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):

\[ \text{Max } Z_0 = \sum_{r=1}^{s} u_r y_{r0} + \sum_{i=1}^{m} v_i x_{i0} \]

s.t.

\[ \sum_{i=1}^{m} v_i x_{i0} = 1 \]

\[ \sum_{r=1}^{s} u_r y_{rj} - \sum_{i=1}^{m} v_i x_{ij} + w \leq 0; \quad (j = 1, 2, \ldots, n) \]

\[ u_r, v_j \geq 0; w : \text{Free} \]

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.
- \( u_r \) 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 \( q \) is the variable corresponding to the first constraint of the initial problem and \( l_j \) is the variable corresponding to other constraints, then the following envelopment model can be obtained:

\[
\begin{align*}
\text{Min } & y_0 = q \\
\text{s.t. } & \sum_{j=1}^n \lambda_j y_{rj} \geq y_{r0}; \\ & (r = 1, 2, \ldots, s) \\
\sum_{j=1}^n \lambda_j x_{ij} \leq \theta x_{i0}; \\ & (i = 1, 2, \ldots, m) \\
\sum_{j=1}^n \lambda_j = 1 \\
\lambda_j \geq 0; \quad \theta : \text{Free} \\ & (j = 1, 2, \ldots, n)
\end{align*}
\]

where \( \lambda_j \) is the corresponding variable, \( l_j \) 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]:

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

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:

\[
\begin{align*}
\text{Max } & \left( \sum_{r=1}^s \mu_{r1} y_{r0} - \mu_0 - \theta_0^1 \right) \\
\text{s.t. } & \sum_{r=1}^s \mu_{r1} y_{r0} - \mu_0 \geq \theta_0^1 \\
& \left( a \sum_{r=1}^s \mu_{r1} y_{r0} - \alpha \mu_0 - \theta_0^2 \right) \geq \theta_0^2 \\
& \sum_{r=1}^s \mu_{r1} y_{rj} - \alpha \mu_0 - \sum_{i=1}^m v_i^1 x_{ij}^1 \leq 0 \\
& a \sum_{r=1}^s u_r y_{rj} - \alpha \mu_0 - \sum_{k=1}^m v_k x_{j0}^k \leq 0, \quad j = 1, \ldots, n \\
& \sum_{i=1}^{m_1} v_i^1 x_{i0}^1 = 1 \\
& \sum_{k=1}^{m_2} v_k x_{j0}^k = 1 \\
\mu_0 \in \mathbb{R}, \quad \alpha, \mu_{r1}, v_i^1, v_k^2 > 0, \quad i = 1, \ldots, m_1, \; j = 1, \ldots, n, \; k = 1, \ldots, m_2, \; r = 1, \ldots, s
\end{align*}
\]

where \( \mu_r^j \) shows the importance of output \( r \), \( \alpha \) shows the ratio of the importance of inputs and functional area, \( u_r^j \) 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 (CRS), 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 DEA 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 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. Fang 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.

| 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 improvement |
| 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 [117] | 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 Peres Jr [61] | Power sector | DEA frontier | Performance assessment |
| Liu, Ren, Li and Zhao [62] | Wind power industry | CRS and VRS DEA | Industrial performance |
| Authors | Application Scheme | DEA Models | Application Fields |
|---------|--------------------|------------|-------------------|
| Jan, Dux, Lips, Ali and Dumondel [78] | Dairy farms | DEA frontier | Economic and environmental performance |
| Pardo Martinez and Silveira [79] | Service industries | CCR DEA | Energy use and CO₂ emission |
| Ren, Tan, Dong, Mazzzi, Sepioni and Sozio [80] | Biofuel systems | CCR DEA | Life cycle energy efficiency |
| Banasian, 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 |
| Ebrahim and Salesi [88] | Button mushroom production | CCR and BCC models | Energy use efficiency and CO₂ emission reduction |
| Nabavi-Porosaraei, Abdi, Raftee and Mobtaker [89] | Orange production | CCR and BCC models | Energy efficiency and GHG emissions |
| Khoshevisian, Raftee, Omid and Moussazadeh [85] | Cucumber production | CCR and BCC models | Energy efficiency |
| Mousavi-Arvand, Raftee, Jafari and Mohammad [82] | Canola production | CCR and BCC models | Energy use efficiency |
| Hu and Kao [93] | Types of efficient electricity, gasoline oil savings, and coal | CRS and VRS DEA | Energy-saving targets |
| Wang and Wu [96] | 30 municipalities, provinces, and autonomous | Two-stage network DEA | Emission reduction efficiency and energy saving |
| Siözen, Alp and Özdemir [97] | Thermal power plants | CRS, CCR, VRS and BCC DEA | Environmental and operational performance |
| Chen and Ja [98] | 31 regions' industry | SIBM DEA | Environmental efficiency analysis |
| Yan et al. [101] | Biomass Industry | Network DEA | Economic and Technical Efficiency |
| Ramasubhuni et al. [102] | Manufacturing firms | DEA-FA-regression | Environmental regulations |
| Gan, Xu, Hu and Wang [104] | Renewable Energy Project | TFN-AHP-DEA | Economic Feasibility Analysis |
| Saeyoshi and Wang [107] | Rooftop photovoltaic systems | RTS DEA | Operational efficiency, performance and inefficiency |
| Hu, Liao and Zhou [108] | Provincial industry sectors | DEA-RS-FANN | Industrial energy efficiency |
| Vlontzos and Pardalos [109] | Agricultural production | DEA Window analysis | GHG emissions |
| Chen, Gao, An, Wang and Neralic [110] | Cities transportation | DEA window analysis | Energy efficiency measurement |
| Koutrit et al. [111] | World cities | Multi-temporal DEA | Sustainability performers |
| Zhou, Meng, Bai and Cai [112] | 19 APEC countries | VRS DEA | Congestion assessment and energy efficiency |
| Wang, Li, Meng and Wu [113] | Twenty-five global cities | DEA, decision tree and K-means clustering | Energy efficiency |
| Meng et al. [114] | Resource efficiency of 31 provinces | Synthesized DEA | Resource efficiency evaluation |
| Han, Long, Deng and Zhang [115] | Industrial departments | CRS DEA | Environment efficiency analysis |
| Geng, Dong, Han and Zhu [116] | Complex chemical processes | CCR DEA | Energy and environment efficiency |
| Nabavi-Porosaraei, Raftee, Mohi, Bandbalha, and Chau [117] | Paddy production | CCR and BCC DEA | Energy use and environmental evaluation |
| Chen, Han and Zhu [118] | Petrochemical industries | CCR DEA | Environmental and Energy efficiency evaluation |
| 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 |
| Varinovsky [126] | Global economic data | Stochastic DEA | Energy-environmental efficiency |
| Chen et al. [127] | Airline industry | Stochastic network DEA | Efficiency assessment |
| Liu, 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 (SEAF) and DDF DEA | Energy conservation |
| Zha et al. [132] | Regional efficiencies 30 provinces | Radial stochastic DEA | Energy efficiency and CO2 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 | CO2 emissions and Energy efficiency |
| Song and Zheng [107] | Thermoelectric enterprises | SBM DEA model | Environmental efficiency |
| Gao, Zhou, 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 (CRS) and Variable Returns to Scale (VRS) | 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 Gong [143] | 26 Organization | Non-radial Malmquist index (NMI) | CO2 emissions reduction and fossil energy saving |
| Liu and Wu [144] | Transportation sectors | Slack-based DEA | Environmental and energy efficiency |
| Martinez and Piha [145] | Manufacturing industries | Malmquist-DEA | Energy use |
| Boutian et al. [146] | Pulp and paper industry | Network DEA | Environmental investment |
| Shermeh et al. [147] | Power companies | Fuzzy network SBM model | Company efficiency |
| Kwun et al. [149] | 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 |
| Vlentzos 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. [193]         | Photovoltaic Power | Super-efficient DEA (SE-DEA) | Comprehensive Efficiency  |
| Li et al. [169]          | 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.](image-url)

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.
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.
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), CO₂ 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.](image)

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, further 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 compared 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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**References**

1. Mardani, A.; Zavadskas, E.K.; Streimikiene, D.; Jusoh, A.; Khoshnoudi, M. A comprehensive review of data envelopment analysis (DEA) approach in energy efficiency. *Renew. Sustain. Energy Rev.* 2017, 70, 1298–1322. [CrossRef]
2. Farrell, M.J. The measurement of productive efficiency. *J. R. Stat. Soc. Ser. A* 1957, 120, 253–290. [CrossRef]
3. Shabanpour, H.; Yousefi, S.; Saen, R.F. Forecasting efficiency of green suppliers by dynamic data envelopment analysis and artificial neural networks. *J. Clean. Prod.* 2017, 142, 1098–1107. [CrossRef]
4. Ji, X.; Wu, J.; Zhu, Q.; Sun, J. Using a hybrid heterogeneous DEA method to benchmark China’s sustainable urbanization: An empirical study. *Ann. Oper. Res.* 2018, 1–55. [CrossRef]
5. Toloow, M.; Allahyar, M.; Hančlová, J. A non-radial directional distance method on classifying inputs and outputs in DEA: Application to banking industry. *Expert Syst. Appl.* 2018, 92, 495–506. [CrossRef]
6. Han, Y.; Geng, Z.; Zhu, Q.; Qu, Y. Energy efficiency analysis method based on fuzzy DEA cross-model for ethylene production systems in chemical industry. *Energy* 2015, 83, 685–695. [CrossRef]
7. Li, W.H.; Liang, L.; Cook, W.D. Measuring efficiency with products, by-products and parent-offspring relations: A conditional two-stage DEA model. *Omega* 2017, 68, 95–104. [CrossRef]
8. Azadi, M.; Jafarian, M.; Saen, R.F.; Mirhadayatian, S.M. A new fuzzy DEA model for evaluation of efficiency and effectiveness of suppliers in sustainable supply chain management context. *Comput. Oper. Res.* 2015, 54, 274–285. [CrossRef]
9. An, Q.; Chen, H.; Wu, J.; Liang, L. Measuring slacks-based efficiency for commercial banks in China by using a two-stage DEA model with undesirable output. *Ann. Oper. Res.* 2015, 235, 13–35. [CrossRef]
10. Tone, K.; Tsutsui, M. Dynamic DEA with network structure: A slacks-based measure approach. *Omega* 2014, 42, 124–131. [CrossRef]
11. Niu, D.; Song, Z.; Xiao, X.; Wang, Y. Analysis of wind turbine micrositing efficiency: An application of two-subprocess data envelopment analysis method. *J. Clean. Prod.* 2018, 170, 193–204. [CrossRef]
12. Pérez-López, G.; Prior, D.; Zafría-Gómez, J.L. Temporal scale efficiency in DEA panel data estimations. An application to the solid waste disposal service in Spain. *Omega* 2018, 76, 18–27. [CrossRef]
13. Önnüt, S.; Suner, S. Energy efficiency assessment for the Antalya Region hotels in Turkey. *Energy Build.* 2006, 38, 964–971. [CrossRef]
14. Lee, W.-S. Benchmarking the energy efficiency of government buildings with data envelopment analysis. *Energy Build.* 2008, 40, 891–895. [CrossRef]
15. Lee, W.-S.; Lee, K.-P. Benchmarking the performance of building energy management using data envelopment analysis. *Appl. Therm. Eng.* 2009, 29, 3269–3273. [CrossRef]
16. Grösche, P. Measuring residential energy efficiency improvements with DEA. *J. Product. Anal.* 2009, 31, 87–94. [CrossRef]
17. Hui, S.; Wan, M. Study of hotel energy performance using data envelopment analysis. In Proceedings of the 12th International Conference on Sustainable Energy Technologies, Hong Kong, China, 26–29 August 2013.
18. Wang, E.; Shen, Z.; Alp, N.; Barry, N. Benchmarking energy performance of residential buildings using two-stage multifactor data envelopment analysis with degree-based simple-normalization approach. *Energy Convers. Manag.* 2015, 106, 530–542. [CrossRef]
19. Bian, Y.; Yang, F. Resource and environment efficiency analysis of provinces in China: A DEA approach based on Shannon’s entropy. *Energy Policy* 2010, 38, 1909–1917. [CrossRef]
20. Olanrewaju, O.; Jimoh, A.; Kholopane, P. Integrated IDA–ANN–DEA for assessment and optimization of energy consumption in industrial sectors. *Energy* 2012, 46, 629–635. [CrossRef]
21. Lee, S.K.; Mogi, G.; Hui, K.S. A fuzzy analytic hierarchy process (AHP)/data envelopment analysis (DEA) hybrid model for efficiently allocating energy R&D resources: In the case of energy technologies against high oil prices. *Renew. Sustain. Energy Rev.* 2013, 21, 347–355.
22. Zografidou, E.; Petridis, K.; Arabatzis, G.; Dey, P.K. Optimal design of the renewable energy map of Greece using weighted goal-programming and data envelopment analysis. *Comput. Oper. Res.* 2016, 66, 313–326. [CrossRef]
23. Kazemilari, M.; Mardani, A.; Streimikiene, D.; Zavodskas, E.K. An overview of renewable energy companies in stock exchange: Evidence from minimal spanning tree approach. *Renew. Energ.* 2017, 102, 107–117. [CrossRef]
24. Babazadeh, R.; Razmi, J.; Rabbani, M.; Pishvaee, M.S. An integrated data envelopment analysis–mathematical programming approach to strategic biodiesel supply chain network design problem. *J. Clean. Prod.* 2017, 147, 694–707. [CrossRef]
25. Lee, W.-S.; Lee, K.-P. Benchmarking the performance of building energy management using data envelopment analysis. In Proceedings of the 12th International Conference on Sustainable Energy Technologies, Hong Kong, China, 26–29 August 2013.
26. Mardani, A.; Jusoh, A.; Nor, K.M.D.; Khoshnoudi, M. Using fuzzy multiple criteria decision making techniques and their applications—A review of the literature from 2000 to 2014. *Econ. Res. Ekon. Istraz.* 2015, 28, 516–571.
27. Mardani, A.; Jusoh, A.; Nor, K.M.D.; Khoshnoudi, M. Using fuzzy multiple criteria decision making approaches for evaluating energy saving technologies and solutions in five star hotels: A new hierarchical framework. *Energy* 2016, 117, 131–148. [CrossRef]
28. Mardani, A.; Jusoh, A.; Nor, K.M.D.; Khoshnoudi, M. Using fuzzy multiple criteria decision making techniques in tourism and hospitality industry: A systematic review. *Transform. Bus. Econ.* 2016, 15, 192–213.
29. Mardani, A.; Jusoh, A.; Zavodskas, E.K.; Kazemilari, M.; Ahmad, U.N.U.; Khalifah, Z. Application of multiple criteria decision making techniques in tourism and hospitality industry: A systematic review. *Transform. Bus. Econ.* 2016, 15, 192–213.
30. Mardani, A.; Nilashi, M.; Zakuan, N.; Loganathan, N.; Soheilirad, S.; Saman, M.Z.M.; Ibrahim, O. A systematic review and meta-Analysis of SWARA and WASPAS methods: Theory and applications with recent fuzzy developments. *Appl. Soft Comput.* 2017, 57, 265–292. [CrossRef]
31. Mardani, A.; Jusoh, A.; Zavodskas, E.K.; Cavallaro, F.; Nilashi, M.; Jusoh, A.; Zare, H. Application of Structural Equation Modeling (SEM) to Solve Environmental Sustainability Problems: A Comprehensive Review and Meta-Analysis. *Sustainability* 2017, 9, 1814. [CrossRef]
32. Mardani, A.; Zavodskas, E.; Govindan, K.; Amat Senin, A.; Jusoh, A. VIKOR Technique: A Systematic Review of the State of the Art Literature on Methodologies and Applications. *Sustainability* 2016, 8, 37. [CrossRef]
35. Mardani, A.; Zavadskas, E.K.; Khalifah, Z.; Zakuan, N.; Jusoh, A.; Nor, K.M.; Khoshnoudi, M. A review of multi-criteria decision-making applications to solve energy management problems: Two decades from 1995 to 2015. Renew. Sustain. Energy Rev. 2017, 71, 216–256. [CrossRef]

36. Widya-Hasuti, A.; Mardani, A.; Streimikiene, D.; Sharifara, A.; Cavallaro, F. The Role of Process Innovation between Firm-Specific Capabilities and Sustainable Innovation in SMEs: Empirical Evidence from Indonesia. Sustainability 2018, 10, 2244. [CrossRef]

37. Soheilirad, S.; Govindan, K.; Mardani, A.; Zavadskas, E.K.; Nilashi, M.; Zakuan, N. Application of data envelopment analysis models in supply chain management: A systematic review and meta-analysis. Ann. Oper. Res. 2017, 1–55. [CrossRef]

38. Zare, M.; Pahl, C.; Rahnama, H.; Nilashi, M.; Mardani, A.; Ibrahim, O.; Ahmadi, H. Multi-criteria decision making approach in E-learning: A systematic review and classification. Appl. Soft Comput. 2016, 45, 108–128. [CrossRef]

39. Zavadskas, E.K.; Mardani, A.; Turskis, Z.; Jusoh, A.; Nor, K.M. Development of TOPSIS method to solve complicated decision-making problems: An overview on developments from 2000 to 2015. Int. J. Inf. Technol. Decis. Mak. 2016, 645–682, 645–682. [CrossRef]

40. Adler, N.; Friedman, L.; Sinuany-Stern, Z. Review of ranking methods in the data envelopment analysis context. Eur. J. Oper. Res. 2002, 140, 249–265. [CrossRef]

41. Emrouznejad, A.; Yang, G.-L. A survey and analysis of the first 40 years of scholarly literature in DEA: 1978–2016. Socioecon. Plan. Sci. 2018, 61, 4–8. [CrossRef]

42. Emrouznejad, A.; Parker, B.R.; Tavares, G. Evaluation of research in efficiency and productivity: A survey and analysis of the first 30 years of scholarly literature in DEA. Socioecon. Plan. Sci. 2008, 42, 151–157. [CrossRef]

43. Hatami-Marbini, A.; Emrouznejad, A.; Tavana, M. A taxonomy and review of the fuzzy data envelopment analysis literature: Two decades in the making. Eur. J. Oper. Res. 2011, 214, 457–472. [CrossRef]

44. Zhou, P.; Ang, B.W.; Poh, K.-L. A survey of data envelopment analysis in energy and environmental studies. Eur. J. Oper. Res. 2008, 189, 1–18. [CrossRef]

45. Liu, J.S.; Lu, L.Y.; Lu, W.-M.; Lin, B.J. Data envelopment analysis 1978–2010: A citation-based literature survey. Omega 2013, 41, 3–15. [CrossRef]

46. Cook, W.D.; Seiford, L.M. Data envelopment analysis (DEA)–Thirty years on. Eur. J. Oper. Res. 2009, 192, 1–17. [CrossRef]

47. Kuah, C.T.; Wong, K.Y.; Behrouzi, F. A Review on Data Envelopment Analysis (DEA). In Proceedings of the 2010 Fourth Asia International Conference on Mathematical/Analytical Modelling and Computer Simulation, Kota Kinabalu, Borneo, Malaysia, 26–28 May 2010; pp. 168–173.

48. Johnes, J. Data envelopment analysis and its application to the measurement of efficiency in higher education. Econ. Educ. Rev. 2006, 25, 273–288. [CrossRef]

49. Cooper, W.W.; Seiford, L.M.; Zhu, J. Data Envelopment Analysis: History, Models, and Interpretations. In Handbook on Data Envelopment Analysis; Cooper, W.W., Seiford, L.M., Zhu, J., Eds.; Springer: Boston, MA, USA, 2011; pp. 1–39.

50. Song, M.; An, Q.; Zhang, W.; Wang, Z.; Wu, J. Environmental efficiency evaluation based on data envelopment analysis: A review. Renew. Sustain. Energy Rev. 2012, 16, 4465–4469. [CrossRef]

51. Kao, C. Network data envelopment analysis: A review. Eur. J. Oper. Res. 2014, 239, 1–16. [CrossRef]

52. Charnes, A.; Cooper, W.W.; Rhodes, E. Measuring the efficiency of decision making units. Eur. J. Oper. Res. 1978, 2, 429–444. [CrossRef]

53. Banker, R.D.; Charnes, A.; Cooper, W.W. Some models for estimating technical and scale inefficiencies in data envelopment analysis. Manag. Sci. 1984, 30, 1078–1092. [CrossRef]

54. Doyle, J.; Green, R. Efficiency and cross-efficiency in DEA: Derivations, meanings and uses. Eur. J. Oper. Res. 1994, 45, 567–578.

55. Denyer, D.; Tranfield, D. Producing a systematic review. In The Sage Handbook of Organizational Research Methods; SAGE Publications Ltd.: Thousand Oaks, CA, USA, 2009; pp. 671–689.

56. Fang, H.; Wu, J.; Zeng, C. Comparative study on efficiency performance of listed coal mining companies in China and the US. Energy Policy 2009, 37, 5140–5148. [CrossRef]

57. Lin, B.; Du, K. Energy and CO2 emissions performance in China’s regional economies: Do market-oriented reforms matter? Energy Policy 2015, 78, 113–124. [CrossRef]
58. Wang, K.; Wei, Y.-M.; Zhang, X. A comparative analysis of China’s regional energy and emission performance: Which is the better way to deal with undesirable outputs? Energy Policy 2012, 46, 574–584. [CrossRef]
59. Iribarren, D.; Vázquez-Rowe, I.; Rugani, B.; Benetto, E. On the feasibility of using energy analysis as a source of benchmarking criteria through data envelopment analysis: A case study for wind energy. Energy 2014, 67, 527–537. [CrossRef]
60. Madlener, R.; Antunes, C.H.; Dias, L.C. Assessing the performance of biogas plants with multi-criteria and data envelopment analysis. Eur. J. Oper. Res. 2009, 197, 1084–1094. [CrossRef]
61. Lins, M.E.; Oliveira, L.B.; da Silva, A.C.M.; Rosa, L.P.; Pereira, A.O., Jr. Performance assessment of Alternative Energy Resources in Turkey by using data envelopment analysis. Energy Policy 2012, 16, 898–903. [CrossRef]
62. Liu, Y.; Ren, L.; Li, Y.; Zhao, X.G. The industrial performance of wind power industry in China. Renew. Sust. Energ. Rev. 2015, 43, 644–655. [CrossRef]
63. Hu, J.-L.; Kao, C.-H. Efficient energy-saving targets for APEC economies. Energy Policy 2007, 35, 373–382. [CrossRef]
64. Lee, Y.-C.; Hu, J.-L.; Kao, C.-H. Efficient saving targets of electricity and energy for regions in China. Int. J. Electr. Power Energy Syst. 2011, 33, 1211–1219. [CrossRef]
65. Song, M.; Yang, L.; Wu, J.; Lv, W. Energy saving in China: Analysis on the energy efficiency via bootstrap-DEA approach. Energy Policy 2013, 57, 1–6. [CrossRef]
66. Bian, Y.; He, P.; Xu, H. Estimation of potential energy saving and carbon dioxide emission reduction in China based on an extended non-radial DEA approach. Energy Policy 2013, 63, 962–971. [CrossRef]
67. Wu, J.; Lv, L.; Sun, J.; Ji, X. A comprehensive analysis of China’s regional energy saving and emission reduction efficiency: From production and treatment perspectives. Energy Policy 2015, 84, 166–176. [CrossRef]
68. Hu, J.-L.; Lio, M.-C.; Kao, C.-H.; Lin, Y.-L. Total-factor energy efficiency for regions in Taiwan. Energy Source Part B 2012, 7, 292–300. [CrossRef]
69. Mandal, S.K.; Madheswaran, S. Energy use efficiency of Indian cement companies: A data envelopment analysis. Hwa Zhong Power 2008, 36, 1023–1026.
70. Welch, E.; Barnum, D. Joint environmental and cost efficiency analysis of electricity generation. Ecol. Econ. 2009, 68, 2336–2343. [CrossRef]
71. Süzen, A.; Alp, I.; Özdemir, A. Assessment of operational and environmental performance of the thermal power plants in Turkey by using data envelopment analysis. Energy Policy 2010, 38, 6194–6203. [CrossRef]
72. Hoang, V.-N.; Alauddin, M. Input-orientated data envelopment analysis framework for measuring and decomposing economic, environmental and ecological efficiency: An application to OECD agriculture. Environ. Resour. Econ. 2012, 51, 431–452. [CrossRef]
73. Chang, D.-S.; Yeh, L.-T.; Liu, W. Incorporating the carbon footprint to measure industry context and energy consumption effect on environmental performance of business operations. Clean. Technol. Environ. 2014, 17, 359–371. [CrossRef]
74. Wang, Z.; Feng, C. A performance evaluation of the energy, environmental, and economic efficiency and productivity in China: An application of global data envelopment analysis. Appl. Energy 2015, 147, 617–626. [CrossRef]
75. Mohammadi, A.; Rafiee, S.; Jafari, A.; Keyhani, A.; Dalgaard, T.; Knudsen, M.T.; Nguyen, T.L.T.; Borek, R.; Hermansen, J.E. Joint Life Cycle Assessment and Data Envelopment Analysis for the benchmarking of environmental impacts in rice paddy production. J. Clean. Prod. 2015, 106, 521–532. [CrossRef]
76. Jan, P.; Dux, D.; Lips, M.; Alig, M.; Dumondel, M. On the link between economic and environmental performance of Swiss dairy farms of the alpine area. Int. J. Life Cycle Assess. 2012, 17, 706–719. [CrossRef]
77. Yeh, T.L.; Chen, T.Y.; Lai, P.Y. A comparative study of energy utilization efficiency between Taiwan and China. Energy Policy 2010, 38, 2386–2394. [CrossRef]
78. Shi, G.-M.; Bi, J.; Wang, J.-N. Chinese regional industrial energy efficiency evaluation based on a DEA model of fixing non-energy inputs. Energy Policy 2010, 38, 6172–6179. [CrossRef]
81. Wang, K.; Wei, Y.-M. China’s regional industrial energy efficiency and carbon emissions abatement costs. Appl. Energy 2014, 130, 617–631. [CrossRef]

82. Mousavi-Avval, S.H.; Rafiee, S.; Jafari, A.; Mohammadi, A. Improving energy use efficiency of canola production using data envelopment analysis (DEA) approach. Energy 2011, 36, 2765–2772. [CrossRef]

83. Khoshevisan, B.; Rafiee, S.; Omid, M.; Mousazadeh, H. Reduction of CO₂ emission by improving energy use efficiency of greenhouse cucumber production using DEA approach. Energy 2013, 55, 676–682. [CrossRef]

84. Nabavi-Pelesaraei, A.; Abdi, R.; Rafiee, S.; Mobtaker, H.G. Optimization of energy required and greenhouse gas emissions analysis for orange producers using data envelopment analysis approach. J. Clean. Prod. 2014, 65, 311–317. [CrossRef]

85. Ebrahimi, R.; Salehi, M. Investigation of CO₂ emission reduction and improving energy use efficiency of button mushroom production using Data Envelopment Analysis. J. Clean. Prod. 2015, 103, 112–119. [CrossRef]

86. Pang, R.Z.; Deng, Z.Q.; Hu, J.I. Clean energy use and total-factor efficiencies: An international comparison. Renew. Sust. Energy Rev. 2015, 52, 1158–1171. [CrossRef]

87. Banaeian, N.; Omid, M.; Ahmadi, H. Greenhouse strawberry production in Iran, efficient or inefficient in energy. Energy Effic. 2012, 5, 201–209. [CrossRef]

88. Ren, J.; Tan, S.; Dong, L.; Mazzi, A.; Scipioni, A.; Sovacool, B.K. Determining the life cycle energy efficiency of six biofuel systems in China: A Data Envelopment Analysis. Bioresour. Technol. 2014, 162, 1–7. [CrossRef] [PubMed]

89. Pardo Martínez, C.I.; Silveira, S. Analysis of energy use and CO₂ emission in service industries: Evidence from Sweden. Renew. Sustain. Energy Rev. 2012, 16, 5285–5294. [CrossRef]

90. Wang, J.; Zhao, T. Regional energy-environmental performance and investment strategy for China’s non-ferrous metals industry: A non-radial DEA based analysis. J. Clean. Prod. 2017, 163, 187–201. [CrossRef]

91. Han, Y.; Long, C.; Geng, Z.; Zhang, K. Carbon emission analysis and evaluation of industrial departments in China: An improved environmental DEA cross model based on information entropy. J. Environ. Manag. 2018, 205, 298–307. [CrossRef] [PubMed]

92. Geng, Z.; Dong, J.; Han, Y.; Zhu, Q. Energy and environment efficiency analysis based on an improved environment DEA cross-model: Case study of complex chemical processes. Appl. Energy 2017, 205, 465–476. [CrossRef]

93. Nabavi-Pelesaraei, A.; Rafiee, S.; Mohtasebi, S.S.; Hosseinzadeh-Bandbafha, H.; Chau, K.W. Energy consumption enhancement and environmental life cycle assessment in paddy production using optimization techniques. J. Clean. Prod. 2017, 155, 571–586. [CrossRef]

94. Chen, Y.; Han, Y.; Zhu, Q. Energy and environmental efficiency evaluation based on a novel data envelopment analysis: An application in petrochemical industries. Appl. Therm. Eng. 2017, 119, 156–164. [CrossRef]

95. Nazarko, J.; Chodakowska, E. Labour efficiency in construction industry in Europe based on frontier methods: Data envelopment analysis and stochastic frontier analysis. J. Civ. Eng. Manag. 2017, 23, 787–795. [CrossRef]

96. Nazarko, J.; Chodakowska, E. Measuring productivity of construction industry in EU with Data Envelopment Analysis. Procedia Eng. 2015, 122, 204–212. [CrossRef]

97. Zhou, D.; Meng, F.; Bai, Y.; Cai, S. Energy efficiency and congestion assessment with energy mix effect: The case of APEC countries. J. Clean. Prod. 2017, 142, 819–828. [CrossRef]

98. Toma, P.; Miglietta, P.P.; Zurlini, G.; Valente, D.; Petrosillo, L. A non-parametric bootstrap-data envelopment analysis approach for environmental policy planning and management of agricultural efficiency in EU countries. Ecol. Indic. 2017, 78, 132–143. [CrossRef]

99. Moutinho, V.; Madaleno, M.; Robaina, M. The economic and environmental efficiency assessment in EU cross-country: Evidence from DEA and quantile regression approach. Ecol. Indic. 2017, 78, 85–97. [CrossRef]

100. Kim, J.-R.; Jeon, E.-C.; Cho, S.; Kim, H. The Promotion of Environmental Management in the South Korean Health Sector—Case Study. Sustainability 2018, 10, 2081. [CrossRef]

101. Yu, S.-H.; Gao, Y.; Shiue, Y.-C. A Comprehensive Evaluation of Sustainable Development Ability and Pathway for Major Cities in China. Sustainability 2017, 9, 1483. [CrossRef]

102. Vlontzos, G.; Pardalos, P. Assess and prognosticate green house gas emissions from agricultural production of EU countries, by implementing, DEA Window analysis and artificial neural networks. Renew. Sust. Energy Rev. 2017, 76, 155–162. [CrossRef]
103. Chen, X.; Gao, Y.; An, Q.; Wang, Z.; Neralić, L. Energy efficiency measurement of Chinese Yangtze River Delta’s cities transportation: A DEA window analysis approach. Energ. Eff. 2018. [CrossRef]

104. Lin, S.; Sun, J.; Marinova, D.; Zhao, D. Evaluation of the green technology innovation efficiency of China’s manufacturing industries: DEA window analysis with ideal window width. Technol. Anal. Strateg. 2018, 1–16, 1–16. [CrossRef]

105. Chen, L.; Jia, G. Environmental efficiency analysis of China’s regional industry: A data envelopment analysis (DEA) based approach. J. Clean. Prod. 2017, 142, 846–853. [CrossRef]

106. Hu, X.; Liu, C. Slacks-based data envelopment analysis for eco-efficiency assessment in the Australian construction industry. Constr. Manag. Econ. 2017, 35, 693–706. [CrossRef]

107. Song, M.; Zheng, W. Computational analysis of thermoelectric enterprises’ environmental efficiency and Bayesian estimation of influence factors. Soc. Sci. J. 2016, 53, 88–99. [CrossRef]

108. Guo, X.; Zhu, Q.; Lv, L.; Chu, J.; Wu, J. Efficiency evaluation of regional energy saving and emission reduction in China: A modified slacks-based measure approach. J. Clean. Prod. 2017, 140, 1313–1321. [CrossRef]

109. Chu, J.-F.; Wu, J.; Song, M.-L. An SBM-DEA model with parallel computing design for environmental efficiency evaluation in the big data context: A transportation system application. Ann. Oper. Res. 2016. [CrossRef]

110. Li, N.; Liu, C.; Zha, D. Performance evaluation of Chinese photovoltaic companies with the input-oriented dynamic SBM model. Renew. Energ. 2016, 89, 489–497. [CrossRef]

111. Shin, J.; Kim, C.; Yang, H. The Effect of Sustainability as Innovation Objectives on Innovation Efficiency. Sustainability 2018, 10, 1966. [CrossRef]

112. Masuda, K. Energy Efficiency of Intensive Rice Production in Japan: An Application of Data Envelopment Analysis. Sustainability 2018, 10, 120. [CrossRef]

113. Wang, X.; Han, L.; Yin, L. Environmental Efficiency and Its Determinants for Manufacturing in China. Sustainability 2017, 9, 47. [CrossRef]

114. Gan, L.; Xu, D.; Hu, L.; Wang, L. Economic Feasibility Analysis for Renewable Energy Project Using an Integrated TPN–AHP–DEA Approach on the Basis of Consumer Utility. Energies 2017, 10, 2089. [CrossRef]

115. He, Y.; Liao, N.; Zhou, Y. Analysis on provincial industrial energy efficiency and its influencing factors in China based on DEA-RS-FANN. Energy 2018, 142, 79–89. [CrossRef]

116. Wang, X.; Li, Z.; Meng, H.; Wu, J. Identification of key energy efficiency drivers through global city benchmarking: A data driven approach. Appl. Energy 2017, 190, 18–28. [CrossRef]

117. Li, K.; Lin, B. An application of a double bootstrap to investigate the effects of technological progress on total-factor energy consumption performance in China. Energy 2017, 128, 575–585. [CrossRef]

118. Li, K.; Lin, B. Impact of energy conservation policies on the green productivity in China’s manufacturing sector: Evidence from a three-stage DEA model. Appl. Energy 2016, 168, 351–363. [CrossRef]

119. Zhou, D.; Wang, Q.; Su, B.; Zhou, P.; Yao, L. Industrial energy conservation and emission reduction performance in China: A city-level nonparametric analysis. Appl. Energy 2016, 166, 201–209. [CrossRef]

120. Duan, N.; Guo, J.-P.; Xie, B.-C. Is there a difference between the energy and CO2 emission performance for China’s thermal power industry? A bootstrapped directional distance function approach. Appl. Energy 2016, 162, 1552–1563. [CrossRef]

121. Yan, Q.; Wan, Y.; Yuan, J.; Yin, J.; Baležentis, T.; Streimikiene, D. Economic and Technical Efficiency of the Biomass Industry in China: A Network Data Envelopment Analysis Model Involving Externalities. Energies 2017, 10, 1418. [CrossRef]

122. Ramanathan, R.; Ramanathan, U.; Bentley, Y. The debate on flexibility of environmental regulations, innovation capabilities and financial performance—A novel use of DEA. Omega 2018, 75, 131–138. [CrossRef]

123. Suyeshi, T.; Wang, D. Measuring scale efficiency and returns to scale on large commercial rooftop photovoltaic systems in California. Energy Econ. 2017, 65, 389–398. [CrossRef]

124. Kourtit, K.; Suzuki, S.; Nijkamp, P. Tracing high-sustainability performers among world cities-design and application of a multi-temporal data envelopment analysis. Habitat. Int. 2017, 68, 43–54. [CrossRef]

125. Meng, S.; Zhou, W.; Chen, J.; Zhang, C. A synthesized data envelopment analysis model and its application in resource efficiency evaluation and dynamic trend analysis. Energy Environ. 2018, 29, 260–280. [CrossRef]

126. Vaninsky, A. Energy-environmental efficiency and optimal restructuring of the global economy. Energy 2018, 153, 338–348. [CrossRef]
127. Chen, Z.; Wanke, P.; Antunes, J.J.M.; Zhang, N. Chinese airline efficiency under \( CO_2 \) emissions and flight delays: A stochastic network DEA model. *Energy Econ.* 2017, 68, 89–108. [CrossRef]
128. Moon, H.; Min, D. Assessing energy efficiency and the related policy implications for energy-intensive firms in Korea: DEA approach. *Energy* 2017, 133, 23–34. [CrossRef]
129. Guo, X.; Lu, C.-C.; Lee, J.-H.; Chiu, Y.-H. Applying the dynamic DEA model to evaluate the energy efficiency of OECD countries and China. *Energy* 2017, 134, 392–399. [CrossRef]
130. Cui, Q.; Wei, Y.-M.; Li, Y. Exploring the impacts of the EU ETS emission limits on airline performance via the Dynamic Environmental DEA approach. *Appl. Energy* 2016, 183, 984–994. [CrossRef]
131. Cui, Q.; Li, Y.; Yu, C.-I.; Wei, Y.-M. Evaluating energy efficiency for airlines: An application of virtual frontier dynamic slacks based measure. *Energy* 2016, 113, 1231–1240. [CrossRef]
132. Zha, Y.; Zhao, L.; Bian, Y. Measuring regional efficiency of energy and carbon dioxide emissions in China: A slack-based DEA approach. *Comput. Oper. Res.* 2016, 66, 351–361. [CrossRef]
133. Wu, J.; Xiong, B.; An, Q.; Sun, J.; Wu, H. Total-factor energy efficiency evaluation of Chinese industry by using two-stage DEA model with shared inputs. *Ann. Oper. Res.* 2017, 255, 257–276. [CrossRef]
134. Guo, X.; Lu, C.-C.; Lee, J.-H.; Chiu, Y.-H. Applying the dynamic DEA model to evaluate the energy efficiency of OECD countries and China. *Energy* 2017, 134, 392–399. [CrossRef]
135. Ifitikhar, Y.; He, W.; Wang, Z. Energy and \( CO_2 \) emissions efficiency of major economies: A non-parametric analysis. *J. Clean. Prod.* 2016, 139, 779–787. [CrossRef]
136. Wu, J.; Yin, P.; Sun, J.; Chu, J.; Liang, L. Evaluating the environmental efficiency of a two-stage system with undesired outputs by a DEA approach: An interest preference perspective. *Eur. J. Oper. Res.* 2016, 254, 1047–1062. [CrossRef]
137. Huang, J.; Du, D.; Hao, Y. The driving forces of the change in China’s energy intensity: An empirical research using DEA-Malmquist and spatial panel estimations. *Econ. Model.* 2017, 65, 41–50. [CrossRef]
138. Olfat, I.; Amiri, M.; Soufi, J.B.; Pishdrad, M. A dynamic network efficiency measurement of airports performance considering sustainable development concept: A fuzzy dynamic network-DEA approach. *J. Air Transp. Manag.* 2016, 57, 272–290. [CrossRef]
139. Sueyoshi, T.; Yuan, Y. Social sustainability measured by intermediate approach for DEA environmental assessment: Chinese regional planning for economic development and pollution prevention. *Energy Econ.* 2017, 66, 154–166. [CrossRef]
140. Kang, D.; Lee, D.H. Energy and environment efficiency of industry and its productivity effect. *J. Clean. Prod.* 2016, 135, 184–193. [CrossRef]
141. Chen, W.; Liu, B.; Shen, Y.; Wang, X. The energy efficiency of China’s regional construction industry based on the three-stage DEA model and the DEA-DA model. *KSCE J. Civ. Eng.* 2016, 20, 34–47. [CrossRef]
142. Wang, J.; Zhao, T.; Zhang, X. Environmental assessment and investment strategies of provincial industrial sector in China—Analysis based on DEA model. *Environ. Impact Assess. Rev.* 2016, 60, 156–168. [CrossRef]
143. Chen, W.; Geng, W. Fossil energy saving and \( CO_2 \) emissions reduction performance, and dynamic change in performance considering renewable energy input. *Energy* 2017, 120, 283–292. [CrossRef]
144. Liu, X.; Wu, J. Energy and environmental efficiency analysis of China’s regional transportation sectors: A slack-based DEA approach. *Energy Syst.* 2017, 8, 747–759. [CrossRef]
145. Martinez, C.I.P.; Pina, W.H.A. Regional analysis across Colombian departments: A non-parametric study of energy use. *J. Clean. Prod.* 2016, 115, 130–138. [CrossRef]
146. Bostian, M.; Färe, R.; Grosskopf, S.; Lundgren, T. Environmental investment and firm performance: A network approach. *Energy Econ.* 2016, 57, 243–255. [CrossRef]
147. Shermeh, H.E.; Najafi, S.; Alavidoost, M. A novel fuzzy network SBM model for data envelopment analysis: A case study in Iran regional power companies. *Energy* 2016, 112, 686–697. [CrossRef]
148. Kwon, D.S.; Cho, J.H.; Sohn, S.Y. Comparison of technology efficiency for \( CO_2 \) emissions reduction among European countries based on DEA with decomposed factors. *J. Clean. Prod.* 2017, 151, 109–120. [CrossRef]
149. Song, T.; Yang, Z.; Chahine, T. Efficiency evaluation of material and energy flows, a case study of Chinese cities. *J. Clean. Prod.* 2016, 112, 3667–3675. [CrossRef]
150. Song, X.; Jiang, X.; Zhang, X.; Liu, J. Analysis, Evaluation and Optimization Strategy of China Thermal Power Enterprises’ Business Performance Considering Environmental Costs under the Background of Carbon Trading. *Sustainability* 2018, 10, 2006. [CrossRef]
151. Cheng, S.; Liu, W.; Lu, K. Economic Growth Effect and Optimal Carbon Emissions under China’s Carbon Emissions Reduction Policy: A Time Substitution DEA Approach. *Sustainability* 2018, 10, 1543. [CrossRef]

152. Wang, L.; Xue, X.; Shi, Y.; Wang, Z.; Ji, A. A Dynamic Analysis to Evaluate the Environmental Performance of Cities in China. *Sustainability* 2018, 10, 862. [CrossRef]

153. Zhang, A.; Li, A.; Gao, Y. Social Sustainability Assessment across Provinces in China: An Analysis of Combining Intermediate Approach with Data Envelopment Analysis (DEA) Window Analysis. *Sustainability* 2018, 10, 732. [CrossRef]

154. Vlontzos, G.; Niavis, S.; Pardalos, P. Testing for Environmental Kuznets Curve in the EU Agricultural Sector through an Eco-(in)Efficiency Index. *Energies* 2017, 10, 1992. [CrossRef]

155. Gong, Z.; Chen, X. Analysis of Interval Data Envelopment Efficiency Model Considering Different Distribution Characteristics—Based on Environmental Performance Evaluation of the Manufacturing Industry. *Sustainability* 2017, 9, 2080. [CrossRef]

156. Xiong, S.; Tian, Y.; Ji, J.; Ma, X. Allocation of Energy Consumption among Provinces in China: A Weighted ZSG-DEA Model. *Sustainability* 2017, 9, 2115. [CrossRef]

157. Liu, J.-P.; Yang, Q.-R.; He, L. Total-Factor Energy Efficiency (TFEE) Evaluation on Thermal Power Industry with DEA, Malmquist and Multiple Regression Techniques. *Energies* 2017, 10, 1039. [CrossRef]

158. Guerrini, A.; Romano, G.; Indipendenza, A. Energy Efficiency Drivers in Wastewater Treatment Plants: A Double Bootstrap DEA Analysis. *Sustainability* 2017, 9, 1126. [CrossRef]

159. Liu, J.; Long, Y.; Song, X. A Study on the Conduction Mechanism and Evaluation of the Comprehensive Efficiency of Photovoltaic Power Generation in China. *Energies* 2017, 10, 723.

160. Li, H.; Dong, K.; Sun, R.; Yu, J.; Xu, J. Sustainability Assessment of Refining Enterprises Using a DEA-Based Model. *Sustainability* 2017, 9, 620. [CrossRef]

161. Chen, X.; Gong, Z. DEA Efficiency of Energy Consumption in China’s Manufacturing Sectors with Environmental Regulation Policy Constraints. *Sustainability* 2017, 9, 210. [CrossRef]

162. Tsai, W.-H.; Lee, H.-L.; Yang, C.-H.; Huang, C.-C. Input-Output Analysis for Sustainability by Using DEA Method: A Comparison Study between European and Asian Countries. *Sustainability* 2016, 8, 1230. [CrossRef]

163. Li, G.; Huang, D.; Li, Y. China’s Input-Output Efficiency of Water-Energy-Food Nexus Based on the Data Envelopment Analysis (DEA) Model. *Sustainability* 2016, 8, 927. [CrossRef]

164. Zhang, Y.-J.; Chen, M.-Y. Evaluating the dynamic performance of energy portfolios: Empirical evidence from the DEA directional distance function. *Eur. J. Oper. Res.* 2018, 269, 64–78. [CrossRef]

165. Angulo-Meza, L.; González-Araya, M.; Iriarte, A.; Rebollo-Leiva, R.; de Mello, J.C.S. A multiobjective DEA model to assess the eco-efficiency of agricultural practices within the CF+ DEA method. *Comput. Electron. Agric.* 2018. [CrossRef]

166. Meng, D.; Shao, C.; Zhu, L. Ethylene cracking furnace TOPSIS energy efficiency evaluation method based on dynamic energy efficiency baselines. *Energy* 2018, 156, 620–634. [CrossRef]