Data Envelopment Analysis in Energy and Environmental Economics: An Overview of the State-of-the-Art and Recent Development Trends

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Keywords: efficiency measures, Energy Efficiency, data envelopment analysis (DEA), environmental economics, energy economics

Abstract:

Measurement of environmental and energy economics presents an analytical foundation for environmental decision making and policy analysis. Applications of data envelopment analysis (DEA) models in the assessment of environmental and energy economics are increasing notably. The main objective of this review paper is to provide the comprehensive overview of the application of DEA models in the fields of environmental and energy economics. In this regard, a total 145 articles published in the high-quality international journals extracted from two important databases (Web of Science and Scopus) were selected for review. The 145 selected articles are reviewed and classified based on different criteria including author(s), application scheme, different DEA models, application fields, the name of journals and year of publication. This review article provided insights into the methodological and conceptualization study in the application of DEA models in the environmental and energy economics fields. This study should enable scholars and practitioners to understand the state of art of input and output indicators of DEA in the fields of environmental and energy economics.

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Review

Data Envelopment Analysis in Energy and Environmental Economics: An Overview of the State-of-the-Art and Recent Development Trends

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Abstract: Measurement of environmental and energy economics presents an analytical foundation for environmental decision making and policy analysis. Applications of data envelopment analysis (DEA) models in the assessment of environmental and energy economics are increasing notably. The main objective of this review paper is to provide the comprehensive overview of the application of DEA models in the fields of environmental and energy economics. In this regard, a total 145 articles published in the high-quality international journals extracted from two important databases (Web of Science and Scopus) were selected for review. The 145 selected articles are reviewed and classified based on different criteria including author(s), application scheme, different DEA models, application fields, the name of journals and year of publication. This review article provided insights into the methodological and conceptualization study in the application of DEA models in the environmental and energy economics fields. This study should enable scholars and practitioners to understand the state of art of input and output indicators of DEA in the fields of environmental and energy economics.

Keywords: energy economics; environmental economics; data envelopment analysis (DEA); energy efficiency; efficiency measures

1. Introduction

Data Envelopment Analysis (DEA) is a non-parametric multi input-output linear approach for the calculation of energy efficiency that measures the relative efficiency of a set of comparable Decision-Making Units (DMUs) [1]. DEA was introduced by Farrell [2] and it is a relatively technical efficient approach using operations research methods to calculate the weights assigned to the inputs and outputs of the DMUs being assessed. The actual input-output data values are then multiplied by the calculated weights to determine the efficiency scores [3]. The key contribution of DEA to efficiency analysis, and empirical production analysis in general, is the possibility to approximate unobservable production technologies from empirical input output data of DMUs without imposing overly restrictive parameter assumptions [3]. In recent years, several types of DEA method have been introduced for measuring the relative efficiency of DMUs. Ji et al. [4] introduced the hybrid heterogeneous DEA approach for segment prediction in 206 Chinese sustainable urbanization cities. The results of this study demonstrated that there is a serious unsustainability and development target mismatch in the urbanization of cities in China and it is independent of urban scale; the results also found that two complementary forces—emission pollution and resource consumption—are slow for urbanization in China. Toloo et al. [5] developed a non-radial directional distance approach for inputs and outputs classification in a DEA method applied to 61 banks. Han et al. [6] introduced the fuzzy DEA cross-approach for energy efficiency analysis in the production systems of the chemical industry. Li et al. [7] developed the two stage DEA method for measuring the efficiency of products based on partial input to output impacts. Azadi et al. [8] introduced the novel fuzzy DEA method for measuring the effectiveness and efficiency of suppliers by integrating the non-radial DEA. An et al. [9] used a two stage DEA method for measuring slacks-based efficiency with undesirable outputs. Tone and Tsutsui [10] proposed the dynamic DEA method based on a slacks-based measure model for measuring the overall efficiency. Niu et al. [11] proposed a two sub-process DEA method for analysing wind turbines based on their efficiency score. The findings of this study found that environmental factors were the most important factors for micro-siting efficiency. Pérez-López et al. [12] proposed a new approach for measuring time variant and time invariant scale inefficiency based on DEA panel data for a solid waste disposal service. The outcome of this paper indicated that the joint management practices achieved the best long-term scale efficiency.

In addition, previous studies have integrated DEA methods with different techniques for solving problems and measuring the relative efficiency in different application areas such as the energy and environmental fields. Önüt and Soner [13] used a DEA approach to benchmark energy usage of 32 five-star hotels based on utility billing data and identified the most energy-efficient hotels as the ones that are on the frontier. Lee [14] used multiple linear regression to find out the predicted energy usage intensity (EUI) of units investigated and a DEA approach for measuring overall energy efficiency, using the forecast EUI as output and the observed EUI as input. Lee and Lee [15] proposed a DEA approach to benchmark the energy efficiency of 47 government office buildings and divided the overall energy efficiency into scale factors and management factors. Grösche [16] used data from a U.S. residential energy consumption survey to improve a DEA approach to calculate energy efficiency improvements of single-family residential buildings. It was concluded that a substantial part of the variation in energy scores is due to climatic influences but households have nevertheless improved their energy efficiency. Hui and Wan [17] used a DEA approach to examine the energy benchmarking of hotels in Hong Kong and demonstrated that DEA presented a useful benchmarking model for understanding efficiency within an organization that uses a variety of resources to provide a complex set of services in multiple locations. Wang et al. [18] utilized a two-stage DEA method to benchmark the energy consumption of 189 one-story single-family buildings in Woodbine (IA, USA), combining the DEA method with Tobit regression for further efficiency analysis. Bian and Yang [19] integrated DEA and Shannon's entropy for efficiency analysis of resources and the environment. A DEA method has been applied for calculating the relative efficiency of DMUs in numerous areas such as hospitals, financial institutions and transport, but most importantly it has been extensively applied to EPS worldwide. Olanrewaju et al. [20] integrated a DEA approach, artificial neural network (ANN), Index Decomposition Analysis (IDA) and Logarithmic Mean Divisia Index (LMDI) for measuring the total energy efficiency and optimisation in the industrial sector. Lee et al. [21] integrated DEA and a fuzzy analytic hierarchy process (AHP) for measuring the efficiency of energy technologies. Han et al. [22] proposed a new hybrid method by integrating DEA and interpretative structural model (ISM) for measuring energy efficiency in the ethylene production system. Kuo et al. [23] developed a new hybrid model for selection of green suppliers based on ANN, DEA and analytic network process (ANP). Babazadeh et al. [24] integrated the mathematical programming and a DEA approach for solving the problem regarding the strategic design in the network of a biodiesel supply chain. Zografidou et al. [25] integrated the DEA approach with the Goal Programming method for optimal design of renewable energy production based on economic, social and environmental criteria.

Additionally, some previous studies have reviewed the application of various methods such as DEA, structural equation modeling and multiple criteria decision-making (MCDM) techniques in different areas [26–39]. For example, a review of ranking methods (Adler et al. [40]), research in efficiency and productivity (Emrouznejad et al. [41]; Emrouznejad and Yang [42]), fuzzy DEA (Hatami-Marbini et al. [43]), energy and environmental studies (Zhou et al. [44]), operation research (Liu et al. [45], Cook and Seiford [46], Kuah et al. [47]), measuring efficiency in the context of higher education (Johnes [48]), performance measurement and evaluation(Cooper et al. [49]), environmental efficiency evaluation (Song et al. [50]), network DEA (Kao [51]), or energy efficiency (Mardani et al. [1]). While previous scholars have reviewed the application of DEA methods in different areas, we believe that there is a need for a review of the most important recent studies conducted in the considered area. In addition, researchers think that there is a need for a comprehensive paper, combining the available studies and methods. The presented review attempts to describe some previous studies that employed the considered methods and techniques. In addition, this paper attempts to discuss the exponentially growing interest in the DEA models and provide a comprehensive literature survey of the current DEA methodologies and applications. This study contributes to the theory of DEA and current body of knowledge by evolving a classification structure with practical considerations, structurally reviewing the literature with the aim of presenting a guide to these studies of DEA methods offered by previous scholars, and some recommendations for future studies. Moreover, the current study takes into consideration some new perspectives in reviewing the articles, author(s) and year application area and scope, study purpose as well as results and outcomes. The structure of the paper is organized as follows: Section 2 presents an example of DEA model. Section 3 provides the research methods used for this study. Section 4 presents the results. Section 5 discusses the conclusions, limitations and recommendations for future studies.

2. Literature Review

A DEA model was presented for the first time by Charnes, Cooper and Rhodes [52] (the so-called CCR model) for measuring the technical efficiency based on decision making units (DMUs) assuming constant returns to scale which consider multiple outputs and multiple inputs. After Charnes et al. [52], Banker et al. [53] (BCC) extended the CCR model to allow variable returns to scale and showed that solutions to both CCR and BCC allowed a decomposition of CCR efficiency into technical and scale components.

The generic multiplicative and envelopment BCC models are in the form of Models (1) and (2):

$$\begin{array}{c} Max\ Z_0 = \sum\limits_{r=1}^{s} u_r y_{r0} + w \\ s.t. \\ \sum\limits_{i=1}^{m} v_i x_{i0} = 1 \\ \sum\limits_{r=1}^{s} u_r y_{rj} - \sum\limits_{i=1}^{m} v_i x_{ij} + w \leq 0;\ (j = 1, 2, \cdots, n) \\ u_r,\ v_j \geq 0; w : Free \end{array} \tag{1}$$

where

X_{ij} shows the vector of i-th inputs for j-th DMU.
v_i shows the weight to be determined of j-th input.
Y_{rj} shows the vector of l-th outputs for j-th DMU.
μ_r shows the weight to be determined of j-th output.
n shows the number of DMUs.
s shows the number of inputs.
r shows the number of outputs.

If θ is the variable corresponding to the first constraint of the initial problem and λ_j is the variable corresponding to other constraints, then the following envelopment model can be obtained:

$$\begin{array}{c} Min\ y_0 = \theta \\ s.t. \\ \sum_{j=1}^{n} \lambda_j y_{rj} \geq y_{r0}; \qquad (r = 1, 2, \cdots, s) \\ \sum_{j=1}^{n} \lambda_j x_{ij} \leq \ \theta\ x_{i0}; \qquad (i = 1, 2, \cdots, m) \\ \sum_{j=1}^{n} \lambda_j = 1 \\ \lambda_j \geq 0; \quad \theta : Free \qquad (j = 1, 2, \cdots, n) \end{array} \tag{2}$$

where λ_j is the corresponding variable, $\lambda_j Y_{rj}$ shows the vector of r-th inputs for j-th DMU. $\lambda_j x_{ij}$ shows the vector of i-th outputs for j-th DMU.

Cross-Efficiency Calculation

The cross-efficiency is the level of efficiency that is obtained by considering the available resources and the value (weight) of inputs and outputs of the model. Equation (3) shows the method of calculation of the cross-efficiency of the DMUs based on the method proposed by [54]:

$$E_{kj} = \frac{\sum_{r=1}^{s} u_r^k y_{rj}}{\sum_{i=1}^{m} v_i^k x_{ij}}; \ k, j = 1, \ldots\ldots, n \tag{3}$$

This mathematical model is founded upon a generic DEA structure of the BCC type but allows the breakdown points (cross-efficiency scores) to be used for integrating efficiency improvement policies through better use of resources. Equation (4) illustrates the general form of the multiplicative-envelopment BCC-I model:

$$\begin{array}{c} Max\left(\sum_{r=1}^{s} \mu_{r1} y_{r0} - \mu_0 - \theta_0^1\right)\left(\alpha \sum_{r=1}^{s} \mu_{r1} y_{r0} - \alpha\mu_0 - \theta_0^2\right) \\ s.t. \\ \sum_{r=1}^{s} \mu_{r1} y_{r0} - \mu_0 \geq \theta_0^1 \\ \left(\alpha \sum_{r=1}^{s} \mu_{r1} y_{r0} - \mu_0\right) \geq \theta_0^2 \\ \sum_{r=1}^{s} \mu_{r1} y_{rj} - \alpha\mu_0 - \sum_{i=1}^{m_1} v_i^1 x_{ij}^1 \leq 0 \\ a \sum_{r=1}^{s} u_{r1} y_{rj} - \alpha\mu_0 - \sum_{k=1}^{m_2} v_k^2 X_{kj}^2 \leq 0, j = 1, \ldots, n \\ \sum_{i=1}^{m_1} v_i^1 x_{i0}^1 = 1 \\ \sum_{k=1}^{m_2} v_k^2 x_{k0}^2 = 1 \\ \mu_0 \in R, \quad \alpha.\mu_{r1},\ v_i^1, v_k^2 > 0, \quad i = 1, \ldots, m_1,\ j = 1, \ldots, n,\ \ k = 1, \ldots, m_2, \quad r = 1, \ldots, s \end{array} \tag{4}$$

where μ_i^k shows the importance of output r, α_r shows the ratio of the importance of inputs and functional area, u_r^n shows the importance of output r; Y_{rj} shows the value of output r in the unit j and x_{rj} shows the value of input i in the unit j.

3. Review Method

In this review paper, we conducted a review regarding the application of DEA methods in the fields of environmental and energy economics. Denyer and Tranfield [55] indicated that, the aim of a review is to find relevant existing studies based on research questions, to evaluate and synthesize their respective contributions and to report the evidence in a way that clear conclusions with regard to further research and managerial practice can be drawn. Our search strategy consisted of looking for relevant studies within scientific literature sources, represented by academic studies published in peer-reviewed journals. To identify the published papers in field of environmental and energy economics and DEA methods we searched two online databases (Web of Science and Scopus) between 2000 and 2018 to identify eligible articles. The selected articles were then classified and reviewed based on authors, application scheme, DEA models, application fields, number of publications, journal distribution and publication year. In the following sections, we briefly present the articles and related literature based on the above classifications.

4. Results

4.1. Distribution of Articles Based on DEA Models and Application Scheme

In recent years the applications of DEA have increased in field of environmental and energy economics, in areas, for example; energy performance [56–62], energy savings [63–69], and energy efficiency [70–79], Shi et al. [80–89]. In this regard, various DEA models were employed in different industries and sectors such as non-radial DEA, bootstrap DEA, CCR and BCC models, DEA window analysis, non-radial and constant returns to scale (CRS), DEA frontier, (VRS), directional distance function (DDF), DEA-Malmquist, slacks-based DEA, DEA-bargaining game, DEA–MBP model, network DEA, stochastic DEA, stochastic network DEA, double-bootstrap DEA, dynamic environmental DEA, stochastic frontier analysis (SFA), radial stochastic DEA, network range adjusted environmental DEA, fuzzy dynamic network-DEA, constant returns to scale (CRTS), variable returns to scale (VRTS), DEA discriminant analysis (DEA-DA), fuzzy network slack-based measure (SBM) model, interval DEA-CCR, super-efficient DEA (SE-DEA) and other DEA models. Wang and Zhao [90] used a non-radial DEA in the non-ferrous metals industry. Lin and Du [57] applied a non-radial DEA for assessment of energy and CO_2 emissions performance by using panel data set of 30 provinces. Iribarren et al. [59] developed a non-radial and constant returns to scale (CRS) method for the wind energy industry. Bian et al. [66] employed non-radial DEA for evaluating of energy saving and CO_2 emission in the various provinces, municipalities and autonomous regions of China. Fang et al. [56] used CCR and BCC DEA models for coal mining companies. Ebrahimi and Salehi [85] applied DEA-CCR and BCC models to the production of button mushrooms. Nabavi-Pelesaraei et al. [84] employed DEA CCR and BCC models in the study of orange production. Khoshnevisan et al. [3] utilized CCR and BCC models in cucumber production. Mousavi-Avval et al. [82] used CCR and BCC models in canola production. Shi et al. [80] employed CCR and BCC models for 28 Chinese administrative regions to examine industrial energy efficiency. Yeh et al. [79] examined the energy utilization efficiency of 31 DMUs of China and Taiwan by using a CCR–DEA model. Song et al. [65] studied energy savings using nearly 20 years of data by application of a CCR-DEA model. Mandal and Madheswaran [69] applied BCC DEA to cement companies. Han et al. [91] used CRS-DEA in industrial departments. Geng et al. [92] applied CCR DEA in the process of complex chemical manufacture. Nabavi-Pelesaraei et al. [93] employed CCR and BCC DEA in paddy production. Chen et al. [94] used CCR DEA in the petrochemical industries. Liu et al. [62] applied CRS and VRS DEA to the wind power industry. Nazarko and Chodakowska [95] used SFA-DEA labour efficiency analysis in the construction industry. Nazarko and Chodakowska [96] used the Tobit regression and DEA approach for labour productivity analysis in the construction sectors in different European nations. Banaeian et al. [87] utilized the CRS and VRS DEA for evaluating strawberry yields. Lee et al. [64] used CRS and VRS DEA for different types of efficient electricity, gasoline oil and coal savings studies.

Wang and Wei [81] examined the industrial energy and emissions efficiency by using VRS model in the 30 major Chinese cities. Mohammadi et al. [77] employed the CRS-DEA in the study of rice paddy production. Zhou et al. [97] applied VRS DEA to examine congestion assessment and energy efficiency in the 19 APEC countries. Toma et al. [98] used CRS and VRS DEA for efficiency of the agricultural industry. Moutinho et al. [99] developed VRS and CRS-DEA for environmental and economic efficiency in the European countries. Kim et al. [100] used CRS and VRS in the healthcare industry. Yu et al. [101] employed CRS and VRS DEA models for assessing sustainable development in 34 major cities. Wang et al. [58] used DEA window analysis based on labor and capital stock for evaluating the energy and emission performance of Chinese regions. Vlontzos and Pardalos [102] employed a DEA window analysis in agricultural production. Chen et al. [103] utilized a DEA window analysis for transportation efficiency in cities. Lin et al. [104] applied a DEA window analysis in the manufacturing industries. Chang et al. [75] used a DEA- SBM model for assessing of the environmental performance in the top Fortune 500 companies. Chen and Jia [105] employed an SBM-DEA method for environmental efficiency analysis in the 31 China's regional industry. Hu and Liu [106] utilized slacks-based-DEA in the construction industry. Song and Zheng [107] applied an SBM DEA model for evaluating the efficiency in thermoelectric enterprises. Guo et al. [108] employed an SBM-DEA model to evaluate natural resource allocation in the 26 provincial regions of China. Chu et al. [109] used an SBM-DEA model in the transportation system. Li et al. [110] applied a DEA-SBM model for assessment of efficiency in photovoltaic companies. Shin et al. [111] applied an SBM-DEA model in the manufacturing industry. Masuda [112] utilized the SBM model in rice production. Wang et al. [113] employed an SBM-DEA model in the manufacturing sector. Pang et al. [86] integrated the directional distance function (DDF) and SBM to assess the total clean energy use of 86 countries. Hu and Kao [63] combined the SBM-DEA and radial DEA in the 17 APEC economies for their energy-saving targets. Welch and Barnum [72] used a DEA–MBP model for the efficiency of electricity generation. Rezaee et al. [70] integrated the DEA-bargaining game models for thermal power plants. Wu et al. [67] used a two-stage network DEA to evaluate emission reduction efficiency and energy saving in the 30 municipalities, provinces, and autonomous of China's regional. Gan et al. [114] integrated the triangular fuzzy numbers (TFNs), AHP and DEA in a renewable energy project. He et al. [115] integrated the DEA, fuzzy artificial neural network (FANN) and rough set theory (RS) to assess industrial energy efficiency in the provincial industry sectors. Wang et al. [116] integrated the DEA, decision tree and K-means clustering for twenty-five global cities. Li and Lin [117] combined a non-radial and double-bootstrap for energy consumption performance across 30 Chinese provinces. Li and Lin [118] integrated the stochastic frontier analysis (SFA) and DDF DEA in the manufacturing sector. Distributions of other DEA models with application schemes and fields are presented in Table 1.

Table 1. Distribution of articles based on DEA models in different schemes and fields.

Authors	Application Scheme	DEA Models	Application Fields
Wang and Zhao [90]	Non-ferrous metals industry	Non-radial DEA	Investment strategy and Energy-environmental performance
Zhou et al. [119]	Industrial sectors	Non-radial Malmquist	emission reduction performance and industrial energy conservation and
Duan et al. [120]	Thermal power industry	Bootstrap DEA	Energy and CO_2 emission performance
Fang, Wu and Zeng [56]	Coal mining companies	CCR and BCC models	Efficiency performance
Wang, Wei and Zhang [58]	Labor and capital stock	DEA window analysis	Energy and emission performance
Lin and Du [57]	Panel data set of 30 provinces	Non-radial DEA	Energy and CO_2 emissions performance
Iribarren, Vázquez-Rowe, Rugani and Benetto [59]	Wind energy	Non-radial and constant returns to scale (CRS)	Benchmark multiple resembling entities
Madlener, Antunes and Dias [60]	Agricultural biogas plants	CCR model	Measures of radial efficiency performance
Lins, Oliveira, da Silva, Rosa and Pereira Jr [61]	Power sector	DEA frontier	Performance assessment
Liu, Ren, Li and Zhao [62]	Wind power industry	CRS and VRS DEA	Industrial performance

Table 1. *Cont.*

Authors	Application Scheme	DEA Models	Application Fields
Jan, Dux, Lips, Alig and Dumondel [78]	Dairy farms	DEA frontier	economic and environmental performance
Pardo Martínez and Silveira [89]	Service industries	CCR DEA	Energy use and CO_2 emission
Ren, Tan, Dong, Mazzi, Scipioni and Sovacool [88]	Biofuel systems	CCR DEA	Life cycle energy efficiency
Banaeian, Omid and Ahmadi [87]	Strawberry yield	CRS and VRS DEA	Effective energy utilization
Pang, Deng and Hu [86]	Total energy use of 86 countries	Directional distance function (DDF) and SBM (slack-based measure)	Clean energy use
Ebrahimi and Salehi [85]	Button mushroom production	CCR and BCC models	Energy use efficiency and CO_2 emission reduction
Nabavi-Pelesaraei, Abdi, Rafiee and Mobtaker [84]	Orange production	CCR and BCC models	energy efficiency and GHG emissions
Khoshnevisan, Rafiee, Omid and Mousazadeh [83]	Cucumber production	CCR and BCC models	Energy use efficiency
Mousavi-Avval, Rafiee, Jafari and Mohammadi [82]	Canola production	CCR and BCC models	Energy use efficiency
Lee, Hu and Kao [64]	Types of efficient electricity, gasoline oil savings and coal	CRS and VRS DEA	Energy-saving targets
Hu and Kao [63]	17 APEC economies	Slack and radial DEA	Energy-saving targets
Wang and Wei [81]	30 Chinese major cities	VRS model	Industrial energy and emissions efficiency
Shi, Bi and Wang [80]	28 administrative regions	CCR and BCC models	Industrial energy efficiency
Yeh, Chen and Lai [79]	31 DMUs of China and Taiwan	CCR–DEA model	Energy utilization efficiency
Mohammadi, Rafiee, Jafari, Keyhani, Dalgaard, Knudsen, Nguyen, Borek and Hermansen [77]	Rice paddy production	CRS-DEA	Benchmarking of environmental impacts
Wang and Feng [76]	E3 productivity	DEA-Malmquist	Energy economic and environmental efficiency
Chang, Yeh and Liu [75]	Top Fortune 500 companies	DEA-SBM model	Environmental performance
Hoang and Alauddin [74]	Agricultural production	CRS and VRS DEA	Environmental, economic, and ecological efficiency
Song, Yang, Wu and Lv [65]	Nearly 20 years of data	CCR-DEA	Energy saving
Welch and Barnum [72]	Electricity generation	DEA–MBP model	Environmental and cost efficiency
Rezaee, Moini and Makui [70]	Thermal power plants	DEA-bargaining game	Operational and non-operational performance
Mandal and Madheswaran [69]	Cement companies	BCC DEA	Energy use efficiency
Hu, Lio, Kao and Lin [68]	23 administrative regions	CRS DEA	Energy efficiency
Bian, He and Xu [66]	Provinces, municipalities and autonomous region	Non-radial DEA	energy saving and CO_2 emission
Wu, Lv, Sun and Ji [67]	30 municipalities, provinces, and autonomous	Two-stage network DEA	Emission reduction efficiency and energy saving
Sözen, Alp and Özdemir [73]	Thermal power plants	CRS, CCR, VRS and BCC DEA	Environmental and operational and performance
Chen and Jia [105]	31 regions' industry	SBM DEA	Environmental efficiency analysis
Yan et al. [121]	Biomass Industry	Network DEA	Economic and Technical Efficiency
Ramanathan et al. [122]	Manufacturing firms	DEA-FA- regression	Environmental regulations
Gan, Xu, Hu and Wang [114]	Renewable Energy Project	TFN–AHP–DEA	Economic Feasibility Analysis
Sueyoshi and Wang [123]	Rooftop photovoltaic systems	RTS DEA	Operational efficiency, performance and inefficiency
He, Liao and Zhou [115]	Provincial industry sectors	DEA-RS-FANN	Industrial energy efficiency
Vlontzos and Pardalos [102]	Agricultural production	DEA Window analysis	GHG emissions
Chen, Gao, An, Wang and Neralić [103]	Cities transportation	DEA window analysis	Energy efficiency measurement
Kourtit et al. [124]	World cities	Multi-temporal DEA	Sustainability performers
Zhou, Meng, Bai and Cai [97]	19 APEC countries	VRS DEA	Congestion assessment and energy efficiency
Wang, Li, Meng and Wu [116]	Twenty-five global cities	DEA, decision tree and K-means clustering	Energy efficiency
Meng et al. [125]	Resource efficiency of 31 provinces	Synthesized DEA	Resource efficiency evaluation
Han, Long, Geng and Zhang [91]	Industrial departments	CRS DEA	Environment efficiency analysis
Geng, Dong, Han and Zhu [92]	Complex chemical processes	CCR DEA	Energy and environment efficiency
Nabavi-Pelesaraei, Rafiee, Mohtasebi, Hosseinzadeh-Bandbafha and Chau [93]	Paddy production	CCR and BCC DEA	Energy use and environmental evaluation
Chen, Han and Zhu [94]	Petrochemical industries	CCR DEA	Environmental and Energy efficiency evaluation

Table 1. *Cont.*

Authors	Application Scheme	DEA Models	Application Fields
Toma, Miglietta, Zurlini, Valente and Petrosillo [98]	Agricultural efficiency	CRS and VRS DEA	Environmental policy management and planning
Vaninsky [126]	Global economic data	Stochastic DEA	Energy-environmental efficiency
Chen et al. [127]	Airline industry	Stochastic network DEA	Efficiency assessment
Lin, Sun, Marinova and Zhao [104]	Manufacturing industries	DEA window analysis	Green technology innovation efficiency
Li and Lin [117]	Across 30 provinces	Non-radial and double-bootstrap	Energy consumption performance
Moon and Min [128]	Energy-intensive firms	Network DEA	Energy efficiency
Hu and Liu [106]	Construction industry	Slacks-based DEA	Eco-efficiency assessment
Guo et al. [129]	Energy stock	Dynamic DEA	Energy efficiency
Cui et al. [130]	Airline performance	Dynamic Environmental DEA	GHG emissions
Cui et al. [131]	Airlines' energy efficiencies	Slacks Based DEA	Energy efficiency
Li and Lin [118]	Manufacturing sector	Stochastic frontier analysis (SFA) and DDF DEA	Energy conservation
Zha et al. [132]	Regional efficiencies 30 provinces	Radial stochastic DEA	Energy efficiency and CO_2 emissions
Wu et al. [133]	Data of 30 provinces	Two-stage DEA approach	Energy efficiency
Cui and Li [134]	Airline efficiency	Slacks-Based Measure (SBM)	Energy efficiency
Hu and Liu [106]	29 international airlines	Network Range Adjusted Environmental DEA	Carbon neutral growth
Iftikhar et al. [135]	Major economies	SBM DEA model	CO_2 emissions and Energy efficiency
Song and Zheng [107]	Thermoelectric enterprises	SBM DEA model	Environmental efficiency
Guo, Zhu, Lv, Chu and Wu [108]	26 provincial regions	SBM-DEA model	Natural resource allocation
Wu et al. [136]	Data of 30 provinces	CCR and CRS DEA	Environmental efficiency
Chu, Wu and Song [109]	Transportation system	SBM-DEA model	Environmental efficiency
Huang et al. [137]	Three sectors and industry	DEA Malmquist	Energy intensity
Moutinho, Madaleno and Robaina [99]	EU cross-country	VRS and CRS-DEA	Environmental and economic efficiency
Olfat et al. [138]	Airports performance	Fuzzy dynamic network-DEA	Efficiency measurement
Sueyoshi and Yuan [139]	30 provinces	Constant Returns to Scale (CRTS) and Variable Returns to Scale (VRTS)	Social sustainability
Kang and Lee [140]	154 industries	CRS and VRS DEA	Environmental and energy efficiency
Chen et al. [141]	Construction industry	DEA Discriminant Analysis (DEA-DA)	Energy efficiency
Wang et al. [142]	Provincial industrial sector	Non-radial DEA model	Environmental assessment
Li, Liu and Zha [110]	Photovoltaic companies	SBM model	Operational efficiency
Chen and Geng [143]	26 Organization	Non-radial Malmquist index (NMI)	CO_2 emissions reduction and fossil energy saving
Liu and Wu [144]	Transportation sectors	Slack-based DEA	Environmental and energy efficiency
Martínez and Piña [145]	Manufacturing industries	Malmquist-DEA	Energy use
Bostian et al. [146]	Pulp and paperindustry	Network DEA	Environmental investment
Shermeh et al. [147]	Power companies	Fuzzy network SBM model	Company efficiency
Kwon et al. [148]	12 EU countries	CRS and VRS DEA	Technology efficiency
Song et al. [149]	31 cities	VRS DEA	Efficiency evaluation
Kim, Jeon, Cho and Kim [100]	Health Sector	CRS and VRS	Environmental Management
Song et al. [150]	Thermal power companies	CCR model	Environmental costs and business performance
Shin, Kim and Yang [111]	Manufacturing companies	SBM DEA	Innovation Efficiency
Cheng et al. [151]	Panel data for 29 provinces	DEA-CCR	Economic Growth
Wang et al. [152]	Panel data for 285 cities	DDF-DEA	Environmental Performance
Zhang et al. [153]	30 provinces for expression convenience	DEA Window	Social Sustainability Assessment
Masuda [112]	Rice Production	SBM model	Energy Efficiency
Vlontzos et al. [154]	Agricultural Sector	DDF-DEA	Eco-Efficiency

Table 1. *Cont.*

Authors	Application Scheme	DEA Models	Application Fields
Gong and Chen [155]	Manufacturing Industry	Interval DEA-CCR	Environmental Performance
Xiong et al. [156]	30 provinces	CCR-DEA	Energy Consumption
Yu, Gao and Shiue [101]	34 major cities	CRS and VRS DEA	Sustainable Development
Liu et al. [157]	Thermal power industry	CCR and CRS DEA	Energy Efficiency
Guerrini et al. [158]	127 selected plants	Double Bootstrap DEA	Energy Efficiency
Liu et al. [159]	Photovoltaic Power	Super-efficient DEA (SE-DEA)	Comprehensive Efficiency
Li et al. [160]	Refining Enterprises	DEA-based model	Sustainability Assessment
Chen and Gong [161]	Manufacturing Sectors	CCR-DEA	Efficiency of Energy Consumption
Wang, Han and Yin [113]	Manufacturing Sectors	SBM model	Environmental Efficiency
Tsai et al. [162]	37 European countries and 36 Asian countries	SBM model	Sustainability Assessment
Li et al. [163]	30 provinces	CRR and BCC DEA	Efficiency of Water-Energy

4.2. Distribution of Paper Based on Journal Selection

This review paper attempts to cover all recently published papers regarding the application of DEA models in the environmental and energy economics areas. According to Table 2 and Figure 1, 45 high-quality journals published several articles on the application of DEA models in these fields.

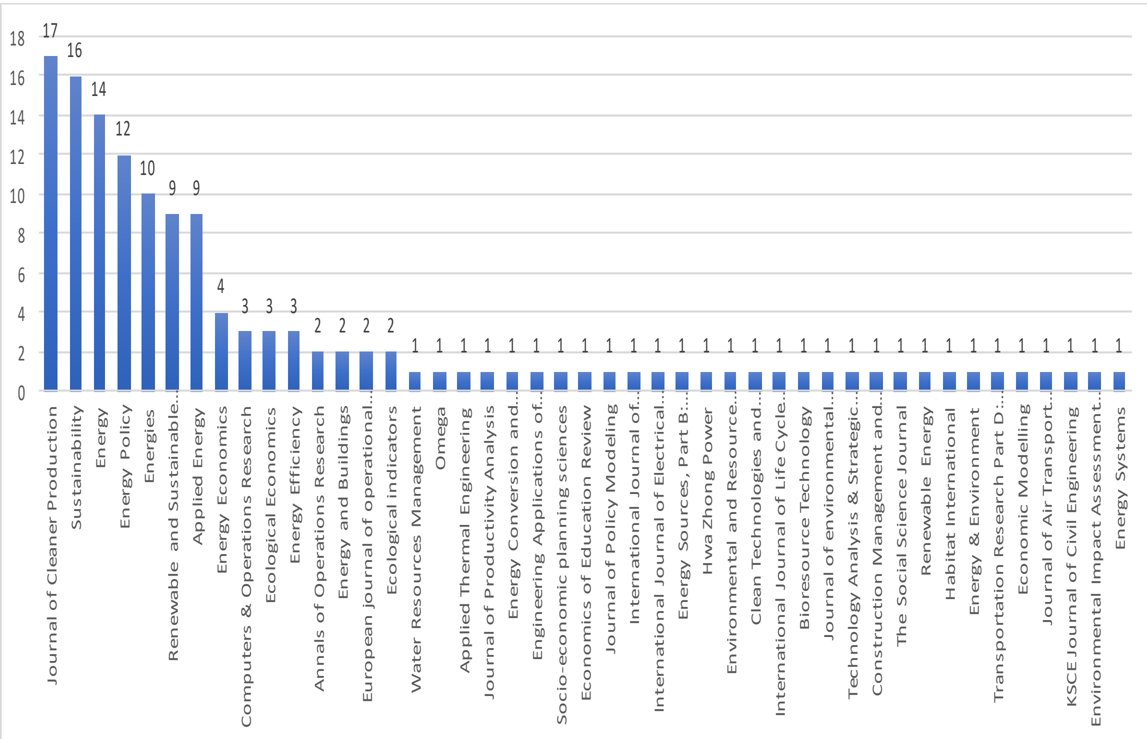

Figure 1. Distribution of papers by journal.

In this regard, *Journal of Cleaner Production* ranks first, with 17 publications. The second was *Journal of Sustainability*. In addition, *Journal of Energy* and *Journal of Energy Policy* occupy the third and fourth ranks with 14 and 12 articles, respectively. Other important journals in these areas were *Journal of Energies*, *Journal of Renewable and Sustainable Energy Reviews* and *Applied Energy*. The information regarding the distribution of other journals is provided in Table 2 and Figure 1.

Table 2. Distribution of articles by journal.

Name of Journal	Number of Papers	Percentage
Journal of Cleaner Production	17	12.32%
Sustainability	16	11.59%
Energy	14	10.14%
Energy Policy	12	8.70%
Energies	10	7.25%
Renewable and Sustainable Energy Reviews	9	6.52%
Applied Energy	9	6.52%
Energy Economics	4	2.90%
Computers & Operations Research	3	2.17%
Ecological Economics	3	2.17%
Energy Efficiency	3	2.17%
Annals of Operations Research	2	1.45%
Energy and Buildings	2	1.45%
European journal of operational research	2	1.45%
Ecological indicators	2	1.45%
Water Resources Management	1	0.72%
Omega	1	0.72%
Applied Thermal Engineering	1	0.72%
Journal of Productivity Analysis	1	0.72%
Energy Conversion and Management	1	0.72%
Engineering Applications of Artificial Intelligence	1	0.72%
Socio-economic planning sciences	1	0.72%
Economics of Education Review	1	0.72%
Journal of Policy Modeling	1	0.72%
International Journal of Environment and Pollution	1	0.72%
International Journal of Electrical Power & Energy Systems	1	0.72%
Energy Sources, Part B: Economics, Planning, and Policy	1	0.72%
Hwa Zhong Power	1	0.72%
Environmental and Resource Economics	1	0.72%
Clean Technologies and Environmental Policy	1	0.72%
International Journal of Life Cycle Assessment	1	0.72%
Bioresource Technology	1	0.72%
Journal of environmental management	1	0.72%
Technology Analysis & Strategic Management	1	0.72%
Construction Management and Economics	1	0.72%
The Social Science Journal	1	0.72%
Renewable Energy	1	0.72%
Habitat International	1	0.72%
Energy & Environment	1	0.72%
Transportation Research Part D: Transport and Environment	1	0.72%
Economic Modelling	1	0.72%
Journal of Air Transport Management	1	0.72%
KSCE Journal of Civil Engineering	1	0.72%
Environmental Impact Assessment Review	1	0.72%
Energy Systems	1	0.72%
Total	138	100.00%

4.3. Distribution of Papers Based on Year of Publication

Figure 2 shows the distribution of papers based on the year of publication. The findings show that in the recent years' application of DEA models in the areas of energy and environmental economics have increased considerably and there is now an increasing body of literature devoted to the using these models in these fields. According to results of this section, there were 40 papers published in 2017, eventually followed by 2016 with a total number of 23 papers, 19 papers in 2018 and 2015 had a total of 12 published papers. Although it can be argued that a growing number of papers suggests an increased level of interest towards studies of activities in the subject area. The results of other years are provided in the Figure 2.

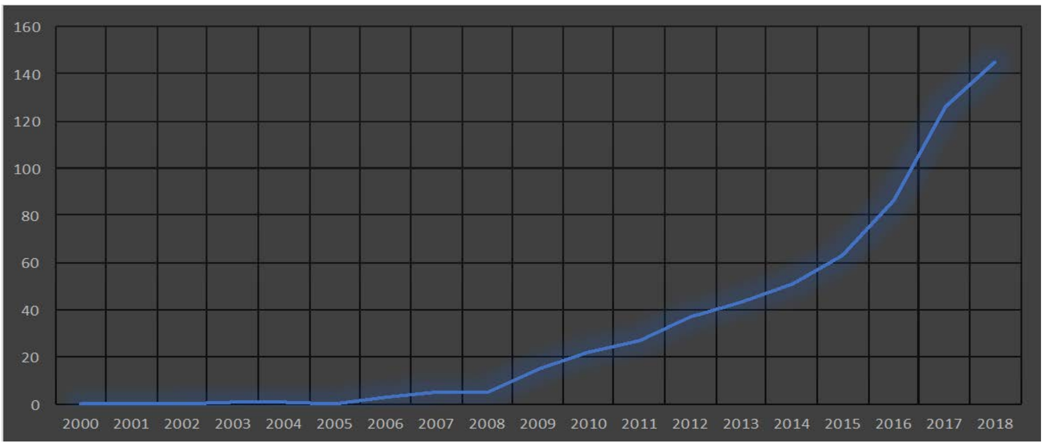

Figure 2. Distribution of papers based on publication year.

4.4. Distribution of Paper Based on Keywords Networks by VOS-Viewer

In this section of the paper for visualization, we searched several keywords related to the applications of DEA in energy and environmental economics such as DEA and energy efficiency (1103 records), DEA and environmental efficiency (1359 records), DEA and energy economics (23 records), DEA and environmental economics (44 records), energy performance and DEA (707 records), efficiency performance and DEA (4805 records), CO_2 emissions and DEA (374 records), energy consumption and DEA (421 records) energy saving and data envelopment analysis (183 records) energy use efficiency and DEA (804), and total factor efficiencies and DEA (531 records). In Figure 3 we show the keywords which come up repeatedly in published papers dealing with the application of DEA in the assessment of energy and environmental economics in the Web of Science (WoS) database.

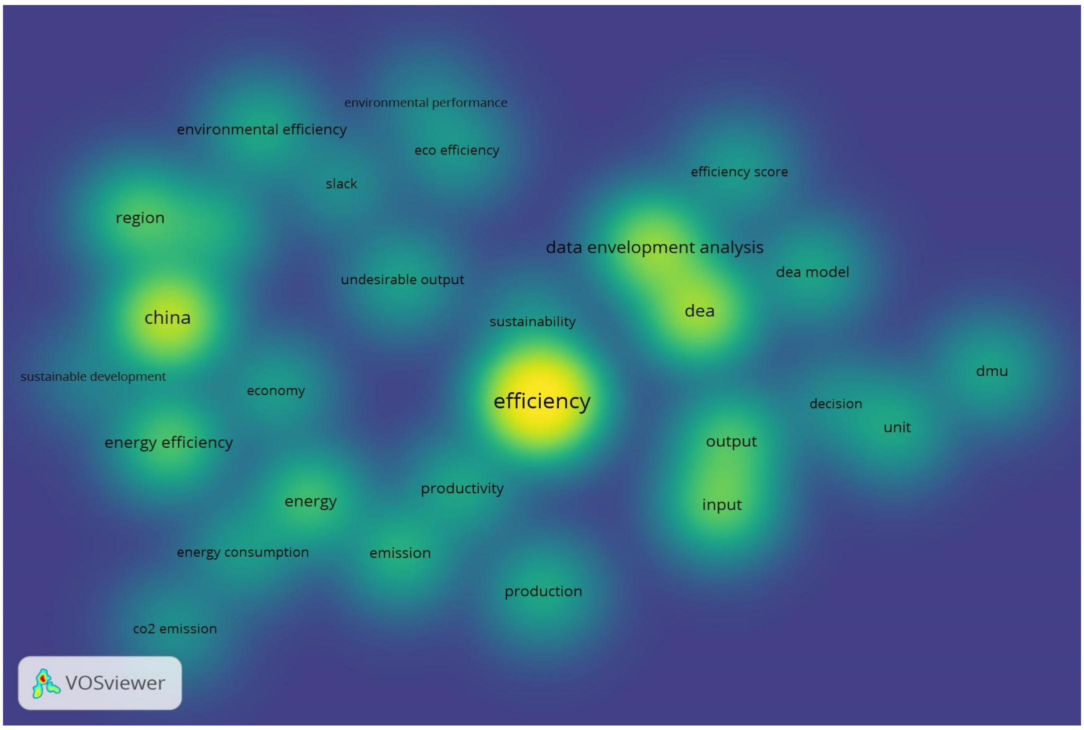

Figure 3. Related keywords in published papers regarding DEA and energy and environmental economics in Web of Science.

In the final step of the visualization process, we provide the relationships between keywords by using VOS-viewer for generating keyword networks. The most important keywords are located in the center of the map (Figure 4). Each point shows a word, the font size of a word and related sizes as well as the frequency of that word. According to Figure 4, the word that has indicated in the most of the published papers showing the strongest relationships with other words. According to Figure 4, the keyword "efficiency" had the strongest relationships to other keywords compared to other keywords. The results of other keywords are represented in Figure 4. VOS-viewer allowed us to join the most important words into relevant clusters shown in different colours. In addition, there are three different clusters regarding the analysis of co-occurrence of keywords. The details of the three clusters with important keywords are presented in Figure 4.

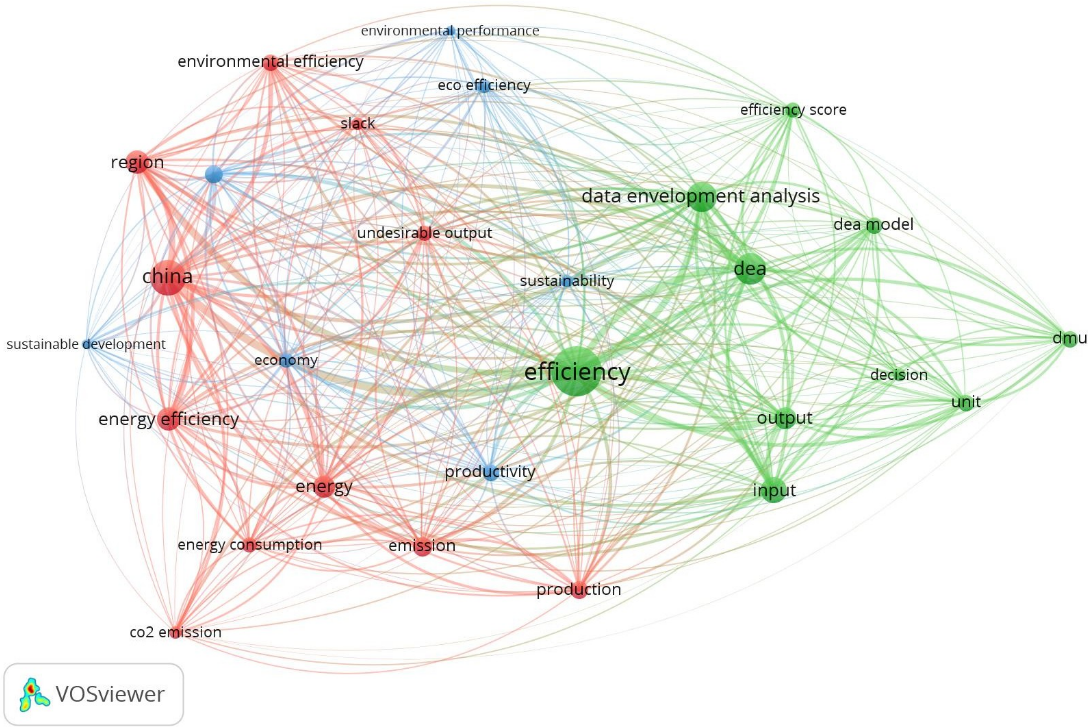

Figure 4. Map showing regarding the relationships between keywords with different clusters dealing with applications of DEA in assessment of energy and environmental economics.

5. Conclusions

In this section, we discuss the application of DEA for assessment of energy and environmental economics fields. According to results of this review article, there are various types of DEA models that have been used in different fields of energy and environmental economics. According to the current literature review, these areas have attracted much interest in the last two decades, spawning a number of studies, and many literature reviews have been undertaken, therefore, there are a number of key challenges regarding these subjects which can be interesting for discussion. This is the first review paper to comprehensively review the application of DEA models in the evaluation of energy and environmental economics. Notwithstanding the contributions offered in this review paper, the findings were to be considered in light of many limitations. As we classified the selected articles in different application areas, there are other issues for more discussion. For example; this review paper provided insights into the methodological and conceptualization study in the application of DEA models in energy and environmental economics fields. This review study should enable scholars and practitioners to understand the state of art of inputs and outputs indicators in the fields of DEA models and environmental and energy economics. This review article attempted to present an overview of the body of 145 published articles in 45 different international journals in the field of environmental and energy economics and DEA models in different parts of papers such as title, keywords, abstract, introduction, methodology, results, and conclusion. This research review examined the different models of DEA by considering the related journals based on application scheme, DEA models, scope, results, and publication year.

Some of the previous studies used a non-radial DEA approach for environmental and energy performance, however, further studies would be integrated the environmental non-radial DEA approach with some other techniques such as statistical inference to predict the environmental and energy performance based on time series data. In addition, further investigations could use the stochastic and fuzzy data for improving the energy efficiency and energy performance. In addition, some of the past published papers focused on environment and energy efficiency for improving environment DEA cross-model (DEACM), in this regard, future studies can use the high-dimension initial data by principal component analysis. The SFA model is used for analysis of energy and environmental efficiency, therefore, the further investigations would use other techniques and compare these results with their results. Structural equations modelling (SEM) is a technique for regression analysis, therefore, further studies would integrate the SEM approach with DEA models. Guo et al. [108] evaluated the efficiency of emission reduction and energy saving by modifying an SMB. Therefore, future scholars can focus on the allocation for decreasing the emission and energy based on decentralized and centralized views. Zhang and Chen [164] used the DEA based on DDF for assessing the dynamic performance of energy portfolios in the daily fossil-fuel prices between 2006 and 2015. Regarding this, further investigation would focus on the different commodities based on energy portfolios and their effect of risk and return volatility. Angulo-Meza et al. [165] evaluated the eco-efficiency of agricultural sectors by using a multiple objective DEA approach. Consequently, future articles can extend the proposed model of this study by developing the different methods such as decision support system. In addition, future works would use the multiple objective DEA approach to evaluate the economic perspectives of eco-efficiency assessment. Meng et al. [166] integrated the DEA model and TOPSIS approach to evaluating the dynamic energy efficiency, thus, further studies would integrate the DEA model with other decision-making approaches and fuzzy decision-making methods.

There are some motivations behind this review paper which can be useful for further studies. From the prior literature review, there are some review papers in the fields of DEA and environmental and energy economics. First, this review paper found there are various models of DEA have been used in previous studies. The important of DEA models were non-radial DEA (Wang et al. [142]; Bian et al. [66]), bootstrap DEA (Duan et al. [120]), CCR and BCC models (Shi et al. [80]; Mousavi-Avval et al. [82]; Khoshnevisan et al. [83]), DEA window analysis (Vlontzos and Pardalos [102]; He et al. [115]), DEA frontier (Jan et al. [78]; Lins et al. [61]), VRS (Wang and Wei [81]; Zhou et al. [97]), DDF (Vlontzos et al. [154]; Wang et al. [152]), DEA-Malmquist (Martínez and Piña [145]; Huang et al. [137]; Wang and Feng [76]), SBM-DEA (Guo et al. [108]; Chu et al. [109]), DEA–MBP model (Welch and Barnum [72]), network DEA (Wu et al. [67]; Yan et al. [121]), stochastic DEA (Vaninsky [126]), stochastic network DEA (Chen et al. [127]), SFA (Li and Lin [118];), radial stochastic DEA (Zha et al. [132]), fuzzy dynamic network-DEA (Olfat et al. [138]), CRTS and VRTS (Sueyoshi and Yuan [139]), DEA-DA (Chen et al. [141]), fuzzy network SBM model (Shermeh et al. [147]), Interval DEA-CCR (Gong and Chen [155]) and SE-DEA (Liu et al. [159]). In addition, the results found that one previous review study classifies and review the recent DEA models under the methodological aspect, application schemes, efficiency measure, inputs, outputs. Another study reviewed the application of environmental efficiency, measurement methods. Another a review studies categorized and review the application of DEA models in the different application area of energy efficiency, scope, time duration, study objective, findings, and outcome.

Regarding the journal selection, this review study found that the *Journal of Cleaner Production* had the highest number of published paper followed by *Journal of Sustainability*, *Journal of Energy*, *Journal of Energy Policy*, *Journal of Energies*, *Journal of Renewable and Sustainable Energy Reviews* and *Applied Energy*.

Moreover, this review paper found that in recent years the application of DEA models has increased and the results of this study demonstrated that in the year of 2014, authors published 40 papers with compare to other years.

There are some limitations to this particular review paper which provides recommendations and opportunities for further investigation. First, this review categorized the published papers in the fields of DEA and environmental and energy economics, therefore it is an opportunity for further study to classify the published papers based on different application areas. Moreover, this study categorized the selected papers based on DEA models, thus further research would examine more details about methodological parts such as benchmark ranking method, multivariate statistics, cross-efficiency ranking methods, ratios discriminant analysis, linear discriminant analysis, canonical correlation analysis, inefficient decision-making units, DEA and MCDM methods, super-efficiency ranking techniques, inputs and outputs indicators and, fuzzy DEA principles, efficiency measures. Moreover, in Section 2 this paper presented an example of DEA models based on CCR-DEA and BCC-DEA, therefore, researchers could further focus on other different DEA models such as SBM-DEA, DEA window analysis, stochastic network DEA, fuzzy dynamic network-DEA, fuzzy network SBM model, network DEA and stochastic DEA.

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