficiency.

2.2.1 Renewable energy efficiency

The focal point of the energy efficiency field is to enhance the utilization of energy sources (Greening, Greene & Difiglio, 2000). In this context, energy efficiency is understood as the efficient use of energy to achieve a specific outcome (Schipper *et al.*, 1989). To address climate change, it is crucial to diminish the consumption of polluting energy sources (Camimoto *et al.*, 2018). Hence, energy efficiency and the replacement of polluting energy with renewable sources are interrelated topics that necessitate comprehensive examination (Pablo-Romero *et al.*, 2016).

Saygin *et al.* (2015) focus on the implications for innovation in renewable energy to increase the share of renewable sources worldwide between the years 2010 and 2030. The authors conceptualize that by improving energy efficiency the use of renewable energy will increase. This means that one field of study relates to another in a direct and positive way. Shrestha *et al.* (2022) investigate the evolution of the energy matrix in emerging markets. The data establishes a positive relationship with modern renewable and non-renewable energy, but a negative relationship with traditional renewable energy. Thus, the authors consider that it is necessary to implement policies that encourage the adoption of modern renewable energy, which is the role of governments.

Lo (2014) carries out an analysis of renewable energy and energy efficiency policies in China. The data indicates that renewable energy policies contribute to energy security, climate change, economic competitiveness, pollution and human livelihoods. In this way, such policies need to be solidly constructed by governments, as well as guaranteed that they will be complied with. Murshed (2020) conducts an empirical analysis of the impacts of trade openness in information and communication technology on the renewable energy transition, energy efficiency, access to clean cooking fuel, and environmental sustainability in South Asia. The study concludes through the trade of information and communications that technology maximizes renewable energy consumption, reduces energy use, assists in the adoption of cleaner cooking fuels, and reduces carbon dioxide emissions. Akram *et al.* (2020) measures the

heterogeneous effects of energy efficiency and renewable energy on carbon emissions in emerging markets. The results point out that both energy efficiency and sustainable energy contribute to the reduction of environmental and air pollution. It also defends the need to design appropriate economic and energy policies in the context of these markets to be able to achieve environmental sustainability.

Hou *et al.* (2019) aims to develop a comprehensive energy efficiency and environmental performance index by constructing a set of indicators, including the energy self-sufficiency ratio, energy production over consumption ratio, energy imports, diversification index of energy imports, energy reserve ratio, GDP productivity, energy intensity, per capita energy consumption index, carbon emission index, carbon emission index per unit of energy consumption, and share of renewable energy. In contrast to other studies, the authors evaluated each indicator before estimating a combined score for each country, which offers a more nuanced analysis of energy efficiency and environmental performance. Hou *et al.* (2019) findings indicate that Bhutan has achieved the highest level of energy self-sufficiency, with a score of 100.6, whereas Afghanistan has the lowest score, with a mere 12.90. The research concludes that, presently, it is more prudent for countries to evaluate their emission rates in relation to their energy consumption, rather than energy production. Given the significance of both consumption and production, a comprehensive analysis of both aspects was made.

2.2.2 Renewable energy and air pollution

Environmental pollution has been a pervasive issue since the 1970s. However, it was only in the early 1990s that this concern was extensively addressed in academic literature (Shafik & Bandyopadhyay, 1992; Alvarez-Herranz *et al.*, 2017). The proliferation of technology and production systems has contributed to the damage inflicted on the environment, resulting in increased consumption and the proliferation of waste (Tansel, 2017). Given this scenario, one of the most pressing challenges humanity faces is to ensure that resources, such as energy, are reused to minimize the impact of production and consumption on the environment (Cooper & Gutowski, 2017).

The regulation of energy consumption is essential to mitigate global warming and promote sustainable economic growth (Dogan & Seker, 2016). Environmental regulations directly impact pollution levels (Bilgili, Kocak, & Bulut, 2016). Alvarez-Herranz *et al.* (2017) investigates the relationship between innovation in renewable energy and air pollution reduction. Their findings reveal a correlation between income and environmental degradation,

as well as a positive relationship between economic growth, promotion of renewable energy, public investment in renewable energy research, and air pollution reduction. Thus, it is evident that renewable energy and air pollution are interrelated.

Novan (2015) has ascertained the renewable energy and air pollution policies. The research quantifies the heterogeneity on the hazardous impact from renewable energy on pollution, so, the results have enforced that the creation of a policy which considers the heterogeneous benefits so that governments keep supporting renewable energy is necessary. Zhu *et al.* (2020) have themselves inquired about the technological innovation in renewable energy controlling the air pollution in China. Among the listed results by the authors, the technological innovation in renewable energy decreasing the nitrogen oxide concentrations and breathable suspended particles stands out. The authors have recommended that governments consider the most affected locations when developing policies to improve the air quality.

Kotrikla, Lilas and Nikitakos (2017) investigate the air pollution reduction through renewable energy in a harbor located in one of the Aegean islands. The authors have found that the ship's emission could be reduced by providing them with electricity using a hybrid renewable energy system which utilizes wind and photovoltaic turbines. Consequently, it would result in cleaner air and a healthier environment. Koengkan, Fuinhas and Silva (2021) have explored the capacity of renewable energy consumption, to reduce the mortality rate caused by air pollution in Latin America and in the Caribbeans. According to the authors, renewable energy consumption can reduce the mortality rate caused by air pollution by increasing the renewable energy and decreasing the consumption of energy from fossil fuel. The authors also propose that governments should pay attention to the transition between the fossil energy use to renewable ones to better the air quality.

Boudri *et al.* (2002) have observed the contribution of renewable energy potential to the reduction of air pollution in China and India. The results achieved by the authors permit them to assess that if the use of renewable energy was maximized, it could reduce the sulfur dioxide control costs between 17% to 35% in China and in India by about two thirds. Chen *et al.* (2016) have built a simulation model for renewable energy and control air pollution with the aim of generating electrical energy. The authors conclude that this model could promote influences and restrictions among those who have decided, however, they can allow the interested parties to run the conflict interaction between the system cost, pollutant mitigation and system infringing risk.

Jacobson (2017) has developed itineraries for countries which are transitioning to clean and renewable energy. The itineraries consist of alternatives for the use of sustainable energy

sources, so they can speed up the transition to minimize the growing climatic problems such as the energy pollution and safety. Longo, Yaïci and Zaninelli (2015) have developed a study in Canada and Italy concerning the feasibility in integrating electric cars and motorcycles. The authors defend that the use of these vehicles would represent an opportunity to decrease environmental damage, highlighting that it is a governmental duty to stimulate and ensure renewable energy policies.

Yousefi *et al.* (2018) have analyzed the effects of the economy and pollution on the use of renewable energy in Tehran. The research has registered that it is crucial not only to list the positive effects to the environment, but also to consider the capital cost estimated and the time of return to implement renewable energy. The authors have also identified that after using renewable energy for only 17 months, the Tehran government reached a \$ 150.956,25 reduction in environmental costs.

Shen *et al.* (2020) focus on green innovation in renewable energy, fossil energy consumption and air pollution, all in a Chinese context. The authors have observed that renewable energy inhibits local and nearby air pollution. Thus, it is recommended that the green innovation in renewable energy be stimulated resulting in the reduction of fossil energy and the negative effects in the air and environment. Rodriguez-Alvarez (2021) analyzes the connection between air pollution and life expectancy, besides inquiring whether or not renewable energy is indeed worth the investment. The results lead us to understand that to minimize the air quality global production effects, a bigger investment in renewable energy is necessary, resulting in a better worldwide health.

Rita, Chizoo, Cyril (2021) analyze the impact of air pollution during the Covid-19 Pandemic. According to the results, during the Pandemic, there has been a decrease in the emission of greenhouse gasses because the blockages have significantly decreased the air pollution. The authors consider that it is possible to keep this reduction after the pandemic scenario by using biofuels to generate energy, reducing the emission of atmospheric pollutants as a result. Koengkan *et al.* (2022) paid attention to the effect of renewable energy policies on deaths caused by air pollution with samples from Latin America and the Caribbeans. The work concluded that the variables: energy consumption of non-renewable energy sources, urbanization and globalization have increased the deaths related to air pollution. However, the solution to this issue depends on the variables: electricity consumption, which came from new renewable energy sources, policies of financial/tax incentives of economic tools to allow the implantation and the use of renewable energy, economic growth, and social globalization.

Begum (2013) has researched the use of palm oil debris as a renewable energy source, in addition to its impact on the reduction of air pollution. The author claims that renewable energy sources are the key to environmental pollution reduction, such a claim is based on his results, because it is noted that the use of biogas derived from palm oil reduces the air pollution, generating clean energy. Shah *et al.* (2022) have investigated the interface between the income of foreign investment, the renewable energy consumption, the air pollution and human mortality in China. The empirical results register that the bigger the direct foreign investment flux, the bigger the mortality tends to be and so the use of renewable energy is compromised. Therefore, researchers say that the government needs to generate public policies to balance this equation, such as the creation of correct laws made for foreign companies.

As it has been shown, the literature registers the existence of a direct interface between renewable energy and air pollution (Novan, 2015, Alvarez-Herranz *et al.*, 2017, Koengkan *et al.*, 2022). In addition, the necessity of governmental stimulation to increase the use of renewable energy and to reduce harmful environmental and air damage, stands out (Yousefi *et al.*, 2018, Shah *et al.*, 2022). It also indicates the connection between sustainable energy implantation and financial income (Bilgili; Koçak; Bulut, 2016). As a result, the themes are essential to be not only analyzed but also developed together. Among the related topics, there is another field which needs emphasis: energy efficiency is the key to an effective renewable energy so that the air pollution can be reduced. Consequently, the next chapter identifies studies among the energy efficiency which enables sustainability.

2.3 Method

This section aims to present the data and procedures utilized to generate a comprehensive and normalized indicator that assesses the performance of countries worldwide in terms of renewable energy.

2.3.1 Inputs and Outputs Variables

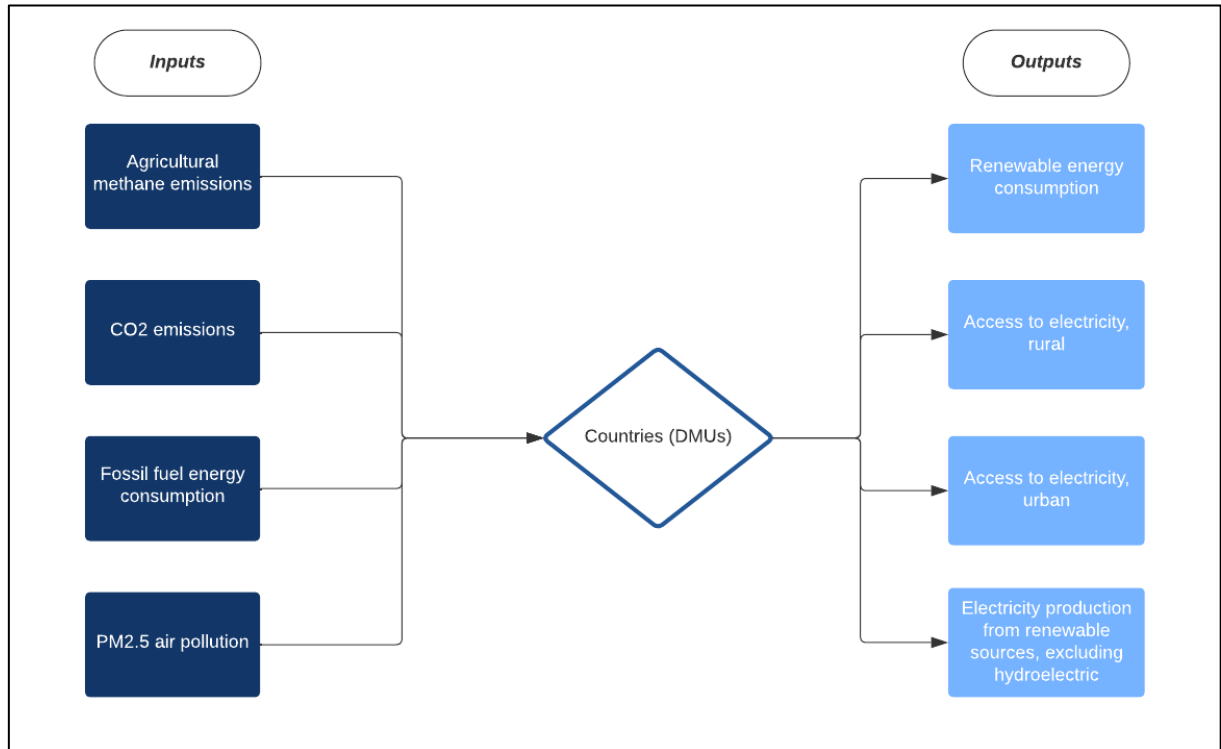
In this study, we examine the renewable energy efficiency in 2016 among 133 countries, following the exclusion of 84 countries with a population of less than 1,000,000 inhabitants. To select inputs for our analysis, we considered both environmental and energy variables that are crucial for achieving sustainable development, such as agricultural methane emissions, CO₂ emissions, fossil fuel energy consumption, and PM2.5 air pollution. While previous studies have focused on CO₂ emissions as a measure of environmental degradation (Yu *et al.*, 2020; Du *et al.*, 2019; Fang, Zhang and Zhou 2018), we also incorporated methane emissions into our DEA model (Herrero, 2016; Smith, 2008), as the United Nations (United Nations, 2021) and the Sustainable Development Goals have emphasized the importance of reducing methane emissions globally. In addition, we chose environmental outputs that should be increased by policymakers to promote environmental sustainability, including renewable energy consumption, access to electricity in rural and urban areas, and electricity production from renewable sources (excluding hydroelectric). All data used in our analysis were obtained from the World Development Indicators database (World Bank, 2023), and a summary of the inputs is presented in Table 4.

Table 4. Inputs and outputs definition

Indicator	Unit	Type	Definition
Agricultural methane emissions	Thousand metric tons of CO ₂ equivalent	Input	Emissions from animals, animal waste, rice production, agricultural waste burning (non energy, on-site), and savanna burning.
CO ₂ emissions	Metric tons per capita	Input	Carbon dioxide emissions.
PM _{2.5} air pollution, mean annual exposure	Micrograms per cubic meter	Input	Population-weighted exposure to ambient PM _{2.5} pollution is defined as the average level of exposure of a nation's population to concentrations of suspended particles measuring less than 2.5 microns in aerodynamic diameter, which are capable of penetrating deep into the respiratory tract and causing severe health damage. Exposure is calculated by weighting mean annual concentrations of PM _{2.5} by population in both urban and rural areas.
Renewable energy consumption	% of total final energy consumption	Output	Renewable energy consumption is the share of renewables energy in total final energy consumption.
Access to electricity, rural	Percentage	Output	Rural population with access to electricity.
Access to electricity, urban	Percentage	Output	Urban population with access to electricity.
Electricity production from renewable sources, excluding hydroelectric	kWh	Output	Electricity production from renewable sources, excluding hydroelectric, includes geothermal, solar, tides, wind, biomass, and biofuels.

Source: The author.

The theoretical framework is represented in Figure 9, illustrating the fundamental concept of a dual set consisting of inputs and outputs. The set of inputs is composed of agricultural methane emissions, CO₂ emissions, fossil fuel energy consumption, and PM_{2.5} air pollution, whereas the set of outputs comprises renewable energy consumption, access to electricity, and electricity production from renewable sources. The overarching aim of this model is to decrease inputs while simultaneously augmenting outputs.

Figure 9. Flowchart of the DEA model

Source: The author.

2.3.2 Data Envelopment Analysis

Utilizing mathematical and linear programming, Data Envelopment Analysis (DEA) is a non-parametric technique employed to measure efficiency, as established by Charnes *et al.* (1978). The analysis involves Decision-Making Units (DMUs), revealing a linear frontier that illustrates the efficiency of these units in converting inputs into outputs. This process identifies DMUs (i.e., countries) that effectively utilize inputs to generate the maximum possible outputs, representing the production limit within the sample (Cook *et al.*, 2014; Santana *et al.*, 2014). Cook and Zhu (2015) propose ranking DMUs (i.e., countries) based on the efficiency scores derived from the DEA model, ranging from zero (indicating no efficiency) to one (representing highly efficient DMUs).

DEA optimizes weights based on the strengths of each analyzed entity, facilitating the attainment of a top-ranking position (Mariano *et al.*, 2015). However, various DEA models consider factors such as returns to scale and model orientation. The Constant Return of Scale (CRS) model posits that inputs and outputs vary proportionally (Charnes *et al.*, 1978). Conversely, the Variable Return of Scale (VRS) model allows for different frontier areas, including increasing, constant, and decreasing returns to scale (Banker *et al.*, 1986). Moreover,

the DEA model can be oriented towards inputs, highlighting how a country can minimize its inputs for a given set of outputs, or towards outputs, revealing how a country can maximize its outputs given available inputs. Table 5 provides a concise overview of the CRS and VRS models.

Table 5. Main DEA radial models in the form of multipliers

Mode	Input Oriented	Output Oriented
1		
CRS	$MAX \sum_{i=1}^m u_i \cdot y_{i0}$ Subject to: $\sum_{j=1}^n v_j \cdot x_{j0} = 1$ $\sum_{i=1}^m u_i \cdot y_{ik} - \sum_{j=1}^n v_j \cdot x_{jk} \leq 0 \text{ for } k = 1, 2, \dots, h$	$MIN \sum_{j=1}^n v_j \cdot x_{j0}$ Subject to: $\sum_{i=1}^m u_i \cdot y_{i0} = 1$ $\sum_{i=1}^m u_i \cdot y_{ik} - \sum_{j=1}^n v_j \cdot x_{jk} \leq 0 \text{ for } k = 1, 2, \dots, h$
VRS	$MAX \sum_{i=1}^m u_i \cdot y_{i0} + w$ Subject to: $\sum_{j=1}^n v_j \cdot x_{j0} = 1$ $\sum_{i=1}^m u_i \cdot y_{ik} - \sum_{j=1}^n v_j \cdot x_{jk} + w \leq 0 \text{ for } k = 1, 2, \dots, h$ <i>w without sign restriction</i>	$MIN \sum_{j=1}^n v_j \cdot x_{j0} - w$ Subject to: $\sum_{i=1}^m u_i \cdot y_{i0} = 1$ $\sum_{i=1}^m u_i \cdot y_{ik} - \sum_{j=1}^n v_j \cdot x_{jk} + w \leq 0 \text{ for } k = 1, 2, \dots, h$ <i>w without sign restriction</i>

Source: Mariano and Rebelatto (2014, p. 5).

Where: x_{jk} represents the amount of the inputs j of a company k ; y_{ik} represents the amount of the outputs i of a company k ; x_{j0} represents the amount of the inputs j of the company; y_{i0} represents the amount of outputs i of the company; v_j represents the weight of the inputs j for the company; u_i represents the weight of outputs i for the company; θ means the efficiency of the electricity company being analyzed; λ_k is the contribution of the company k to the goal of the company; m is the quantity of analyzed outputs; n is the quantity of inputs analyzed; and W represents the scale factor.

This study adopts the VRS model with an output orientation due to its suitability for comparing countries of varying sizes, aligning with the goal of increasing renewable energy

worldwide. However, this study still needs to address the tie-breaking issue, which is a limitation of DEA models.

2.3.3 Inverted Frontier

In addressing the challenge of ties in the efficiency scores of countries within the DEA rank, this research employs the Inverted Frontier (IF) technique. The issue of multiple countries obtaining identical scores in the DEA rank introduces complexities in interpreting rank positions, a concern addressed by Angulo-Meza and Lins (2002) through the application of the IF technique. Initially proposed by Yamada *et al.* (1994) and further endorsed by Leta *et al.* (2005), the IF technique serves as a tie-breaking function by altering the positioning of inputs and outputs within the traditional DEA model. Consequently, the IF exposes the suboptimal practices inherent in the analyzed phenomenon.

The IF technique offers two notable advantages. Firstly, it provides a metric grounded in the shortcomings of each country. Secondly, the frontier generated by the IF delineates the worst practices among countries, as opposed to the conventional frontier that highlights best practices. In this study, we applied the IF to assess the renewable energy efficiency, proposing a composite index calculated as the average between the traditional DEA frontier ($DEA_{traditional}$) and the quantity obtained by subtracting the indicator derived from the Inverted Frontier ($DEA_{InvertedFrontier}$) from one (Expression 1) (Leta *et al.*, 2005).

Expression 1

$$CI = \gamma * DEA_{traditional} + (1 - \gamma) * (1 - DEA_{InvertedFrontier}), with 0 \leq \gamma \leq 1$$

In this sense, the composite index considers two situations: when countries are compared based on their strongest points (traditional frontier) and when countries are compared based on their weakest points (inverted frontier). This research work computes the value γ equal to 0.5 to aggregate the classical and inverted boundary results (in Expression 1), which means that this study used the average between the two boundaries.

The composite indicator, which combines the traditional and inverted frontiers, is called Renewable Energy Index (REI). This metric holds significance as it incorporates variables that have been overlooked in prior studies but are highly regarded in the context of sustainable development strategies, particularly those endorsed by organizations such as the United Nations

(UN). Notably, the REI encompasses factors such as methane emissions and PM 2.5 air pollution, which align with the broader goals of sustainable development. Moreover, a distinctive contribution of this research lies in its empirical investigation of various developmental (i.e., developed and developing countries) and income groups (i.e., high-, middle-, and low-income), as discussed in the following section.

2.3.4 Development and Income Group tests

Through the development (i.e., developed and developing countries) and income groups (i.e., high-, middle-, and low-income) analysis, the study aims to discern patterns of renewable energy efficiency across diverse segments. This approach represents a novel dimension, shedding light on the nuanced dynamics of environmental efficiency within different socio-economic groups, thereby enriching the understanding of the broader implications of renewable energy adoption. This analysis enables testing of several hypotheses regarding the relationship between renewable energy performance and environmental factors.

Hypothesis 1. There will be differences in the renewable energy efficiency between developed and developing countries.

Hypothesis 2. There will be differences in renewable energy efficiency between income groups (i.e., low-, middle-, and high-income).

To analyze these hypotheses, our study first measures the DEA environmental efficiency of the countries under analysis. Subsequently, we will test the hypotheses using the calculated efficiency. However, as recommended by Min *et al.* (2020), it is essential to perform the Kolmogorov–Smirnov test to check for data normality before testing the hypotheses. In the event that the DEA efficiency does not exhibit a normal distribution, non-parametric methods such as the Mann-Whitney U test and Kruskal-Wallis H test must be conducted. It is important to note that a non-normal distribution precludes regression analysis, as it requires the validation of the assumption that residuals at each value of the independent variable adhere to a normal distribution (Min *et al.*, 2020).

This study compares the efficiency of country groups through nonparametric test methods that do not make any assumptions regarding the distribution's shape (Cooper *et al.*, 2007). In line with the approach proposed by Min *et al.* (2020), we employ the Mann-Whitney U test to test hypothesis 1, which compares developed and developing country groups.

Additionally, we use the Kruskal-Wallis H test to test Hypothesis 2, which compares low-, middle-, and high-income groups.

In general, nonparametric tests, such as the Mann-Whitney U test and the Kruskal-Wallis H test, are preferred when data do not meet the assumptions of parametric tests. The Mann-Whitney U test (Mann and Whitney, 1947) is commonly used to compare the renewable energy efficiency of two independent groups. Unlike the t-test for independent samples, which assumes normally distributed data, the Mann-Whitney U test is suitable for nonparametric data. The null hypothesis of the Mann-Whitney U test is that there is no difference in the rank of renewable energy efficiency between the developed and developing country groups. In this study, we will combine the two groups and rank them before performing the test. The Mann-Whitney U statistics, U_1 and U_2 , are defined as:

Expression 2

$$U_1 = n_1 n_2 + n_1(n_1 + 1)/2 - R_1$$

$$U_2 = n_1 n_2 + n_2(n_2 + 1)/2 - R_2$$

Where, R_1 and R_2 are the sum of the ranks of the developed and developing country groups, respectively, and n_1 and n_2 are the number of observations of the developed and developing country groups. If the number of observations in each group is larger than eight, z statistics can be used to test the difference between U_1 and U_2 (Mann and Whitney, 1947). The statistics are:

Expression 3

$$z = U - \frac{\mu}{\sigma} = U - \left(\frac{n_1 n_2}{2} \right) / \sqrt{\frac{n_1 n_2 (n_1 + n_2 + 1)}{12}}$$

In the above formula, $U = \min\{U_1, U_2\}$ and $\mu = (U_1 + U_2)/2 = n_1 n_2 / 2$. μ corresponds to the average of U distribution and σ refers to its standard deviation.

The Kruskal-Wallis H test (Kruskal and Wallis, 1952) is a nonparametric method that is similar to ANOVA, as it compares the distributions of three or more groups. However, ANOVA is used for data that follows the F-distribution, whereas Kruskal-Wallis H test is used for nonparametric data. In our study, the Kruskal-Wallis H test can compare low-, middle-, and high-income countries according to renewable energy efficiency. The null hypothesis of the

Kruskal-Wallis H test states that there is at least one group (i.e., high-income) with a median that is significantly different from the others (i.e., low- and middle-income).

Expression 4

$$H = \left(\frac{12}{N(N+1) \sum_{i=1}^k R_i^2 / n_i} \right) - 3(N+1)$$

The H statistics is defined as follows: N is total number of observations, k is the number of groups, n_i is the number of observations in group i , and R_i is the rank sum of group i .

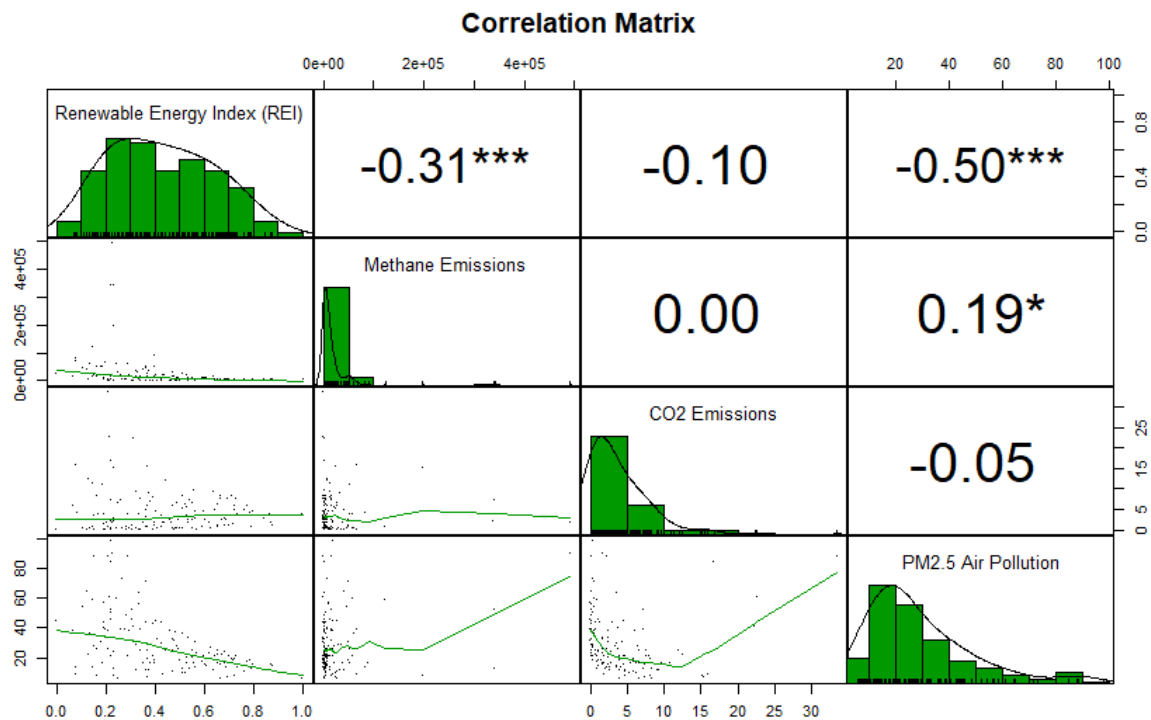
2.4 Results

This section undertakes a comprehensive analysis of the outcomes derived from the Renewable Energy Index (REI) across global, developmental (i.e., developed and developing countries), and income group (i.e., high-, middle-, and low-income) categories. The study aims to discern patterns and variations in renewable energy efficiency within the context of different world regions, developmental stages (i.e., developed and developing countries), and income group (i.e., high-, middle-, and low-income).

2.4.1 World Analysis

In this section, we summarize the results obtained for the 133 countries comprising the sample in the year 2016. Note that efficiency is assessed on a scale from 0 to 1, indicating a spectrum from lower to higher efficiency. In other words, countries with values closer to 1 are considered more efficient than their counterparts. However, approaching a value of 1 does not imply achieving the utmost efficiency; rather, it signifies being the most efficient within the group of countries under analysis, indicating a relative measure of renewable energy efficiency.

The normalized index exhibits a range between zero and one, where values equal to one signify the most favorable positions. Specifically, these positions pertain to countries that emit fewer pollutants, generate a greater amount of renewable energy, and provide greater access to electricity for both rural and urban populations. Conversely, as the value approaches zero, the position becomes increasingly unfavorable. In this sense, Figure 10 illustrates the correlation between the Renewable Energy Index (REI) and pollutant emissions.

Figure 10. Correlation Matrix

Source: The author.

Note that the REI exhibits a negative correlation with pollutant emissions. Specifically, the PM2.5 air pollution demonstrates a negative correlation of 50% with the REI, followed by Methane emissions with a correlation of -31%, and CO₂ emissions with a correlation of -10%. These findings underscore the inverse relationship between renewable energy efficiency, as measured by the REI, and the levels of these environmentally detrimental emissions.

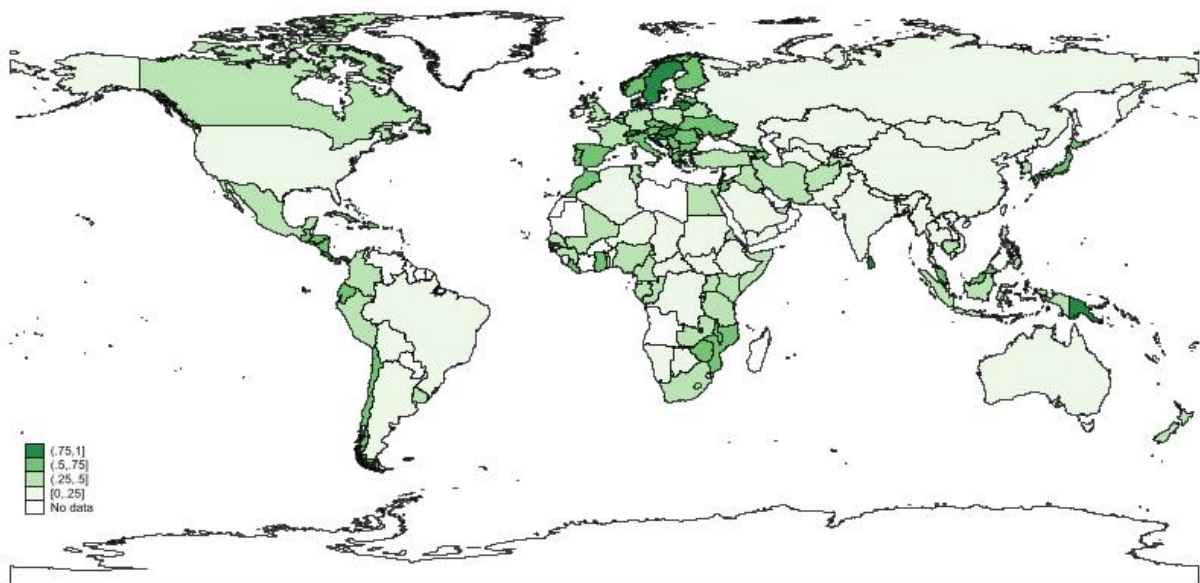
The descriptive statistics of the Renewable Energy Index (REI) across all countries reveal crucial insights. The mean REI is calculated at 0.4318, with a standard deviation of 0.2130 and a coefficient of variation of 49.33%. These statistical measures play a pivotal role in elucidating the broader trend of renewable energy performance at the global level, providing a consolidated perspective on the average performance and central balance point of the distribution of these indicators across countries. Moreover, it is noteworthy that the efficiency scores of 72 countries, constituting more than 54.13% of the sample, fall below the mean value, highlighting a substantial portion of the global sample exhibiting efficiency estimates beneath the average.

Figure 11 provides a visual representation of the global distribution of the Renewable Energy Index (REI). The color-coded scheme in Figure 11 delineates distinct levels of Renewable

Energy Index (REI), with dark green indicating higher REI values, signifying greater efficiency in renewable energy utilization. In contrast, light green corresponds to lower REI scores, indicative of regions with comparatively less efficiency in the adoption and utilization of renewable energy sources. This visual representation serves as a valuable tool for identifying and comparing the efficiency levels across different geographic regions, offering insights into the global landscape of renewable energy utilization. Notably, countries demonstrating high efficiency, falling within the first quartile (REI from 0.75 to 1.0), are predominantly concentrated in Central and North Europe, encompassing nations such as Sweden, Hungary, Switzerland, Portugal, Norway, and others. Interestingly, this cluster of efficient countries also includes some developing regions, such as Sri Lanka, Costa Rica, Lithuania, and Panama. In contrast, the last quartile (REI from 0.0 to 0.25) is primarily populated by nations from developing and low-income regions, including South Sudan, Mongolia, Pakistan, Vietnam, among others.

It is crucial to highlight that certain developed and globally significant economies do not occupy prominent rank positions. For instance, the United States of America holds the 101st position, India the 104th, China the 105th, Russia the 120th, and Brazil the 102nd. This observation underscores the nuanced nature of renewable energy efficiency, with some economically influential countries positioned lower in the ranking, warranting further examination into the factors influencing their relative standings.

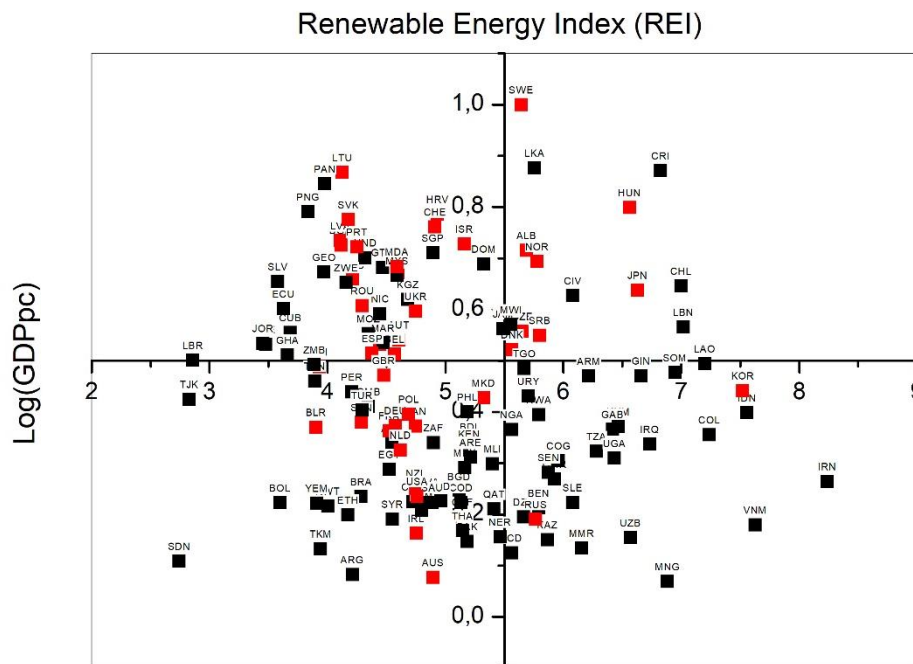
Figure 11. Global distribution of the Renewable Energy Index (REI)



Source: The author.

Figure 12 provides insight into the complex relationship, or lack thereof, between the Renewable Energy Index (REI) and Gross Domestic Product (GDP) per capita across different developmental groups. Within the context of Figure 12, it is noteworthy that the black dots serve to indicate countries with developing economies, whereas the red dots serve to signify those countries which are categorized with developed economies. Notably, the data elucidates that the performance in terms of the Renewable Energy Index varies within affluent nations. For instance, Sweden, classified as a developed nation, attains the highest REI score, exemplifying superior efficiency in renewable energy utilization. Conversely, Australia, also categorized as a developed nation, exhibits one of the lowest REI scores, indicating comparatively poor performance in the adoption and efficacy of renewable energy practices. This discrepancy underscores the nuanced interplay of factors influencing renewable energy efficiency even within economically advanced countries, emphasizing the need for a multifaceted analysis of contributing variables.

Figure 12. REI and GDP per capita across different developmental groups



Source: The author.

The subsequent analysis endeavors to unveil insights into the identification and deliberation of the ten most efficient and inefficient countries, as determined by the Renewable Energy Index (REI). Table 6 succinctly encapsulates the leading ten countries globally in terms

of renewable energy performance. This deliberate emphasis on the "top 10" seeks to spotlight exemplary patterns and strategies indicative of success. The intention is to provide a valuable reference for future initiatives and policy formulations geared towards augmenting global renewable energy efficiency. Through this focused examination, the analysis aims to contribute meaningfully to the ongoing discourse surrounding sustainable practices and policies.

Table 6. Top-10 countries on Renewable Energy Index (REI)

Country	Renewable Energy Index (REI)	Development Group	Income Group	Population
Sweden	1.0000	Developed economies	High income	8,618,398
Sri Lanka	0.8762	Developing economies	Lower middle income	3,882,481
Costa Rica	0.8713	Developing economies	Upper middle income	3,844,155
Lithuania	0.8676	Developed economies	High income	1,932,212
Panama	0.8456	Developing economies	High income	2,698,732
Hungary	0.7992	Developed economies	High income	6,946,267
Papua New Guinea	0.7907	Developing economies	Lower middle income	1,161,342
Croatia	0.7858	Developed economies	High income	2,354,458
Slovak Republic	0.7751	Developed economies	High income	2,922,095
Switzerland	0.7609	Developed economies	High income	6,174,416

Source: The author.

It is noteworthy that within the top 10 countries based on the Renewable Energy Index (REI), there is a discernable balance between developed and developing economies, with 6 of the countries classified as developed and the remaining 4 belonging to developing regions. Additionally, the majority of these top-performing nations, precisely 7 out of 10, fall within the high-income group category. Notably absent from the top 10 are countries characterized by a substantial population size or extensive territorial expanse. This observation suggests a discernible trend wherein countries with smaller populations and territories tend to exhibit more favorable REI indicators. This pattern may be attributed to the REI's incorporation of methane emissions, which are predominantly influenced by agricultural activities. Consequently, nations with large agricultural sectors, such as Brazil and the United States of America, may experience diminished REI performance due to the adverse impact of methane emissions.

As previously highlighted, the mean efficiency of the 133 countries assessed is 0.4318. Consistent with expectations, the average REI score for the top 10 countries (0.8373) significantly surpasses the overall REI mean. This discrepancy underscores the superior renewable energy efficiency exhibited by the top-performing nations, contributing to an enhanced understanding of the global landscape of environmental sustainability.

These countries share a common trait of placing considerable emphasis on environmental concerns, often implementing measures to foster sustainable practices. Moreover, many are recognized for their proactive initiatives in renewable energy, environmental conservation, and endeavors to address climate change. A case in point is Sweden, which has set binding targets to achieve net-zero emissions by 2045 (Salman *et al.*, 2022). Eurostat data from 2017 reveals Sweden leading the European Union in the proportion of renewable energy, with a share of 54.5%, followed by Finland at 41.01% and Latvia at 39.01%. Within the Baltic States, Lithuania reported a noteworthy share of 25.84 (Suharevska and Blumberga, 2019). Switzerland also recognizes the pivotal role of renewable energy in mitigating CO₂ emissions (Saidi and Omri, 2020). This underscores the global acknowledgment of renewable energy's significance in promoting environmental sustainability.

Notably, even certain developing nations exhibit efficiency in reducing pollutant emissions and advancing renewable energy. For example, Sri Lanka (2nd) and Costa Rica (3rd) presented a good performance with REI. Sri Lanka's commendable performance is attributed to a swift expansion of its renewable energy sector, facilitated by a feeding tariff system that encourages diversification of the renewable energy portfolio (Wijayatunga, 2014). Additionally, Sri Lanka has implemented off-grid hybrid renewable-energy-based power systems for rural electrification (Kolhe *et al.*, 2015). Similarly, Costa Rica stands out for its promotion of various renewable sources, including Hydro, Mini hydro, Wind, Geothermal, and Solar, constituting nearly 90% of its electricity production (Nandwani, 2006). These examples underscore the global diversity in adopting sustainable and renewable energy practices.

Table 7 provides a ranking of the bottom-10 countries based on the Renewable Energy Index (REI). Notably, this grouping is predominantly composed of developing nations characterized by low and lower-middle-income statuses. As previously highlighted, the mean efficiency across all 133 countries is recorded at 0.4318. In contrast, the average REI for the bottom-10 countries is notably lower at 0.1027. This discrepancy underscores the considerable performance gap, indicating that these countries exhibit the poorest performance in the conversion of pollutants into renewable energy and in achieving electricity access. The distinct delineation between the average efficiencies of the entire sample and the bottom-10 countries emphasizes the substantial challenges faced by these nations in attaining optimal renewable energy efficiency.

Table 7. Bottom-10 countries on Renewable Energy Index (REI)

Country	Renewable Energy Index (REI)	Development Group	Income Group	Population
South Sudan	0.0000	Developing economies	Low income	2,112,741
Mongolia	0.0693	Developing economies	Lower middle income	2,069,095
Australia	0.0772	Developed economies	High income	20,755,798
Argentina	0.0824	Developing economies	Upper middle income	39,940,546
Sudan	0.1088	Developing economies	Low income	13,435,884
Chad	0.1248	Developing economies	Low income	3,309,161
Turkmenistan	0.1328	Developing economies	Upper middle income	2,977,004
Myanmar	0.1343	Developing economies	Lower middle income	15,610,256
Pakistan	0.1474	Developing economies	Lower middle income	77,368,591
Kazakhstan	0.1504	Developing economies	Upper middle income	10,189,588

Source: The author.

A prevailing characteristic shared among the enumerated countries is the presence of significant challenges, encompassing political instability, economic issues, technological limitations for renewable energy generation, and, in certain instances, internal conflicts or instability (Przychodzen and Przychodzen, 2020; Chen *et al.*, 2021). Additionally, these nations may grapple with socio-economic issues such as poverty, restricted access to essential resources, and, in some cases, human rights concerns. A notable illustration is South Sudan, whose political economy exhibits unconventional traits. Following its independence in 2011, the country descended into renewed civil conflict in 2013, contending with the complexities of a fragile neo-patrimonial guerrilla government. The military-political systems in South Sudan are fragmented, extending across extensive borderlands (NUPI rapport, 2017).

Australia, on the other hand, stands out as one of the less environmentally efficient countries, attributed in part to substantial methane emissions from coal mines (Sadavarte *et al.*, 2021), livestock, and ruminants (Black *et al.*, 2021; Howden and Reyenga, 1999). In Argentina, the considerable cattle population and beef production also contribute to increased methane emissions (Huarte *et al.*, 2010; Rearte *et al.*, 2014). The Argentine economy confronts multiple economic challenges, including inflation, and exhibits a high prevalence of impoverished families, potentially posing challenges for a concentrated focus on renewable energy initiatives (Blanco *et al.*, 2022). This multifaceted analysis sheds light on the intricate interplay between environmental efficiency and the socio-economic landscape, emphasizing the diverse hurdles faced by countries in adopting renewable energy practices.

In summary, the comprehensive global analysis undertaken in this study elucidates a discernible concentration of higher efficiency within regions predominantly constituted by high and upper-middle-income countries. In contrast, the less efficient group is predominantly

composed of low and upper-middle-income regions. This observation carries significant implications, challenging the assumption that countries with elevated income levels inherently demonstrate efficiency, particularly when scrutinizing the inputs and outputs within the framework of the DEA model. Moreover, it is crucial to emphasize that nations characterized by inefficiency may confront challenges emanating from technological deficits, as well as various economic and social impediments. The exploration of these economic differentials among development groups represents a notable stride in this study, contributing to a nuanced evaluation of each group independently. This approach enhances the understanding of the intricate interplay between economic development, efficiency in resource utilization, and the multifaceted challenges faced by countries across different income brackets.

2.4.2 Group Development Analysis

An initial examination was conducted to assess the statistical distinction in the Renewable Energy Index (REI) between developed and developing nations. Mann–Whitney U tests were employed to scrutinize Hypothesis 1 (H_1). The results indicate a statistically significant difference in the efficiency ranks of the two groups at the 1% level (Mann-Whitney $U = 1304$, $z = -5.61112$). Consequently, it can be asserted, with statistical significance at the 1% level, that the process of converting pollutants into renewable energy and achieving electricity access differs between developed and developing countries, as discerned through the application of our DEA model. This finding contributes to a more nuanced understanding of the disparities in renewable energy efficiency across different developmental stages.

In a comparative analysis of indicators, focused on data related to developed and developing countries, distinct patterns emerge. For developed countries, an average of 0.5418. Conversely, in developing countries, statistics reveal an average of 0.3838. In other terms, the findings derived from the DEA model indicate that, on average, developed economies exhibit higher efficiency levels in comparison to their developing counterparts. In this sense, our indicator underscores that, on average, developed countries demonstrate superior efficiency in the realm of environmental renewable energy. The comparison of these statistical parameters provides an understanding of disparities in indicators between these two groups of countries, thereby contributing to the enhancement of understanding distinct socio-economic dynamics among developed and developing nations.

Surprisingly, however, 56.1% of developed countries demonstrate indicators below the calculated average, signifying a substantial portion within this category exhibiting performance

below the mean. Correspondingly, 54.25% of developing countries exhibit values below the computed average, highlighting the prevalence of below-average performance within this group. These findings contribute additional insights into the nuanced variations in the distribution of indicators, underscoring the widespread occurrence of countries with below-average values in both developed and developing regions. Table 8 displays the top 5 developed countries on REI.

Table 8. Top-5 developed countries on Renewable Energy Index (REI)

Countries	Standard Efficiency	Inverted Frontier	Composite Indicator	Renewable Energy Index (REI)
Sweden	1.0000	0.9359	0.9674	1.0000
Japan	0.8604	0.8445	0.8524	0.7917
Spain	0.8854	0.7122	0.7941	0.6860
Lithuania	0.9618	0.6374	0.7830	0.6659
United Kingdom	0.9302	0.6537	0.7798	0.6602

Source: The author.

It is crucial to observe that the top 5 developed nations based on the Renewable Efficiency Index (REI) are Sweden, Japan, Spain, Lithuania, and the United Kingdom. An interesting point of note is that these nations are not geographically concentrated, indicating a dispersion across different regions. One common characteristic shared among these countries is the presence of an adequate productive structure conducive to the provision of technology for the production of renewable energy. This underscores the significance of technological infrastructure and capacity as a pivotal factor contributing to their high efficiency in renewable energy utilization.

Chen and Khattak's (2023) study delves into the Japanese context, exploring the interconnection between economic complexity and the adoption of renewable energy, with a focus on electric hybrid vehicles. It is evident that despite Japan having advanced technology, it faces significant challenges related to air pollution and methane emissions. The population concentration in densely populated urban areas, such as Tokyo, contributes to air pollution due to intense traffic and industrial activity. The authors identified that Japan's economic complexity plays a crucial role in influencing its innovation capacity and adoption of sustainable technologies. In the specific case of electric hybrid vehicles, this economic complexity provides a solid foundation for the development and implementation of these technologies. For researchers, Japan's tendency to invest significantly in research and development over time also contributes to the country's privileged position in the renewable energy landscape.

Furthermore, the research highlights that Japan faces significant challenges related to its historical dependence on non-renewable energy sources and the urgent need to reduce carbon dioxide emissions. The growing environmental awareness and the government's commitment to sustainable goals are driving the search for more ecological solutions, such as electric hybrid vehicles. Thus, the study concludes that the combination of Japan's tradition of innovation, favorable economic complexity, and environmental awareness converge to create an environment conducive to the adoption and continuous development of renewable energy technologies, contributing to Japan's transition to a more sustainable future.

Table 9 ranks the countries that displayed the poorest outcomes. Poland, Ireland, Belarus, the Netherlands, and Australia present the worst performance among the developed nations. As previously discussed, Australia is one of the least environmentally efficient countries, partly due to substantial methane emissions from coal mines, livestock, and ruminants. These methane emissions are cited as one of the factors contributing to the country's low environmental efficiency. Research such as that of Grell et al. (2024) discusses the need to measure the biochemical methane potential values for dairy manure waste, highlighting the lack of specific data in Australia, impacting dairy sector emission estimates and biogas energy potential. Sadavarte *et al.* (2022) address methane emissions in Australian coal mines, highlighting the lack of spatial allocation and clear information on emission control strategies at the mine level. Lumbers, Barley, and Platte (2022) emphasize the importance of significant reductions in methane emissions in hydrogen production to decarbonize iron ore mines in Australia, aligned with environmental commitments and stricter regulations.

Table 9. Bottom-5 developed countries on Renewable Energy Index (REI)

Countries	Standard Efficiency	Inverted Frontier	Composite Indicator	Renewable Energy Index (REI)
Poland	0.5732	0.4187	0.4899	0.1350
Ireland	0.6348	0.3597	0.4778	0.1131
Belarus	0.6313	0.3597	0.4765	0.1108
Netherlands	0.5293	0.4145	0.4684	0.0960
Australia	0.4797	0.3597	0.4154	0.0000

Source: The author.

Table 10 provides insights into the most efficient developing countries in converting pollutant emissions into renewable energy and achieving electricity access. Notably, Panama, Sri Lanka, Costa Rica, Papua New Guinea, and the Dominican Republic emerge as the top 5 countries in this regard. It is noteworthy that these countries share common characteristics, such as a small population size and limited territorial expanse. This aspect is significant to consider in interpreting the Renewable Efficiency Index (REI) indicator, as these countries are less likely to engage in extensive agriculture and emit less methane gas. Furthermore, as previously

mentioned, both Sri Lanka and Costa Rica have implemented policies aimed at diversifying their energy matrices, contributing to their notable efficiency in the renewable energy sector. The conjunction of these factors underscores the importance of not only population and territorial size but also the implementation of strategic policies in achieving high renewable energy efficiency within the developing country context.

Table 10. Top-5 developing countries on Renewable Energy Index (REI)

Countries	Standard Efficiency	Inverted Frontier	Composite Indicator	Renewable Energy Index (REI)
Panama	1.0000	0.8226	0.9070	1.0000
Sri Lanka	1.0000	0.7128	0.8442	0.9127
Costa Rica	1.0000	0.7066	0.8406	0.9076
Papua New Guinea	1.0000	0.6088	0.7803	0.8237
Dominican Republic	0.9822	0.5627	0.7434	0.7724

Source: The author.

Table 11 elucidates the least efficient developing economies based on the Renewable Efficiency Index (REI). A noteworthy observation is that among the bottom 5, economies grappling with political and economic instability are prominently featured. Furthermore, the case of Argentina stands out, and its low REI ranking can be attributed to the significant influence of the cattle and beef industry on the country's economy. This highlights the intricate interplay between economic structures and renewable energy efficiency within the developing country context. The presence of economies facing instability suggests a potential correlation between political and economic challenges and lower renewable energy efficiency, emphasizing the need for a comprehensive understanding of the multifaceted factors influencing renewable energy performance in developing nations.

Table 11. Bottom-5 developing countries on Renewable Energy Index (REI)

Countries	Standard Efficiency	Inverted Frontier	Composite Indicator	Renewable Energy Index (REI)
Argentina	0.6331	0.1263	0.2828	0.1313
Chad	0.6287	0.1263	0.2818	0.1300
Sudan	0.5254	0.1382	0.2695	0.1128
Mongolia	0.5306	0.1263	0.2589	0.0981
South Sudan	0.2810	0.1263	0.1884	0.0000

Source: The author.

In the Sudan and South Sudan cases, Asane-Otoo (2015) analyzed African economies and found that industrialization exerts a discernible influence on carbon emissions within both lower and middle-income nations. However, it was observed that the impact of industrialization on carbon emissions is notably more pronounced in countries characterized by a middle-income

status. In this sense, the rapid economic expansion in developing nations has given rise to significant energy and environmental challenges (Arroyo and Miguel, 2020). Notably, economic growth is closely linked to increased energy consumption. China, for instance, exhibits an energy consumption seven times higher than Africa's, representing 23% of the global primary energy consumption, thereby contributing to adverse impacts on air quality (Jin *et al.*, 2018; Sinton and Levine, 1994).

2.4.3 Income Group Analysis

This section undertakes an analysis of the Renewable Energy Index (REI) through the lens of an income group perspective. We conducted the Kruskal-Wallis H test to verify Hypothesis 2 (H_2). In other terms, we investigated the differences between three income groups (i.e., high-, middle-, and low-income). Our analysis revealed a statistically significant difference among the three income groups at the 1% level (Kruskal-Wallis H test = 20.7915, $N = 133$). In other terms, the Kruskal-Wallis H test validates Hypothesis 2, thereby elucidating discernible distinctions among income groups across various countries.

In conducting a comparative analysis of indicators, examining data pertaining to countries categorized into high-income, middle-income, and low-income groups, discernible patterns come to light. It is noteworthy that high-income countries exhibit the highest Renewable Energy Index (REI) average at 0.5265, followed by middle-income countries at 0.4195, and low-income countries at 0.3003. Surprisingly, a notable 37% of low-income countries fall below the calculated mean, highlighting a considerable proportion of nations with performance below the average in this group. This observed gradient in REI averages across income groups underscores a systematic variation in the efficiency of converting pollutants into renewable energy and achieving electricity access. The disparity in averages highlights the importance of income levels in influencing renewable energy efficiency, suggesting a positive correlation between income and renewable energy performance. Table 12 shows the 5 high income countries with the best REI scores.

Table 12. Top-5 high income countries on Renewable Energy Index (REI)

Countries	Standard Efficiency	Inverted Frontier	Composite Indicator	Renewable Energy Index (REI)
Sweden	1.0000	1.0000	1.0000	1.0000
Hungary	0.9328	0.6877	0.8009	0.7297
Switzerland	0.8707	0.7158	0.7895	0.7142
Israel	0.9964	0.6121	0.7809	0.7026
Slovak Republic	0.9565	0.6287	0.7755	0.6952

Source: The author.

In this sense, the best high income countries are Sweden, Hungary, Switzerland, Israel, and the Slovak Republic. As highlighted by Mazanec and Bartosova (2021), sustainability is a crucial issue in the Slovak Republic, gaining prominence in the economic, environmental, and social spheres. The country's environmental legislation and policies seek to promote sustainable practices, including regulations for environmental protection, waste management, and renewable energy. Active initiatives developed in the Slovak Republic encompass energy efficiency programs, nature conservation, environmental education, and sustainable development. Although the Slovak Republic faces challenges such as waste management, air pollution, and biodiversity conservation, these obstacles are viewed as opportunities for innovation and sustainable solutions. Therefore, coordinated efforts aim to ensure a sustainable future for the country and its population.

In contrast, Table 13 summarizes the worst REI performance among high income countries. Note that countries like New Zealand, Qatar, Slovenia, Ireland, and Australia present the worst REI performance.

Table 13. Bottom-5 high income countries on Renewable Energy Index (REI)

Countries	Standard Efficiency	Inverted Frontier	Composite Indicator	Renewable Energy Index (REI)
New Zealand	0.9673	0.1447	0.3741	0.1502
Qatar	0.9483	0.1447	0.3704	0.1452
Slovenia	0.9436	0.1447	0.3694	0.1439
Ireland	0.6348	0.1447	0.3030	0.0538
Australia	0.4797	0.1447	0.2634	0.0000

Source: The author.

In conducting a comparative analysis of indicators, examining data pertaining to countries categorized into top 5 middle-income, it is noteworthy that top 5 middle-income countries exhibit the Renewable Energy Index (REI) average of 0.8841, standard deviation of 0.0728, and coefficient of variation of 8.23%. Table 14 summarizes the best REI performance

among middle income countries. Note that countries like Sri Lanka, Costa Rica, Honduras, Guatemala and Dominican Republic present the best REI performance.

Table 14. Top-5 Middle income countries on Renewable Energy Index (REI)

Countries	Standard Efficiency	Inverted Frontier	Composite Indicator	Renewable Energy Index (REI)
Sri Lanka	1.0000	0.5182	0.7199	1.0000
Costa Rica	1.0000	0.4759	0.6898	0.9377
Honduras	0.9599	0.4350	0.6462	0.8473
Guatemala	1.0000	0.4015	0.6336	0.8212
Dominican Republic	0.9938	0.3998	0.6303	0.8144

Source: The author.

In conducting a comparative analysis of indicators, examining data pertaining to countries categorized into bottom 5 middle-income, it is noteworthy that bottom 5 middle-income countries exhibit the Renewable Energy Index (REI) average of 0.0580, standard deviation of 0.0537, and coefficient of variation of 92.67%. Table 15 summarizes the worst REI performance among middle income countries. Note that countries like Pakistan, Benin, Mongolia, Botswana and Namibia present the worst REI performance.

Table 15. Bottom-5 Middle income countries on Renewable Energy Index (REI)

Countries	Standard Efficiency	Inverted Frontier	Composite Indicator	Renewable Energy Index (REI)
Pakistan	0.6419	0.1373	0.2969	0.1230
Benin	0.6864	0.1266	0.2948	0.1186
Mongolia	0.5305	0.1266	0.2592	0.0447
Botswana	0.4520	0.1266	0.2392	0.0034
Namibia	0.4458	0.1266	0.2376	0.0000

Source: The author.

In conducting a comparative analysis of indicators, examining data pertaining to countries categorized into top 5 low-income, it is noteworthy that top 5 low-income countries exhibit the Renewable Energy Index (REI) average of 0.5238, standard deviation of 0.1537, and coefficient of variation of 29.34%. Table 16 summarizes the best REI performance among low income countries. Note that countries like Afghanistan, Burundi, Central African Republic, Chad and Congo, Dem. Rep. present the best REI performance.

Table 16. Top-5 Low income countries on Renewable Energy Index (REI)

Countries	Standard Efficiency	Inverted Frontier	Composite Indicator	Renewable Energy Index (REI)
Afghanistan	1.0000	0.9953	0.5023	0.5298
Burundi	1.0000	0.6396	0.6802	0.7936
Central African Republic	0.8856	1.0000	0.4428	0.4415
Chad	0.7320	1.0000	0.3660	0.3276
Congo, Dem. Rep.	1.0000	1.0000	0.5000	0.5263

Source: The author.

In conducting a comparative analysis of indicators, examining data pertaining to countries categorized into bottom 5 low-income, it is noteworthy that bottom 5 low-income countries exhibit the Renewable Energy Index (REI) average of 0.5716, standard deviation of 0.1440, and coefficient of variation of 25.19%. Table 17 summarizes the worst REI performance among low income countries. Note that countries like Sudan, Syrian Arab Republic, Togo, Uganda and Yemen, Rep. present the worst REI performance.

Table 17. Bottom-5 Low income countries on Renewable Energy Index (REI)

Countries	Standard Efficiency	Inverted Frontier	Composite Indicator	Renewable Energy Index (REI)
Sudan	0.7593	1.0000	0.3797	0.3479
Syrian Arab Republic	1.0000	1.0000	0.5000	0.5263
Togo	1.0000	0.7157	0.6421	0.7372
Uganda	0.9126	0.6512	0.6307	0.7202
Yemen, Rep.	1.0000	1.0000	0.5000	0.5263

Source: The Author.

Upon the presented findings, there arises the capability to infer conclusions of a more comprehensive nature regarding the research issue.

CONCLUSION

This chapter has undertaken a comprehensive analysis of countries' performance in the reduction of pollutant emissions, encompassing agricultural methane emissions, CO₂ emissions, fossil fuel energy consumption, and PM_{2.5} 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, CO₂ emissions, fossil fuel energy consumption, and PM_{2.5} 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 argue 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.

REFERENCES

- AHI, P.; SEARCY, C. A comparative literature analysis of definitions for green and sustainable supply chain management. **Journal of cleaner production**, v. 52, p. 329-341, 2013.
- AKRAM, R., CHEN, F., KHALID, F., Ye, Z., & MAJEED, M. T. (2020). Heterogeneous effects of energy efficiency and renewable energy on carbon emissions: Evidence from developing countries. **Journal of cleaner production**, 247, 119122.
- ALBORT-MORANT, G.; RIBEIRO-SORIANO, D. A bibliometric analysis of international impact of business incubators. **Journal of Business Research**, v. 69, n. 5, p. 1775-1779, 2016.
- AL-MULALI, U. et al. Exploring the relationship between urbanization, energy consumption, and CO2 emission in MENA countries. **Renewable and Sustainable Energy Reviews**, v. 23, p. 107-112, 2013.
- ALVAREZ-HERRANZ, A., BALSALOBRE-LORENTE, D., SHAHBAZ, M., & CANTOS, J. M. (2017). Energy innovation and renewable energy consumption in the correction of air pollution levels. **Energy policy**, 105, 386-397.
- ANGULO-MEZA, Lidia; LINS, Marcos Pereira Estellita. Review of methods for increasing discrimination in data envelopment analysis. **Annals of Operations Research**, v. 116, n. 1-4, p. 225-242, 2002.
- ARROYO M, Flavio R.; MIGUEL, Luis J. The role of renewable energies for the sustainable energy governance and environmental policies for the mitigation of climate change in Ecuador. **Energies**, v. 13, n. 15, p. 3883, 2020.
- ASANE-OTOO, Emmanuel. Carbon footprint and emission determinants in Africa. **Energy**, v. 82, p. 426-435, 2015.
- AZAPAGIC, Adisa; PERDAN, Slobodan; CLIFT, Roland (Ed.). Sustainable development in practice: case studies for engineers and scientists. **John Wiley & Sons**, 2004.
- BAI, C.; SARKIS, J. Green supplier development: analytical evaluation using rough set theory. **Journal of cleaner production**, v. 18, n. 12, p. 1200-1210, 2010.
- BANKER, Rajiv D.; MOREY, Richard C. Efficiency analysis for exogenously fixed inputs and outputs. **Operations research**, v. 34, n. 4, p. 513-521, 1986.
- BALM, S. Using Procurement Power to Accelerate Sustainable City Logistics: Lessons from Change Agents in The Netherlands. **Sustainability**, v. 14, n. 10, p. 6225, 2022.
- BAULER, Tom et al. Identifying methodological challenges. **Sustainability indicators: a scientific assessment**, p. 49-64, 2007.

BEGUM, S. (2013, June). Use of oil palm waste as a renewable energy source and its impact on reduction of air pollution in context of Malaysia. In **IOP Conference Series: Earth and Environmental Science** (Vol. 16, No. 1, p. 012026). IOP Publishing.

BI, Gong-Bing et al. Does environmental regulation affect energy efficiency in China's thermal power generation? Empirical evidence from a slacks-based DEA model. **Energy Policy**, v. 66, p. 537-546, 2014.

BIBRI, S. E. et al. Smarter eco-cities and their leading-edge artificial intelligence of things solutions for environmental sustainability: A comprehensive systematic review. **Environmental Science and Ecotechnology**, v. 19, p. 100330, 2024.

BILGILI, F., KOÇAK, E., & BULUT, Ü. (2016). The dynamic impact of renewable energy consumption on CO2 emissions: a revisited Environmental Kuznets Curve approach. **Renewable and Sustainable Energy Reviews**, 54, 838-845.

BLACK, J. L., DAVISON, T. M., & BOX, I. (2021). Methane emissions from ruminants in Australia: mitigation potential and applicability of mitigation strategies. **Animals**, 11(4), 951.

BLANCO, A., DIAZ DE ASTARLOA, B., DRENIK, A., MOSER, C., & TRUPKIN, D. R. (2022). The evolution of the earnings distribution in a volatile economy: Evidence from Argentina. **Quantitative Economics**, 13(4), 1361-1403.

BONILLA, Claudio A.; MERIGÓ, José M.; TORRES-ABAD, Carolina. Economics in Latin America: a bibliometric analysis. **Scientometrics**, v. 105, p. 1239-1252, 2015.

BOCKEN, N. MP et al. A literature and practice review to develop sustainable business model archetypes. **Journal of cleaner production**, v. 65, p. 42-56, 2014.

BOONS, Frank; LÜDEKE-FREUND, Florian. Business models for sustainable innovation: state-of-the-art and steps towards a research agenda. **Journal of Cleaner production**, v. 45, p. 9-19, 2013.

BOUDRI, J. C., et al. (2002). The potential contribution of renewable energy in air pollution abatement in China and India. **Energy policy**, 30(5), 409-424.

CAMIOTO, Flávia de Castro et al. Renewable and sustainable energy efficiency: An analysis of Latin American countries. **Environmental Progress & Sustainable Energy**, v. 37, n. 6, p. 2116-2123, 2018.

CASSMAN, K. G. (1999). Ecological intensification of cereal production systems: yield potential, soil quality, and precision agriculture. **Proceedings of the National Academy of Sciences**, 96(11), 5952-5959.

CHAABAN, Jad; IRANI, Alexandra; KHOURY, Alexander. The composite global well-being index (CGWBI): A new multi-dimensional measure of human development. **Social Indicators Research**, v. 129, p. 465-487, 2016.

CHARNES, Abraham et al. A developmental study of data envelopment analysis in measuring the efficiency of maintenance units in the US air forces. *Ann. Oper. Res.*, v. 2, n. 1, p. 95-112, 1984.

CHAUHAN, Narvendra Singh; MOHAPATRA, Pratap KJ; PANDEY, Keshaw Prasad. Improving energy productivity in paddy production through benchmarking—An application of data envelopment analysis. *Energy conversion and Management*, v. 47, n. 9-10, p. 1063-1085, 2006.

CHARNES, A. et al. Data envelopment analysis and axiomatic notions of efficiency and reference sets. University of Texas. **Center for Cybernetic Studies**, 1987.

CHEN, C., PINAR, M., & STENGOS, T. (2021). Determinants of renewable energy consumption: Importance of democratic institutions. *Renewable Energy*, 179, 75-83.

CHEN, Q.; KHATTAK, S. I. The future of green transportation: evaluating the impact of innovation in hybrid electric vehicles relating technologies on carbon dioxide emissions in Asia's top knowledge-based economies. *Environmental Science and Pollution Research*, v. 30, n. 48, p. 105398-105414, 2023.

CHEN, Y., HE, L., Li, J., CHENG, X., & LU, H. (2016). An inexact bi-level simulation–optimization model for conjunctive regional renewable energy planning and air pollution control for electric power generation systems. *Applied energy*, 183, 969-983.

CHIEN, Taichen; HU, Jin-Li. Renewable energy and macroeconomic efficiency of OECD and non-OECD economies. *Energy Policy*, v. 35, n. 7, p. 3606-3615, 2007.

CHOI, Y.; ZHANG, N.; ZHOU, P. Efficiency and abatement costs of energy-related CO₂ emissions in China: A slacks-based efficiency measure. *Applied Energy*, v. 98, p. 198-208, 2012.

COOK, Wade D.; TONE, Kaoru; ZHU, Joe. Data envelopment analysis: Prior to choosing a model. *Omega*, v. 44, p. 1-4, 2014.

COOK, Wade D. et al. Data envelopment analysis with non-homogeneous DMUs. **Data Envelopment Analysis: A Handbook of Models and Methods**, p. 309-340, 2015.

COOPER, D. R., & GUTOWSKI, T. G. (2017). The environmental impacts of reuse: a review. *Journal of Industrial Ecology*, 21(1), 38-56.

COOPER, W. W., SEIFORD, L. M., & Tone, K. (2007). A comprehensive text with models, applications, references and DEA-solver software. **Data Envelopment Anal.**

CONWAY, B.; LEAHY, K.; MCMAHON, M. Design Education for Sustainability: Identifying Opportunities in Ireland's Second Level Education System. *Sustainability*, v. 13, n. 16, p. 8711, 2021.

ČUČEK, Lidija; KLEMEŠ, Jiří Jaromír; KRAVANJA, Zdravko. A review of footprint analysis tools for monitoring impacts on sustainability. *Journal of Cleaner Production*, v. 34, p. 9-20, 2012.

DESPOTIS, D. K. A reassessment of the human development index via data envelopment analysis. **Journal of the operational research society**, v. 56, p. 969-980, 2005.

DOĞAN, B.; SABOORI, B.; CAN, M. Does economic complexity matter for environmental degradation? An empirical analysis for different stages of development. **Environmental Science and Pollution Research**, v. 26, n. 31, p. 31900-31912, 2019.

DOGAN, E., & SEKER, F. (2016). Determinants of CO2 emissions in the European Union: the role of renewable and non-renewable energy. **Renewable Energy**, 94, 429-439.

DOYLE, G. A new era for reuse social enterprises in Ireland? The capacities required for achieving sustainability. Resources, **Conservation and Recycling**, v. 149, p. 65-74, 2019.

DUPONT, Diane P. et al. Capacity utilization measures and excess capacity in multi-product privatized fisheries. **Resource and energy economics**, v. 24, n. 3, p. 193-210, 2002.

DYLLICK, T., & HOCKERTS, K. (2002). Beyond the business case for corporate sustainability. **Business strategy and the environment**, 11(2), 130-141.

ELSEVIER. **Journal of Cleaner Production**, 2022, Available on: <https://www.journals.elsevier.com/journal-of-cleaner-production>, Accessed on: 24 may 2022.

FÄRE, Rolf; GROSSKOPF, Shawna; HERNANDEZ-SANCHO, Francesc. Environmental performance: an index number approach. **Resource and Energy economics**, v. 26, n. 4, p. 343-352, 2004.

FENERICH, F. C.; DA COSTA, S. E. G.; DE LIMA, E. P. Energy efficiency in industrial environments: overview and research agenda. **IEEE Latin America Transactions**, v. 15, n. 3, p. 415-422, 2017.

FERRAZ, D.; FALGUERA, F. P. S.; MARIANO, E. B.; HARTMANN, D. Linking Economic Complexity, Diversification, and Industrial Policy with Sustainable Development: a structured literature review. **Sustainability**, v. 13, p. 1265, 2021.

FERRAZ, D.; MARIANO, E. B.; REBELATTO, D.; HARTMANN, D. Linking Human Development and the Financial Responsibility of Regions: Combined Index Proposals Using Methods from Data Envelopment Analysis. **Social Indicators Research**, v. 150, p. 439-478, 2020.

FERRAZ, D.; MORALLES, H. F.; CAMPOLI, J. S.; OLIVEIRA, F. C. R.; REBELATTO, D. A. N. Economic Complexity and Human Development: DEA performance measurement in Asia and Latin America. **GESTÃO & PRODUÇÃO**, v. 25, p. 839-853, 2018.

FETSCHERIN, M.; HEINRICH, D. Consumer brand relationships research: A bibliometric citation meta-analysis. **Journal of Business Research**, v. 68, n. 2, p. 380-390, 2015.

FRIED, Harold O. et al. Accounting for environmental effects and statistical noise in data envelopment analysis. **Journal of productivity Analysis**, v. 17, p. 157-174, 2002.

FREEDMAN, M.; JAGGI, B. Global warming, commitment to the Kyoto protocol, and accounting disclosures by the largest global public firms from polluting industries. **The International Journal of Accounting**, v. 40, n. 3, p. 215-232, 2005.

FURLAN, M.; MARIANO, E. A confirmatory factor model for climate justice: Integrating human development and climate actions in low carbon economies. **Environmental Science & Policy**, v. 133, p. 17-30, 2022.

GAVIRIA-MARIN, Magaly; MERIGÓ, José M.; BAIER-FUENTES, Hugo. Knowledge management: A global examination based on bibliometric analysis. **Technological Forecasting and Social Change**, v. 140, p. 194-220, 2019.

GEISSDOERFER, M. et al. The Circular Economy—A new sustainability paradigm?. **Journal of cleaner production**, v. 143, p. 757-768, 2017.

GILL, J. J., CHANG, D. T., MOMODA, L. A.; CARMAN, G. P. (2001). Manufacturing issues of thin film NiTi microwrapper. *Sensors and Actuators A: Physical*, 93(2), 148-156.

GIMENEZ, C.; SIERRA, V.; RODON, J. Sustainable operations: Their impact on the triple bottom line. **International journal of production economics**, v. 140, n. 1, p. 149-159, 2012.

GLAVIČ, Peter; LUKMAN, Rebeka. Review of sustainability terms and their definitions. **Journal of cleaner production**, v. 15, n. 18, p. 1875-1885, 2007.

GONÇALVES, M. C. P. et al. Trends on enzyme immobilization researches based on bibliometric analysis. **Process biochemistry**, v. 76, p. 95-110, 2019.

GOOGLE SCHOLAR. Maria Molinos Senante, 2022, Available on: <https://www.scholar.google.com.br/citations?user=HhXyD8sAAAAJ&hl=pt-BR&oi=ao>, Accessed on: 24 may 2022.

GOVINDAN, K.; KHODAVERDI, R.; JAFARIAN, A. A fuzzy multi criteria approach for measuring sustainability performance of a supplier based on triple bottom line approach. **Journal of Cleaner production**, v. 47, p. 345-354, 2013.

GRIGGS, David et al. Sustainable development goals for people and planet. **Nature**, v. 495, n. 7441, p. 305-307, 2013.

GREENING, L. A.; GREENE, D. L.; DIFIGLIO, C. Energy efficiency and consumption—the rebound effect—a survey. **Energy policy**, 28(6-7), 389-401., 2000.

GRELL, T. et al. Biochemical methane potential of dairy manure residues and separated fractions: An Australia-wide study of the impact of production and cleaning systems. **Bioresource Technology**, v. 391, p. 129903, 2024.

GUMUS, Sedat et al. A systematic review of studies on leadership models in educational research from 1980 to 2014. **Educational Management Administration & Leadership**, v. 46, n. 1, p. 25-48, 2018.

H. FARHANGI, M. et al. High-tech urban agriculture in Amsterdam: An actor network

analysis. **Sustainability**, v. 12, n. 10, p. 3955, 2020.

HAHN, R.; KÜHNEN, M. Determinants of sustainability reporting: a review of results, trends, theory, and opportunities in an expanding field of research. **Journal of cleaner production**, 2013.

HAILU, Atakelty; VEEMAN, Terrence S. Non-parametric productivity analysis with undesirable outputs: an application to the Canadian pulp and paper industry. **American journal of agricultural economics**, v. 83, n. 3, p. 605-616, 2001.

HERNÁNDEZ-SANCHO, Francesc; MOLINOS-SENANTE, Maria; SALA-GARRIDO, Ramón. Energy efficiency in Spanish wastewater treatment plants: A non-radial DEA approach. **Science of the Total Environment**, v. 409, n. 14, p. 2693-2699, 2011.

HERRERO, Mario et al. Greenhouse gas mitigation potentials in the livestock sector. **Nature Climate Change**, v. 6, n. 5, p. 452-461, 2016.

HILLION, Christophe Alfred Pierre. The UK withdrawal from the EU-Legal implications for Norway as party to the EEA Agreement. **NUPI-rapport**, 2017.

HOU, Y. et al. Measuring energy efficiency and environmental performance: a case of South Asia. **Processes**, v. 7, n. 6, p. 325, 2019.

HOWDEN, S. M., & REYENGA, P. J. (1999). Methane emissions from Australian livestock: implications of the Kyoto Protocol. **Australian Journal of Agricultural Research**, 50(8), 1285-1292.

HU, J. L.; WANG, S. C. Total-factor energy efficiency of regions in China. **Energy policy**, v. 34, n. 17, p. 3206-3217, 2006.

HUARTE, A., CIFUENTES, V., GRATTON, R., & CLAUSSE, A. (2010). Correlation of methane emissions with cattle population in Argentine Pampas. **Atmospheric Environment**, 44(23), 2780-2786.

JACOBSON, M. Z. (2017). Roadmaps to transition countries to 100% clean, renewable energy for all purposes to curtail global warming, air pollution, and energy risk. **Earth's Future**, 5(10), 948-952.

JIN, Yuanxiang et al. Polystyrene microplastics induce microbiota dysbiosis and inflammation in the gut of adult zebrafish. **Environmental Pollution**, v. 235, p. 322-329, 2018.

KAARONEN, R. O.; RIETVELD, E. Practical lessons for creating affordance-based interventions for sustainable behavior change. **One earth**, v. 4, n. 10, p. 1412-1424, 2021.

KAUR, H., & GARG, P. (2023). Urban Sustainability Assessment Tool for Hillside Planning, Design, and Development. **Journal of Urban Planning and Development**, 149(2), 4023003.

KEEBLE, B. R. The Brundtland report: 'Our common future'. **Medicine and war**, v. 4, n. 1, p. 17-25, 1988.

KLEWITZ, J.; HANSEN, E. G. Sustainability-oriented innovation of SMEs: a systematic review. **Journal of cleaner production**, v. 65, p. 57-75, 2014.

KOENGGAN, M., FUINHAS, J. A., & SILVA, N. (2021). Exploring the capacity of renewable energy consumption to reduce outdoor air pollution death rate in Latin America and the Caribbean region. **Environmental Science and Pollution Research**, 28, 1656-1674.

KOENGGAN, M. et al. The impact of renewable energy policies on deaths from outdoor and indoor air pollution: Empirical evidence from Latin American and Caribbean countries. **Energy**, v. 245, p. 123209, 2022.

KOLHE, Mohan L.; RANAWEERA, KM Iromi Udumbara; GUNAWARDANA, AGB Sisara. Techno-economic sizing of off-grid hybrid renewable energy system for rural electrification in Sri Lanka. **Sustainable Energy Technologies and Assessments**, v. 11, p. 53-64, 2015.

KORHONEN, P. J.; LUPTACIK, M. Eco-efficiency analysis of power plants: An extension of data envelopment analysis. **European journal of operational research**, v. 154, n. 2, p. 437-446, 2004.

KOTRIKLA, A. M., LILAS, T., & NIKITAKOS, N. (2017). Abatement of air pollution at an aegean island port utilizing shore side electricity and renewable energy. **Marine Policy**, 75, 238-248.

KRUSKAL, William H.; WALLIS, W. Allen. Use of ranks in one-criterion variance analysis. **Journal of the American statistical Association**, v. 47, n. 260, p. 583-621, 1952.

KUO, Renjieh J.; WANG, Yu C.; TIEN, Fangchih C. Integration of artificial neural network and MADA methods for green supplier selection. **Journal of cleaner production**, v. 18, n. 12, p. 1161-1170, 2010.

KUOSMANEN, Timo; PODINOVSKI, Victor. Weak disposability in nonparametric production analysis: reply to Färe and Grosskopf. **American journal of agricultural economics**, v. 91, n. 2, p. 539-545, 2009.

LAMPE, H. W.; HILGERS, D. Trajectories of efficiency measurement: A bibliometric analysis of DEA and SFA. **European journal of operational research**, v. 240, n. 1, p. 1-21, 2015.

LIU, J. S. et al. A survey of DEA applications. **Omega**, v. 41, n. 5, p. 893-902, 2013.

LIU, L. et al. Global, regional, and national causes of under-5 mortality in 2000–15: an updated systematic analysis with implications for the Sustainable Development Goals. **The Lancet**, v. 388, n. 10063, p. 3027-3035, 2016.

LIN, T. Y., CHIU, Y. H., & XU, W. Z. (2022). Environmental efficiency and sustainability of food production and consumption in the EU. **Sustainable Production and Consumption**, 34, 440-452.

LO, K. (2014). A critical review of China's rapidly developing renewable energy and energy efficiency policies. **Renewable and Sustainable Energy Reviews**, 29, 508-516.

LONGO, M., YAİCI, W., & ZANINELLI, D. (2015). “Team play” between renewable energy sources and vehicle fleet to decrease air pollution. **Sustainability**, 8(1), 27.

LU, L. et al. Sustainability efficiency of climate change and global disasters based on greenhouse gas emissions from the parallel production sectors—A modified dynamic parallel three-stage network DEA model. **Journal of Environmental Management**, v. 317, p. 115401, 2022.

LUIZ, O. R. et al. Linking the critical chain project management literature. *International Journal of Managing Projects in Business*, 2019.

LUMBERS, B.; BARLEY, J.; PLATTE, F. Low-emission hydrogen production via the thermo-catalytic decomposition of methane for the decarbonisation of iron ore mines in Western Australia. **International Journal of Hydrogen Energy**, v. 47, n. 37, p. 16347-16361, 2022.

MAHLBERG, Bernhard; OBERSTEINER, Michael. Remeasuring the HDI by data envelopment analysis. Available at SSRN 1999372, 2001.

MANN, Henry B.; WHITNEY, Donald R. On a test of whether one of two random variables is stochastically larger than the other. **The annals of mathematical statistics**, p. 50-60, 1947.

MARDANI, A. et al. Data envelopment analysis in energy and environmental economics: An overview of the state-of-the-art and recent development trends. **Energies**, v. 11, n. 8, p. 2002, 2018.

MARIANO, E. B.; FERRAZ, D.; GOBBO, S. The Human Development Index with Multiple Data Envelopment Analysis Approaches: A Comparative Evaluation Using Social Network Analysis. **Social Indicators Research**, p. 443-500, 2021.

MARIANO, E. B.; GOBBO JUNIOR, J. A.; CAMIOTO, F. C.; REBELATTO, D. A. N. CO2 emissions and logistics performance: a composite index proposal. **Journal of Cleaner Production**, v. 163, p. 166-178, 2017.

MARIANO, E. B.; REBELATTO, D. A. N. Transformation of wealth produced into quality of life: analysis of the social efficiency of nation-states with the DEA's triple index approach. **Journal of the Operational Research Society**, v. 65, n. 11, p. 1664-1681, 2014.

MARIANO, E. B.; SOBREIRO, V. A.; REBELATTO, D. A. N. . Human development and data envelopment analysis: A structured literature review. **Omega (Oxford)**, v. 54, p. 33-49, 2015.

MATSUOKA, Y.; FUJINO, J.; KAINUMA, M. National implications of a 50% global reduction of greenhouse gases, and its feasibility in Japan. **Sustainability Science**, v. 3, n. 1, p. 135-143, 2008.

MAUSS, E. A. Stockholm conference. **Science**, v. 177, n. 4051, p. 746-746, 1972.

MAVI, Reza Kiani; SAEN, Reza Farzipoor; GOH, Mark. Joint analysis of eco-efficiency and eco-innovation with common weights in two-stage network DEA: A big data approach. **Technological Forecasting and Social Change**, v. 144, p. 553-562, 2019.

MAZANEC, J.; BARTOSOVA, V. Prediction model as sustainability tool for assessing financial status of non-profit organizations in the Slovak Republic. **Sustainability**, v. 13, n. 17, p. 9721, 2021.

MIN, S.; KIM, J.; SAWNG, Y.. The effect of innovation network size and public R&D investment on regional innovation efficiency. **Technological Forecasting and Social Change**, v. 155, p. 119998, 2020.

MIKAYILOV, J. I.; GALEOTTI, M.; HASANOV, F. J. The impact of economic growth on CO2 emissions in Azerbaijan. **Journal of cleaner production**, v. 197, p. 1558-1572, 2018.

MISCHE, A. Measuring futures in action: Projective grammars in the Rio+ 20 debates. **Theory and Society**, v. 43, n. 3, p. 437-464, 2014.

MOHSIN, Muhammad et al. Developing low carbon finance index: evidence from developed and developing economies. **Finance Research Letters**, v. 43, p. 101520, 2021.

MPDI. **Sustainability**, 2022, Available on: <https://www.mdpi.com/journal/sustainability>, Accessed on: 24 may 2022.

MUHAMMAD, S. et al. Industrial structure, energy intensity and environmental efficiency across developed and developing economies: The intermediary role of primary, secondary and tertiary industry. **Energy**, v. 247, p. 123576, 2022.

MURSHED, M. (2020). An empirical analysis of the non-linear impacts of ICT-trade openness on renewable energy transition, energy efficiency, clean cooking fuel access and environmental sustainability in South Asia. **Environmental Science and Pollution Research**, 27(29), 36254-36281.

NANDWANI, Shyam S. Uses of solar energy in Costa Rica. **Renewable Energy**, v. 31, n. 5, p. 689-701, 2006.

NASSIRI, Seyed Mehdi; SINGH, Surendra. Study on energy use efficiency for paddy crop using data envelopment analysis (DEA) technique. **Applied energy**, v. 86, n. 7-8, p. 1320-1325, 2009.

NESS, Barry et al. Categorising tools for sustainability assessment. **Ecological economics**, v. 60, n. 3, p. 498-508, 2007.

NOVAN, K. (2015). Valuing the wind: renewable energy policies and air pollution avoided. **American Economic Journal: Economic Policy**, 7(3), 291-326.

OMER, A. M. Energy, environment and sustainable development. **Renewable and sustainable energy reviews**, v. 12, n. 9, p. 2265-2300, 2008.

PABLO-ROMERO, M. D. P., ROMÁN, R., SÁNCHEZ-BRAZA, A., & Yñiguez, R. (2016). Renewable energy, emissions, and health. **Renewable Energy: Utilisation and System Integration**, 173.

PAO, H. T.; TSAI, C. M. Modeling and forecasting the CO₂ emissions, energy consumption, and economic growth in Brazil. **Energy**, v. 36, n. 5, p. 2450-2458, 2011.

PARLASCA, M. C.; QAIM, M. Meat consumption and sustainability. **Annual Review of Resource Economics**, v. 14, p. 17-41, 2022.

PLÓSZ, Benedek Gy et al. Diurnal variations in the occurrence and the fate of hormones and antibiotics in activated sludge wastewater treatment in Oslo, Norway. **Science of the total environment**, v. 408, n. 8, p. 1915-1924, 2010.

POLLONI, E.; COSTA, N. J.; FERRAZ, D.; SCARPA, D.; MORALLES, H. F. The drivers of energy-related CO₂ emissions in Brazil: a regional application of the STIRPAT model. **Environmental Science and Pollution Research**, v. 28, p. 1, 2021.

POLLONI, E.; FERRAZ, D.; CAMIOTO, F. C.; REBELATTO, D. A. N.; MORALLES, H. F. Environmental Kuznets curve and the pollution-halo/haven hypotheses: an investigation in Brazilian municipalities. **Sustainability**, v. 13, p. 4114, 2021.

PRZYCHODZEN, W., & PRZYCHODZEN, J. (2020). Determinants of renewable energy production in transition economies: A panel data approach. **Energy**, 191, 116583.

RAFIQUE, M. Z.; FERRAZ, D.; IKRAM, M.; SHAHZAD, U.; HUANG, S. Exploring the heterogenous impacts of Environmental Taxes on Environmental Footprints: An Empirical Assessment from Developed economies. **ENERGY**, v. 238, p. 121753, 2021.

REARTE, D. H., & PORDOMINGO, A. J. (2014). The relevance of methane emissions from beef production and the challenges of the Argentinean beef production platform. **Meat science**, 98(3), 355-360.

REINHARD, Stijn; LOVELL, CA Knox; THIJSSEN, Geert J. Environmental efficiency with multiple environmentally detrimental variables; estimated with SFA and DEA. **European Journal of Operational Research**, v. 121, n. 2, p. 287-303, 2000.

RESEARCH GATE. Tsuyoshi Sueyoshi, 2022, Available on: <https://www.researchgate.net/profile/Tsuyoshi-Sueyoshi>, Accessed on: 24 may 2022.

RHODES, C. J. The 2015 Paris climate change conference: COP21. **Science progress**, v. 99, n. 1, p. 97-104, 2016.

RITA, E., CHIZOO, E., & CYRIL, U. S. (2021). Sustaining COVID-19 pandemic lockdown era air pollution impact through utilization of more renewable energy resources. **Heliyon**, 7(7), e07455.

ROCA, L.C., SEARCY, C., 2012. An analysis of indicators disclosed in corporate sustainability reports. **Journal of Cleaner Production**. 20, 103-118.

RODRIGUEZ-ALVAREZ, A. (2021). Air pollution and life expectancy in Europe: Does investment in renewable energy matter?. **Science of the Total Environment**, 792, 148480.

ROGELJ, Joeri et al. Paris Agreement climate proposals need a boost to keep warming well below 2 C. **Nature**, v. 534, n. 7609, p. 631-639, 2016.

SADAVARTE, P. et al. (2021). Methane emissions from superemitting coal mines in Australia quantified using TROPOMI satellite observations. **Environmental Science & Technology**, 55(24), 16573-16580.

SADAVARTE, P. et al. A high-resolution gridded inventory of coal mine methane emissions for India and Australia. **Elem Sci Anth**, v. 10, n. 1, p. 00056, 2022.

SAIDI, Kais; OMRI, Anis. The impact of renewable energy on carbon emissions and economic growth in 15 major renewable energy-consuming countries. **Environmental research**, v. 186, p. 109567, 2020.

SALMAN, M. et al. Paris climate agreement and global environmental efficiency: New evidence from fuzzy regression discontinuity design. **Energy Policy**, v. 168, p. 113128, 2022.

SÁNCHEZ, L. E.; CROAL, P. Environmental impact assessment, from Rio-92 to Rio+ 20 and beyond. **Ambiente & Sociedade**, v. 15, p. 41-54, 2012.

SANTANA, Naja Brandão et al. Sustainable development in the BRICS countries: an efficiency analysis by data envelopment. In: **Managing Organizations for Sustainable Development in Emerging Countries**. Routledge, 2017. p. 65-78.

SARKIS, J. Ecoefficiency: How data envelopment analysis can be used by managers and researchers. In: Environmentally Conscious Manufacturing. **International Society for Optics and Photonics**, 2001. p. 194-203.

SAYGIN, D. et al. (2015). The implications for renewable energy innovation of doubling the share of renewables in the global energy mix between 2010 and 2030. **Energies**, 8(6), 5828-5865.

SCHEEL, Holger. Undesirable outputs in efficiency valuations. **European journal of operational research**, v. 132, n. 2, p. 400-410, 2001.

SCHIPPER, L., BARTLETT, S., HAWK, D., & VINE, E. (1989). Linking life-styles and energy use: a matter of time?. **Annual review of energy**, 14(1), 273-320.

SCHULZ, Steven A.; FLANIGAN, Rod L. Developing competitive advantage using the triple bottom line: A conceptual framework. **Journal of Business & Industrial Marketing**, v. 31, n. 4, p. 449-458, 2016.

SEIFORD, Lawrence M.; ZHU, Joe. Modeling undesirable factors in efficiency evaluation. **European journal of operational research**, v. 142, n. 1, p. 16-20, 2002.

SHAFIK, N., & BANDYOPADHYAY, S. (1992). **Economic growth and environmental quality: time-series and cross-country evidence** (Vol. 904). World Bank Publications.

SHAH, M. H., SALEM, S., AHMED, B., ULLAH, I., REHMAN, A., ZEESHAN, M., & FAREED, Z. (2022). Nexus between foreign direct investment inflow, renewable energy consumption, ambient air pollution, and human mortality: a public health perspective from non-linear ARDL approach. **Frontiers in public health**, 9, 814208.

SHAHZAD, U.; FERRAZ, D.; DO'AN, B.; REBELATTO, D. Export product diversification and CO2 emissions: Contextual evidences from developing and developed economies. **Journal of Cleaner Production**, v. 276, p. 124146, 2020.

SHARMA, R.; SINHA, A.; KAUTISH, P. Does renewable energy consumption reduce ecological footprint? Evidence from eight developing countries of Asia. **Journal of Cleaner Production**, v. 285, p. 124867, 2021.

SHEN, N., WANG, Y., PENG, H., & HOU, Z. (2020). Renewable energy green innovation, fossil energy consumption, and air pollution—spatial empirical analysis based on China. **Sustainability**, 12(16), 6397.

SHRESTHA, A., MUSTAFA, A. A., HTIKE, M. M., YOU, V., & KAKINAKA, M. (2022). Evolution of energy mix in emerging countries: Modern renewable energy, traditional renewable energy, and non-renewable energy. **Renewable Energy**, 199, 419-432.

SHUM, C. K.; KUO, Chung-Yen. Observation and geophysical causes of present-day sea-level rise. In: **Climate change and food security in South Asia**. Springer, Dordrecht, 2010. p. 85-104.

SINTON, Jonathan E.; LEVINE, Mark D. Changing energy intensity in Chinese industry: The relatively importance of structural shift and intensity change. **Energy policy**, v. 22, n. 3, p. 239-255, 1994.

SLAPER, H. et al. Estimates of ozone depletion and skin cancer incidence to examine the Vienna Convention achievements. **Nature**, v. 384, n. 6606, p. 256-258, 1996.

SLUTSKY, B.; AYTAC, S. Bibliometric analysis and comparison of two STEM LIS journals: Science & Technology Libraries and Issues in Science & Technology Librarianship (2005–2014). **Science & technology libraries**, v. 35, n. 2, p. 152-171, 2016.

SUEYOSHI, T.; YUAN, Y.; GOTO, M. A literature study for DEA applied to energy and environment. **Energy Economics**, v. 62, p. 104-124, 2017.

SUEYOSHI, Toshiyuki; GOTO, Mika. Data envelopment analysis for environmental assessment: Comparison between public and private ownership in petroleum industry. **European journal of operational research**, v. 216, n. 3, p. 668-678, 2012.

SUHAREVSKA, Karina; BLUMBERGA, Dagnija. Progress in renewable energy technologies: innovation potential in Latvia. **Environmental and Climate Technologies**, v. 23, n. 2, p. 47-63, 2019.

SUMMIT, M. et al. United nations millennium declaration. **U. Nations (Ed.)**, 2000.

TANSEL, B. (2017). From electronic consumer products to e-wastes: Global outlook, waste quantities, recycling challenges. **Environment international**, 98, 35-45.

TILMAN, D., BALZER, C., HILL, J., & BEFORT, B. L. (2011). Global food demand and the sustainable intensification of agriculture. **Proceedings of the national academy of sciences**, 108(50), 20260-20264.

TINGLEY, Diana; PASCOE, Sean; COGLAN, Louisa. Factors affecting technical efficiency in fisheries: stochastic production frontier versus data envelopment analysis approaches. **Fisheries Research**, v. 73, n. 3, p. 363-376, 2005.

TOFALLIS, Chris. An automatic-democratic approach to weight setting for the new human development index. **Journal of population economics**, v. 26, p. 1325-1345, 2013.

TYTECA, Daniel. On the measurement of the environmental performance of firms—a literature review and a productive efficiency perspective. **Journal of environmental management**, v. 46, n. 3, p. 281-308, 1996.

United Nations. (2021). Agricultural Methane. Available on:
<https://www.unccd.int/actions/achieving-land-degradation-neutrality/agricultural-methane>.

VAN ECK, Nees Jan; WALTMAN, Ludo. Citation-based clustering of publications using CitNetExplorer and VOSviewer. **Scientometrics**, v. 111, p. 1053-1070, 2017.

WIJAYATUNGA, Priyantha DC. Regulation for renewable energy development: Lessons from Sri Lanka experience. **Renewable Energy**, v. 61, p. 29-32, 2014.

WILLIAMS, J. (2021). Circular cities: what are the benefits of circular development?. **Sustainability**, 13(10), 5725.

WOO, Chungwon et al. The static and dynamic environmental efficiency of renewable energy: A Malmquist index analysis of OECD countries. **Renewable and Sustainable Energy Reviews**, v. 47, p. 367-376, 2015.

World Commission on Environment and Development. (1987). Our Common Future (The Brundtland Report). In *Medicine and War* (Vol. 4).
<https://doi.org/10.1080/0748800880840878>

YAHYA, W. et al. Future study of renewable energy in Libya. **International Journal of Advanced Engineering Research and Science**, v. 7, n. 10, 2020.

YANG, Guo-liang; FUKUYAMA, Hirofumi; SONG, Yao-yao. Measuring the inefficiency of Chinese research universities based on a two-stage network DEA model. **Journal of Informetrics**, v. 12, n. 1, p. 10-30, 2018.

YANG, Hongliang; POLLITT, Michael. Incorporating both undesirable outputs and uncontrollable variables into DEA: The performance of Chinese coal-fired power plants. **European journal of operational research**, v. 197, n. 3, p. 1095-1105, 2009.

YOUSEFI, H., ROUMI, S., TABASI, S., & HAMLEHDAR, M. (2018). Economic and air pollution effects of city council legislations on renewable energy utilisation in Tehran. **International Journal of Ambient Energy**, 39(6), 626-631.

YU, D.; HE, X. A bibliometric study for DEA applied to energy efficiency: Trends and future challenges. **Applied Energy**, v. 268, p. 115048, 2020.

YUKSEL, I.; KAYGUSUZ, K. Renewable energy sources for clean and sustainable energy policies in Turkey. **Renewable and Sustainable Energy Reviews**, v. 15, n. 8, p. 4132-4144, 2011.

ZAIM, Osman. Measuring environmental performance of state manufacturing through changes in pollution intensities: a DEA framework. **Ecological Economics**, v. 48, n. 1, p. 37-47, 2004.

ZHANG, Bing et al. Eco-efficiency analysis of industrial system in China: A data envelopment analysis approach. **Ecological economics**, v. 68, n. 1-2, p. 306-316, 2008.

ZHOU, H. et al. DEA Application in Sustainability 1996–2019: The Origins, Development, and Future Directions. **Pursuing Sustainability**, p. 71-109, 2021.

ZHOU, Peng; ANG, Beng Wah; POH, Kim Leng. A mathematical programming approach to constructing composite indicators. **Ecological economics**, v. 62, n. 2, p. 291-297, 2007.

ZHOU, Peng; ANG, Beng Wah. Linear programming models for measuring economy-wide energy efficiency performance. **Energy Policy**, v. 36, n. 8, p. 2911-2916, 2008.

ZHOU, P.; ANG, B. W.; HAN, J. Y. Total factor carbon emission performance: a Malmquist index analysis. **Energy Economics**, v. 32, n. 1, p. 194-201, 2010.

ZHOU, P.; ANG, B. W.; WANG, H. Energy and CO2 emission performance in electricity generation: a non-radial directional distance function approach. **European journal of operational research**, v. 221, n. 3, p. 625-635, 2012.

ZHU, Y., WANG, Z., YANG, J., & ZHU, L. (2020). Does renewable energy technological innovation control China's air pollution? A spatial analysis. **Journal of Cleaner Production**, 250, 119515.

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 science 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.