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What Does Cost Structure Have to Say about Thermal Plant Energy Efficiency? The Case from Angola

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Abstract: This paper analyzes the efficiency of thermal power plants in Angola by means of a two-stage Data Envelopment Analysis (DEA) approach. In the first stage, a novel super-efficiency DEA model for undesirable outputs (CO_2 emission levels and discharge of polluted water) is initially used to measure their efficiency levels. Then, in the second stage, relevant cost structure variables frequently used to describe a productive technology are employed as analytical thresholds for assessing energy production performance either in terms of capital or labor-intensity levels. Precisely, bootstrapped regression trees are used to discriminate super-efficiency scores yielding an energy production performance predictive model based on the technology type as proxied by its cost structure and their respective thresholds, since Angolan thermal plants are heterogeneous. Findings suggest that Angolan power plants are old and labor intensive, as some of them date back to the colonial era, and that lack of capital investment should be revised in favor of installing carbon capture devices. The approach developed here consists of a valuable approach for identifying priorities when technologically updating a heterogeneous thermal industry to face pollutant concerns.

Keywords: thermal plants; DEA; super efficiency; cost structures; bootstrapped regression trees; Angola

1. Introduction

This research focuses on a relatively understudied topic in thermal plants, which is the relationship between its productive efficiency and cost structure in a developing country such as Angola, a former Portuguese colony and actually an important oil producer and exporter in Africa. Although the efficiency of thermal power plants at the machine or equipment level is a well-defined and parameterized research stream based on the laws of thermodynamics ([1,2], here we are interested in assessing the efficiency of thermal energy production at the industry level where different plants consist of the units of analysis and represent a reflex of how a set of individual equipment interacts with other factors such as labor, managerial style, capital, etc.

Despite several previous studies focus on power plant efficiency in developed countries, only a handful of them have addressed this issue in developing nations, despite their growing relevance with respect to energy generation [3,4]. Scant previous research on thermal power plant energetic efficiency has employed distinct methods, but the most common rely on non-parametric approaches such as Data Envelopment Analysis (DEA). See for instance [5] and [6] for comprehensive reviews on the subject. This research analyzes the technical efficiency of energy production in thermal plants located in Angola using a new super-efficiency DEA model to account for undesirable outputs. The major underlying idea is to assess whether cost structure variables are related to technical super-efficiency scores in thermal energy production, thus providing a means for describing how different technological patterns can be employed to control for the emission of undesirable outputs (pollutants) such as CO_2 emissions and discharged water. While scores are computed using a super-efficiency model, the cost structure variables are tested as efficiency thresholds in bootstrapped regression trees, thus allowing for the discrimination of different technological patterns in thermal energy production.

It is worth mentioning why the set of Angolan thermal power plants represents a controlled environment for conducting this search. First, these thermal power plants are all state owned and operate in a monopolistic market; therefore, the impact or influence of different managerial practices on efficiency scores and cost structures is quite limited. Additionally, these 32 plants were built over the course of more than forty years after Angola's independence from Portugal and therefore different production technologies used in thermal energy generation and their evolution are reflected within this set of plants.

Another distinctive aspect of this research concerns the analysis of the cost structure as a means to identify technological patterns and propose improvement paths within the ambit of an industry or sector. In fact, there is an emerging research stream that can be observed in a few efficiency studies on energy and infrastructure areas that tries to correlate efficiency levels to the cost structure of the productive process. Wang et al. [5], Lin and Yang [6], and Barros and Wanke [7] analyzed possible improvement paths for energy production efficiency in the thermal power industry based on cost structure variables. Wanke and Barros [8] conducted a similar analysis within the ambit of airport operations. All of these studies focused on the emerging economies of Asia and Africa where issues regarding a better balance between capital intensity and labor expenditure are deemed relevant to achieve higher productivity levels.

This paper contributes to the literature body on energy efficiency planning in three distinct ways. Firstly, and for the first time ever, this research unveils the relationships among capital, labor, pollutant emissions, and energy efficiency with generation thermal power plants. While using Angolan data, the results presented here can be generalized to other contexts since capital and labor cost structure variables are the key fundamentals for energy generation performance. Secondly, this paper adds to this beginning research stream by applying a novel super-efficiency DEA model for undesirable outputs altogether with statistical learning techniques such as bootstrapped regression trees, thus allowing to explore the impact of different productive technologies by proxying them to the cost structure. In fact, this is the first time that DEA and machine learning are complementarily used to explore productive technologies by means of their underlying labor and capital cost structure. Thirdly, this paper contributes to a more general research stream beyond energy generation by digging into the cost structure variables and the respective outcomes of the productive process. While technological patterns are most discussed when different energy sources are compared (e.g., thermal vs. hydro), a deeper analysis within each type is deemed necessary. In this research, the term productive technology describes the technical means by which fuel, labor, and capital are combined to produce thermal energy. While the concept of productive technology transcends the modeling of a functional relationship between inputs and outputs, some of their intrinsic structural concepts could be captured and related to each other such as efficiency and cost structure for decision-making purposes.

This text is structured in five more sections. Section 2 presents the background of thermal power plants in Angola, then Section 3 presents the literature review focusing on the previous efficiency studies on thermal power plants using non-parametric methods such as DEA and its variants as cornerstones. Section 4 presents the new super-efficiency DEA model capable of handling undesirable or bad outputs developed for this research. Section 5 presents the dataset used and the bootstrapped regression trees method, which are followed in Section 6 by the results and discussion. Section 7 makes some concluding remarks.

2. Background on Angolan Thermal Power Plants

This search for different technological patterns in thermal plant energy efficiency and their underlying impact on pollutant emissions is conducted in 32 Angolan thermal plants during the period from 2010 to 2016. It is worth mentioning why this set of plants represents a controlled environment for conducting this search. First of all, these thermal power plants are all state-owned and operate in a monopolistic market, therefore the impact or influence of different managerial practices on efficiency scores and cost structures is quite limited. Besides, these 32 plants have been built over the course of more than forty years since the independence of this country from Portugal. Therefore, different productive technologies used in thermal energy generation and their evolution are reflected within this set of plants.

Precisely, Angolan thermal power plants are state-owned facilities that burn fuel—oil, coal, and natural gas—assuring energy supply for domestic use. The charge of generating electricity has been given to a state firm, ENE-EP (Empresa Nacional de Electricidade—Empresa Pública), which controls energy production in every province of Angola. As regards the planning of thermal energy production, the required fuel resources and other technical capacity issues of each plant are decided in a centralized fashion by ENE-EP. However, another state company, EDEL-EP (Empresa de Distribuição de Electricidade—Empresa Pública), controls electricity distribution in Angola. Specifically in the Luanda region, power distribution is controlled by a subsidiary of EDEL created specifically for this purpose. This arrangement harkens to colonial times when the Portuguese government performed infrastructure planning, which was highly concentrated in the Luanda region.

In fact, the technological choices embedded in the construction of the thermal power plant industry in Angola over the course of the years yielded a unique cost structure that reflects the type of fuel burnt, the age of the plant along with its relatively small size, and the managerial style imposed by the state control. Older technologies, small-scaled operations, and state control are elements (as corroborated by the literature review in Section 3) that are often related to inefficient operations.

It is reasonable to expect that all these elements are not only reflected in the efficiency levels, but also in the different cost structure variables and ratios that characterize the productive technology in thermal plants such as capacity cost, labor and capital costs, besides cost–asset and capital–labor ratios. All these variables are analyzed in this study and are further discussed and operationalized in Section 4. Thus, this study seeks to identify the subset of cost structure variables and ratios that best explain efficiency levels and pollutant emissions in Angolan thermal plants.

3. Literature Review on Thermal Power Plant Efficiency

Thermal power plant efficiency is an emerging research area. More than 20 papers have been published over the course of 18 years with most being published from 2010 on. Not only are these papers characterized by a diversity of methodological approaches, although the non-parametric related DEA methods prevail, but also their research questions are very diverse. They range from efficiency comparison between different technologies or the evolution of efficiency levels over the course of time to the impact of regulatory issues and ownership, besides emerging trends as regards carbon dioxide emissions and other sustainability issues.

For example, seminal papers in the area encompass Park and Lesourd [9] who measured the performance of 64 fuel power plants in South Korea. Lam and Shiu [10] computed the efficiency of China's thermal power generation based on data for 1995 and 1996. Chien et al. [3] applied a DEA–Malmquist model to measure the efficiency of eight thermal power plants in Taiwan. Sarica and Or [11] analyzed and compared the performance of electricity generation plants in Turkey. Barros and Peypoch [12] analyzed the technical efficiency of Portuguese thermoelectric power generating plants with a two-stage procedure. Nakano and Managi [13] assessed efficiency in the Japanese steam-power sector and scrutinized the impact of reforms on the relative performance of its firms over the course of almost two decades. Sozen et al. [14] studied the performance of 11 lignite-fired, 1 coal-fired, and 3 natural gas-fired Turkish state companies using DEA. Liu et al. [15] assessed the efficiency levels of major thermal and combined cycle power plants in Taiwan for the period 2004–2006 using the DEA approach. Rezaee et al. [16] and Rezaee [17] presented a novel model based on game theory and DEA to measure efficiency of Iranian thermal power plants in light of diverse objectives. Shrivastava et al. [18] focused on the relative productivity of 60 Indian coal-fired plants by means of classic DEA models. Sueyoshi and Goto [19] used DEA to conduct an efficiency assessment of coal-fired plants in the US. Du and Mao [20] measured the environmental efficiency and costs related to carbon dioxide emissions in Chinese coal plants by means of a novel DEA model.

Recent papers still maintain this focus. Ghosh and Kathuria [21] investigated the impact of institutional quality typified as regulatory governance on the performance of thermal power plants in India. They estimated a translog stochastic frontier model using an index of state-level independent regulation as one of the determinants of inefficiency. Their findings show that technical efficiency is sensitive to both unbundling of state utilities and regulatory experience. Barros and Wanke [7] utilized a two-stage approach for efficiency evaluation in thermal power plants. First, a DEA Slacks Based Model (SBM) was employed to assess the relative efficiency of thermal power plants. In the second stage, beta regression models were combined with DEA-SBM efficiency scores to produce a model for predicting energy production performance. Yan et al. [22] evaluated the carbon emission efficiency using the Undesirable-SBM model and data from China's power industry in 30 provinces from 2003 to 2014. They performed a spatial autocorrelation analysis that is based on Moran's index to confirm the non-equilibrium spatial distribution of the carbon emission efficiency for the power industry. Wu et al. [23] employed an improved two-stage analysis model to analyze eco-efficiency of 58 Chinese coal-fired power plants. Firstly, the principal component analysis was selected for pre-treatment of variables in order to reduce dimensionality and distinguish prioritized factors. Secondly, the super-efficiency DEA was chosen to assess eco-efficiency with overall discriminatory rankings.

Table 1 presents a literature review synthesis of the previous studies on efficiency in thermal energy generation. These previous studies not only suggest that environmental issues are increasingly growing in importance over the years as more and more plants focus on reducing carbon dioxide emissions, but they also reveal that the production technology of each plant may be a relevant study field to understand efficiency in thermal energy generation. Precisely, plant age, fuel type, scale size, frontier shift, and catching-up effects appear to be the descriptors used the most in previous papers of the technological patterns that lie within thermal energy generation. Besides, ownership and regulatory impacts are also relevant issues addressed by some of these researches undertaken in different countries worldwide, especially in Asia and Europe, while research on African countries is still negligible. Besides, although the use of non-parametric methods such as DEA and SBM (Slacks Based Model) prevail, it is worth noting that the use of super-efficiency models is still scarce and focused on addressing environmental impacts (Wu et al., [23]).

Therefore, this research fills a literature gap by not only addressing the issue of thermal energy production efficiency in an important African country, but also by proposing a novel super-efficiency model to better discriminate efficiency scores in a sector where productivity variations are subtle, especially within the ambit of the Angolan state-owned plants, as discussed in Section 2. Additionally, the review synthesized in Table 1 also sheds some light, by contrast, on the nature of the contributions of this paper since most previous studies did not consider the impact of cost structure to diagnose technological patterns and their relationship with efficiency levels and pollutant emissions (Barros and Wanke, [7]). Some of them, however, use fuel prices to trace their impact on eco-efficiency levels (Wu et al., [23]). In fact, the joint use of super-efficiency DEA models and bootstrapped regression trees is an additional innovative feature of this research when compared to previous research described in Table 1 since for the first time statistical learning methods are employed in the second stage of analysis when efficiency scores are usually correlated or regressed onto contextual variables.

Hence, the distinctive aspect of the current research in comparison to the other previous researches is the joint use of novel super-efficiency models and statistical learning techniques to unveil the relationship between cost structure (as a proxy of the productive technology) and efficiency levels in thermal power plant energy generation. As explored in Section 5.2., statistical learning methods constitute a useful approach for unveiling hidden relationships between efficiency scores and cost structure variables, as long as they do not rely on the traditional parametric assumptions found in the typical regression approach (Tobit, truncated bootstrapped regression, beta, and Generalized Method of Moments (GMM), cf. Table 1), yielding higher analytical flexibility and explanatory power.

Table 1. Literature review synthesis.

Author (Year)	Country	Sample Size	Methods
Park and Lesourd [9]	South Korea	64 fuel power plants	DEA and Stochastic-Frontier
Lam and Shiu [10]	China	Thermal Power Generation in 30 provinces, autonomous regions, and municipalities	DEA and Tobit Regression
Chien et al. [3]	Taiwan	8 thermal power plants	DEA–Malmquist
Sarica and Or [3]	Turkey	65 thermal, hydro, and wind power plants	Constant returns to scale (CRS) DEA, variable returns to scale (VRS) DEA, and Assurance region DEA
Barros and Peypoch [11]	Portugal	7 thermoelectric plants data from 1996 to 2004	DEA and Simar and Wilson bootstrapped procedure
Nakano and Managi [13]	Japan	10 local monopoly companies data from 1965 to 2003	DEA, Luenberger productivity indicator and Generalized Method of Moments (GMM) estimation
Sozen et al. [14]	Turkey	15 thermal power plants	CRS DEA and VRS DEA
Liu et al. [15]	Taiwan	9 thermal power plants	DEA
Rezaee et al. [16]	Iran	24 power plants	DEA and game theory
See and Coelli [24]	Malaysia	14 thermal plants	Stochastic Frontier Analysis (SFA)
Shrivastava et al. [18]	India	60 coal-fired power plants	CRS (Constant Returns-to-Scale) DEA and VRS (Variable Returns-to-Scale) DEA
Sueyoshi and Goto [19]	United States	20 U.S. coal-fired power plants	Non-radial DEA model
Wang et al. [5]	China	30 thermal power	DEA, Malmquist–Luenberger productivity index
Lin and Yang [6]	China	Power industry for 31 provinces from 2005 to 2010	Slacks-Based Measure (SBM) in dynamic DEA model
Rezaee [17]	Iran	20 power plants	Shapley value and multiobjective DEA
Du and Mao [20]	China	1158 power plants data	Parametric Linear Programing
Munisamy and Arabi [25]	Iran	48 thermal power plants	SBM, Malmquist–Luenberger index
Ghosh and Kathuria [21]	India	77 coal-based thermal power plants	SFA
Barros and Wanke [7]	Angola	32 Angolan thermal power plants from 2010 to 2014	SBM-Undesirable and Beta regression
Yan et al. [22]	China	Power industry in 30 provinces	SBM-Undesirable, Malmquist index
Wu et al. [23]	China	58 coal-fired power plants	Super Efficiency DEA, Kruskal–Wallis rank, Tobit regression
Xie et al. [2]	China	Thermal power plants in 30 provinces	Nonparametric weighted Russell directional distance method
Mahmoudi et al. [26]	Iran	52 thermal power plants	Multivariate data analysis techniques, game theory, and Shannon entropy combined with DEA
Wei and Zhang [27]	China	93 coal-fired power plants	Partial parametric environmental production frontier

4. The Proposed Super-Efficiency DEA Model with Undesirable Outputs

A comprehensive review of previous studies shows that most DEA applications have considered primary cross sectional data and evaluated relative efficiencies in a single period, usually one year (Emrouznejad and Yang, [28]; Fernández et al., [29]). Exceptions are found in window analyses (Charnes et al., [30]) and other models based on the Malmquist productivity index (Färe and Grosskopf, [31]; Yao et al., [4]). Looking beyond the inherent differences between these models, we posit that their main objective is to address the changing patterns of efficiency scores along distinct time periods. While these approaches may be useful for decision making, they do not take into account an aggregated measure of efficiency that represents and provides a synthesis of multiperiod productive systems.

In this sense, a clear exception is found within the ambit of dynamic DEA models. Nemoto and Goto [32]s proposed a dynamic DEA model to assess the overall efficiency of a multiperiod production system. This overall efficiency can be viewed as price or economic efficiency. However, even in a particular period, the assumption of exact costs of individual inputs is unrealistic (Thompson et al., [33]). Moreover, the true monetary value (or exact discount factor) of an input in the time horizon remains unknown in practice (for more details see Jahanshahloo et al., [34]; Silva and Stefanou, [35]; Soleimani-damaneh, [36]).

Here, in this paper, we focused on Multiperiod Data Envelopment Analysis (MDEA) in which the aggregative efficiency in the context of time serial data is measured. Any previous information on prices or input and output weights across multiple periods are required. Hence, a Multiperiod Aggregative Efficiency (MAE) that corresponds conceptually to a technical (but not price or economic) efficiency of multiperiod production units can be delivered. This multiperiod technical efficiency, economic-free, is deemed necessary to proxy in an unbiased way for the technological pattern of a thermal plant over the course of time in terms of its cost structure, which is treated here in the ambit of the contextual variable set.

Besides, a distinctive feature of the model here developed is regards super-efficiency. The super-efficiency concept is traditionally a method used in DEA to break the ties between fully efficient units. Putting it into other words, the super-efficiency approach is an alternative to make a better discrimination for each Decision Making Unit (DMU). Suppose we have n DMUs and there are L periods, $t = 1, 2, \ldots, L$, and in each period DMU_j, $j = 1, 2, \ldots, n$, consume m inputs, x^t_{ij}, $i = 1, 2, \ldots, m$, to produce s outputs, y^t_{rj}, $r = 1, 2, \ldots, s$. In order to compute the multiperiod aggregative efficiency, abbreviated as MAE in the context of time serial data, Sam Park and Park [37] proposed a two-phase DEA model (PP-model). The phase-I of the PP-model related to DMU_o $(o \in \{1, 2, \ldots, n\})$ is as follows:

$$
\begin{aligned}
&\text{Phase } (I) \max \psi_o \\
&\text{s.t.} \sum_{j=1}^{n} \mu^t_j y^t_{rj} \geq \psi_o y^t_{ro} \quad r = 1, 2, \ldots, s \quad t = 1, 2, \ldots, L \\
&\sum_{j=1}^{n} \mu^t_j x^t_{ij} \leq x^t_{io} \quad i = 1, 2, \ldots, m \quad t = 1, 2, \ldots, L \\
&\mu^t_j \geq 0, \; j = 1, 2, \ldots, n \quad t = 1, 2, \ldots, L
\end{aligned}
\tag{1}
$$

Indeed, the above model is an aggregated output-oriented CCR model that evaluates DMU_o within all L periods simultaneously [38]. Let $\psi_o{}^*$ be the optimal value of Equation (1), if $\psi_o{}^* = 1$ we say DMU_o is weakly efficient. The following model is solved in phase-II of the PP-model.

$$\begin{aligned}
&\text{Phase } (II) \text{ max} \sum\nolimits_{t=1}^{L} \sum\nolimits_{r=1}^{s} s_r^{+t} + \sum\nolimits_{t=1}^{L} \sum\nolimits_{i=1}^{m} s_i^{-t} \\
&\text{s.t.} \sum\nolimits_{j=1}^{n} \mu_j^t y_{rj}^t - s_r^{+t} = \psi_o{}^* y_{ro}^t \quad r = 1,2,\ldots,s \quad t = 1,2,\ldots,L \\
&\sum_{j=1}^{n} \mu_j^t x_{ij}^t + s_i^{-t} = x_{io}^t, \quad i = 1,2,\ldots,m, \quad t = 1,2,\ldots,L \\
&\mu_j^t \geq 0, \quad j = 1,2,\ldots,n, \quad t = 1,2,\ldots,L \\
&s_r^{+t} \geq 0, \quad r = 1,2,\ldots,s, \quad t = 1,2,\ldots,L \\
&s_i^{-t} \geq 0, \quad i = 1,2,\ldots,m, \quad t = 1,2,\ldots,L
\end{aligned} \tag{2}$$

Generally there is more than one DMU with $\psi_o{}^* = 1$ per Equation (1); therefore, it is necessary to propose a ranking model to rank efficient DMUs. In this study inspired by the AP-model (Andersen and Petersen, [39]) in which DMU_o is removed from the production possibility set, Equations (1) and (2) are converted to the following models, respectively.

$$\begin{aligned}
&\text{Phase } (I) \text{ max } \psi_o \\
&\text{s.t.} \sum_{j=1, j\neq o}^{n} \mu_j^t y_{rj}^t \geq \psi_o y_{ro}^t \qquad r = 1,2,\ldots,s \qquad t = 1,2,\ldots,L \\
&\sum_{j=1, j\neq o}^{n} \mu_j^t x_{ij}^t \leq x_{io}^t \quad i = 1,2,\ldots,m \; t = 1,2,\ldots,L \\
&\mu_j^t \geq 0 \; \forall j \neq o \; = 1,2,\ldots,L
\end{aligned} \tag{3}$$

$$\begin{aligned}
&\text{Phase } (II) \text{ max} \sum_{t=1}^{L} \sum_{r=1}^{s} s_r^{+t} + \sum_{t=1}^{L} \sum_{i=1}^{m} s_i^{-t} \\
&\text{s.t.} \sum\nolimits_{j=1, j\neq o}^{n} \mu_j^t y_{rj}^t - s_r^{+t} = \psi_o{}^* y_{ro}^t \; r = 1,2,\ldots,s \; t = 1,2,\ldots,L \\
&\sum_{j=1, j\neq o}^{n} \mu_j^t x_{ij}^t + s_i^{-t} = x_{io}^t \; i = 1,2,\ldots,m \; t = 1,2,\ldots,L \\
&\mu_j^t \geq 0 \; \forall j \neq o \; t = 1,2,\ldots,L \\
&s_r^{+t} \geq 0 \; r = 1,2,\ldots,s \; t = 1,2,\ldots,L \\
&s_i^{-t} \geq 0 \; i = 1,2,\ldots,m \; t = 1,2,\ldots,L
\end{aligned} \tag{4}$$

The drawback of the above models is that they consider an overall efficiency score for each DMU, whereas the behavior of a DMU may change from one period to another. Consequently, it is reasonable to consider a different efficiency score for each time period; therefore, the following models are proposed.

$$\text{Phase }(I)\ \ \max\ \Psi_o = \frac{1}{\mathrm{L}}\sum_{t=1}^{L}\psi_o^t$$
$$\begin{aligned} \text{s.t.} \sum_{j=1, j\neq o}^{n} \mu_j^t y_{rj}^t &\geq \psi_o^t y_{ro}^t \quad r = 1,2,\ldots,s \quad t = 1,2,\ldots,L \\ \sum_{j=1, j\neq o}^{n} \mu_j^t x_{ij}^t &\leq x_{io}^t \quad i = 1,2,\ldots,m \quad t = 1,2,\ldots,L \\ \mu_j^t &\geq 0 \quad \forall j \neq o \quad t = 1,2,\ldots,L \end{aligned} \tag{5}$$

$$\text{Phase }(II)\ \ \max\ \xi_o = \sum_{t=1}^{L}\sum_{r=1}^{s} s_r^{+t} + \sum_{t=1}^{L}\sum_{i=1}^{m} s_i^{-t}$$
$$\begin{aligned} \text{s.t.} \textstyle\sum_{j=1, j\neq o}^{n} \mu_j^t y_{rj}^t - s_r^{+t} &= \psi_o^{*t} y_{ro}^t \quad r = 1,2,\ldots,s \quad t = 1,2,\ldots,L \\ \sum_{j=1, j\neq o}^{n} \mu_j^t x_{ij}^t + s_i^{-t} &= x_{io}^t \quad i = 1,2,\ldots,m \quad t = 1,2,\ldots,L \\ \mu_j^t &\geq 0 \quad \forall j \neq o \quad t = 1,2,\ldots,L \\ s_r^{+t} &\geq 0 \quad r = 1,2,\ldots,s \quad t = 1,2,\ldots,L \\ s_i^{-t} &\geq 0 \quad i = 1,2,\ldots,m \quad t = 1,2,\ldots,L \end{aligned} \tag{6}$$

Here ψ_o^t represents the efficiency score of DMU_o in t-th, $t = 1,2,\ldots,L$, period. The objective function of Equation (5) is the average efficiency of DMU_o within all L periods. The advantage of Equation (5) is that not only does it maximize the average efficiency of DMU_o, it also computes the ψ_o^t. The objective of Equation (6) is to find a solution that maximizes the sum of input excesses and output shortfalls while keeping $\psi_o^t = \psi_o^{*t}$. Let $\xi_o{}^*$ be the optimal value of Equation (6), then we have the following definitions.

Definition 1. *DMU_o is called efficient if $\Psi_o^* \leq 1$ and $\max\limits_{1\leq t\leq L}\left\{\psi_o^{*t}\right\} \leq 1$. If $\Psi_o^* > 1$ or $\max\limits_{1\leq t\leq L}\left\{\psi_o^{*t}\right\} > 1$, we say DMU_o is inefficient.*

Definition 2. *DMU_o is called weakly efficient if $\Psi_o^* = 1$ and $\xi_o{}^* \neq 0$.*

Conventional DEA models rely on the assumption that outputs have to be maximized. However, it was mentioned already in the literature that the production process might also produce undesirable outputs (Mariano et al., [40]; Ozkan and Ulutas, [41]; Scheel, [42]). In Equation (1), the outputs of the DMUs are all desirable outputs and Equation (1) cannot be applied when some of the outputs are undesirable. Now, assume that each $\mathrm{DMU_j}$ uses m inputs to produce s desirable outputs and k undesirable outputs. The inputs, desirable outputs, and undesirable outputs of each DMU_j, $j = 1,2,\ldots,n$ in period t are defined as x_{ij}^t, $i = 1,2,\ldots,m$, y_{rj}^{gt}, $r = 1,2,\ldots,s$, and y_{pj}^{bt}, $p = 1,2,\ldots,k$, respectively. Similar to Seiford and Zhu [43] and Hadi-Vencheh et al. [44], we assume strong disposability of the undesirable outputs. The data of the undesirable outputs are then transformed using the following Equation (7).

$$\widehat{y_p^{bt}} = -y_p^{bt} + w_p^t > 0,\ p = 1,2,\ldots,k,\ t = 1,2,\ldots,L \tag{7}$$

In Equation (7), w^t is a positive vector for period t, which can be used to let all the negative undesirable outputs be positive. Considering the transformed data, Equations (5) and (6) are converted to Equations (8) and (9), respectively.

$$
\begin{aligned}
&\text{Phase } (I) \ \max \ \Psi_o = \frac{1}{\text{L}} \sum_{t=1}^{L} \psi_o^t \\
&\text{s.t.} \sum_{j=1, j \neq o}^{n} \mu_j^t y_{rj}^t \geq \psi_o^t y_{ro}^t \quad r = 1, 2, \ldots, s \quad t = 1, 2, \ldots, L \\
&\sum_{j=1, j \neq o}^{n} \mu_j^t x_{ij}^t \leq x_{io}^t \quad i = 1, 2, \ldots, m \quad t = 1, 2, \ldots, L \\
&\sum_{j=1, j \neq o}^{n} \mu_j^t \widehat{y_{pj}^{bt}} \leq \widehat{y_{po}^{bt}} \quad p = 1, 2, \ldots, k \quad t = 1, 2, \ldots, L \\
&\mu_j^t \geq 0 \quad \forall j \neq o \quad t = 1, 2, \ldots, L
\end{aligned} \tag{8}
$$

$$
\begin{aligned}
&\text{Phase } (II) \ \max \ \xi_o = \sum_{t=1}^{L} \sum_{r=1}^{s} s_r^{+gt} + \sum_{t=1}^{L} \sum_{p=1}^{k} s_p^{-bt} + \sum_{t=1}^{L} \sum_{i=1}^{m} s_i^{-t} \\
&\text{s.t.} \quad \sum\nolimits_{j=1, j \neq o}^{n} \mu_j^t y_{rj}^t - s_r^{+gt} = \psi_o^{*t} y_{ro}^t \quad r = 1, 2, \ldots, s \quad t = 1, 2, \ldots, L \\
&\sum_{j=1, j \neq o}^{n} \mu_j^t x_{ij}^t + s_i^{-t} = x_{io}^t \quad i = 1, 2, \ldots, m \quad t = 1, 2, \ldots, L \\
&\sum_{j=1, j \neq o}^{n} \mu_j^t \widehat{y_{pj}^{bt}} + s_p^{-bt} = \widehat{y_{po}^{bt}} \quad p = 1, 2, \ldots, k \quad t = 1, 2, \ldots, L \\
&\mu_j^t \geq 0 \quad \forall j \neq o \quad t = 1, 2, \ldots, L \\
&s_r^{+gt} \geq 0 \quad r = 1, 2, \ldots, s \quad t = 1, 2, \ldots, L \\
&s_p^{-bt} \geq 0 \quad p = 1, 2, \ldots, k \quad t = 1, 2, \ldots, L \\
&s_i^{-t} \geq 0 \quad i = 1, 2, \ldots, m \quad t = 1, 2, \ldots, L
\end{aligned} \tag{9}
$$

As can be seen from (8) and (9), the undesirable outputs of the DMUs are considered as inputs when evaluating the performance of the DMUs.

As regards the model fitting the Angolan thermal plant industry analyzed here, it is worth noting the justification for some methodological choices with respect to the returns-to-scale assumption, the model productive orientation, and the strong disposability of pollutant assumption. First, a constant returns-to-scale assumption was adopted here because when compared to international standards, even the largest Angolan plant is small when compared to their USA, UE, or even South African counterparts. Besides, as shown by results analyzed and discussed in Section 5, these thermal plants are labor intensive and in such cases the returns-to-scale effect tends to be behave mostly linearly with respect to the number of employees. Second, an output orientation was chosen due to the socioeconomic characteristics of the country and, why not, for the African region as a whole since energy shortages are frequent and interruptions in energy supply cannot be sourced by alternative transmission lines given that transmission networks within Angola and between African countries barely exist. Third, a strong disposability of undesirable pollutants was considered as an adequate assumption due to the existence of technological devices for reducing CO_2 emissions and water discharges without affecting energy production levels.

5. Data and Bootstrapped Regression Trees

5.1. Data

Data for 2010–2016 encompassing the operation of 32 Angolan thermal plants were obtained from ENE-EP. The inputs of these thermal plants are those commonly used in previous papers and encompassed, besides the costs of investment, fuel, and labor, the productive capacity and the number of employees. It is worth mentioning that productive capacity was adopted here to proxy a relevant resource constraint, thus modeling that energy production cannot be indefinitely expanded in the short and medium terms. In fact, productive capacity is considered here as a fixed input required to produce energy despite severe limitations with respect to its short/medium term variations.

As regards the outputs, energy production is used as the sole desirable output, while on the other hand carbon dioxide emissions and discharged polluted water are considered as the undesirable outputs. It is worth mentioning that, due to a lack of completeness of the dataset, fuel costs had to be estimated as a proportion of the investment costs and the labor costs, observing accepted technical standards (for a conventional coal power plant, capital costs lie around 65%, whereas fuels costs are about 30% (EIA, [45,46]). For conventional gas power plants, capital costs are about 32%, whereas fuels costs are about 61% (EIA, [45,46])). For modern combined cycle gas power plants, the capital costs are 23% and fuel costs increase to over 70% with labor costs tending to be negligible (EIA, [45,46])). Table 2 presents their descriptive statistics and the respective dataset used is given in Appendix A.

Table 2. Descriptive statistics for the sample.

	Variables	Min	Max	Mean	SD
Inputs	Plant capacity in MW	5	70	21.533	16.663
	Investment costs * (log)	10.608	21.945	15.6845	2.3792
	Employee costs per year * (log)	2.657	2.801	2.73681	0.0332
	Fuel costs per year * (log)	6.664	43.891	11.0235	7.3653
	Number of employees	15	69	31.613	13.671
Outputs	Production in 1000 MWh	10	117	35.292	24.206
	Carbon dioxide emissions in tons per year	0.940	2.720	1.989	0.251
	Discharge of polluted water in liters per year	1,018.64	1,898.21	1,190.07	136.460
Trend	Trend	1	7	3.987	2.005
	Trend squared	1	49	19.916	16.407
Cost Structure	Capital–labor ratio	−1.700	11.408	2.257	1.923
	Capacity cost per MW	0.290	4.430	1.571	0.959
	Labor cost per employee	0.230	0.996	0.576	0.226
	Capital cost	0.510	1	0.721	0.089
	Cost–asset ratio	−2.420	12.058	4.237	2.869

* Investment costs, employee costs per year, and fuel costs per year were originally measured in current Kwanzas and subsequently converted to 2016 USD.

In addition, a number of contextual variables are used to proxy the productive technology. They are also described in Table 2 and involve major cost structure elements. These variables are fourfold: the capacity cost per MW (calculated as the ratio of the logarithms between the total cost of the plant and its productive capacity), the labor cost per employee (calculated as the ratio of the logarithms between total salaries paid and number of employees), the capital cost (calculated as the ratio of the logarithms between amortizations and total assets), and the cost–asset ratio (calculated as the ratio of the logarithms between total costs and total assets). Lastly, the capital–labor ratio is calculated as the ratio of the logarithms between total assets and total salaries paid to employees. It is also important to mention that principles of accrual accounting were adopted here to compute the capital cost as the amortizations to total assets ratio. In fact, amortization, depreciation, and depletion are methods that are used to prorate the cost of a specific type of asset over the asset's life. This prorated cost yields, therefore, an accounting proxy for the capital cost.

5.2. Bootstrapped Regression Trees

Tree methods were first used by researchers [2,47,48] and have gained popularity through the major theoretical and practical contributions of Breiman et al. [5]. They involve stratifying and segmenting the predictor space into a number of simple regions (James et al., [49]). These features are particularly useful since (a) efficiency scores reflect uncertainty derived not only from vagueness in input/output collection and (b) explanatory variables may be endogenous or exogenous. Readers should refer to Faraway [2], Opitz and Maclin [50], Polikar [51], and Torgo [52] on how to resample (ensemble) trees using bagging.

Bagging ("bootstrapping aggregation") is a bootstrap ensemble method introduced by Breiman [53] and combines predictors across different subsets of the training data. The R functions used to perform such bootstrapped regression tree analysis and their respective default values used for the analysis are presented in Table 3 (Ledolter, [54]).

Table 3. R packages and respective default values for bootstrapped regression trees.

Method	R Library	R Function	Values
RF-CART	randomForest	randomForest	x, where x represents a data frame or matrix of predictors, y = NULL, xtest = NULL, ytest = NULL, ntree = 500, mtry = max(floor(ncol(x)/3), 1), replace = TRUE, classwt = NULL, sampsize = nrow(x), nodesize = 5, maxnodes = NULL, importance = FALSE, localImp = FALSE, nPerm = 1, norm.votes = TRUE, do.trace = FALSE, keep.forest = TRUE, corr.bias = FALSE, keep.inbag = FALSE
CART	tree	Tree	na.action = na.pass, method = "recursive.partition", split = c("deviance", "gini"), model = FALSE, x = FALSE, y = TRUE, wts = TRUE, mincut = 5, minsize = 10, mindev = 0.01

6. Results and Discussion

The levels of super-efficiency computed for the Angolan thermal power plant sample using the proposed super-efficiency model for undesirable outputs are presented in Figures 1–4. The full rank of DMU scores is given in Appendix B. Readers should recall that a DMU is considered efficient (inefficient) if super-efficiency scores are below (above) 1. If super-efficiency score is exactly 1, the DMU is classified as weakly efficient. As displayed in Figure 1, pooled efficiency scores are strongly concentrated around 1 and inefficiency prevails in Angolan thermal power plants. Super-efficiency levels also appear to be stagnant over the course of the years, as suggested by Figure 2, even though a slight decrease in efficiency is seen from 2014 on. Although this stagnant behavior may be justified by the fact that Angola thermal power generation plants are publicly owned and controlled by ENE-EP, a state company (cf. Section 2), the wide dispersion of super-efficiency scores suggest that inefficiency may be driven by different technological patterns in thermal energy production reflected in cost-structure variables, and that they may also impact the emission of pollutants. Based on the literature review, the evidence implies that the smaller, older, and coal thermal plants are less efficient and more polluting than the larger, newer plants that burn gas. The former would, therefore, be located above one in Figure 1 while the latter below one. One is the super-efficiency threshold that divides efficient from non-efficient plants.

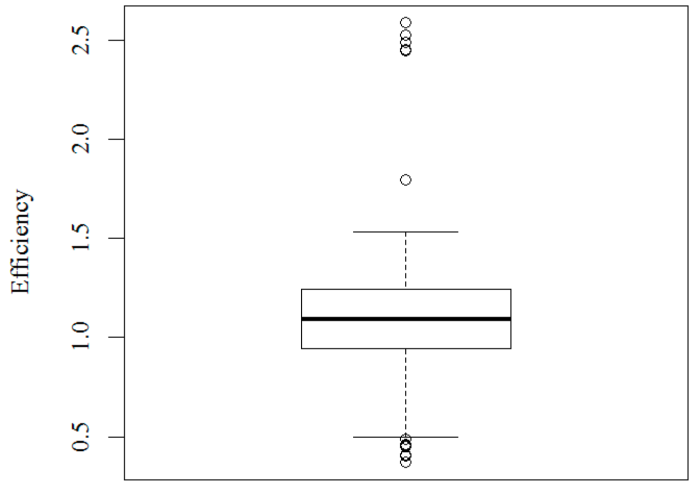

Figure 1. Pooled super-efficiency scores boxplot.

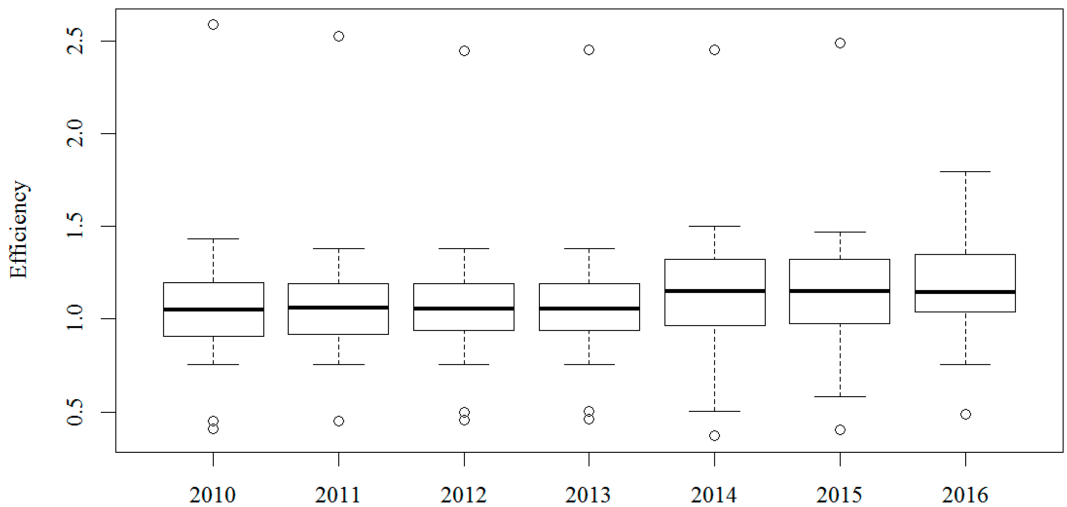

Figure 2. Distribution of the super efficiency scores per year.

Figure 3 presents a scatterplot panel of efficiency levels against the two undesirable outputs. As expected, super-efficiency scores fluctuate around 1, although not symmetrically. Readers should recall that inefficient plants present scores higher than 1.0 and that a score of 0.6, for instance, indicates a less efficient plant than another one with a score of 0.5. Figure 3 reveals that inefficient thermal power plants tended to emit more CO_2, although this direct relationship did not appear to be so strong in terms of polluted water. In fact, the following results could be observed when comparing the groups between efficient and inefficient plants. While the efficient plants present a CO_2 emission level that was 1.08% lower than those observed in the inefficient plants, the discharge of polluted water between both groups presented even a smaller variation (around 0.33% less).

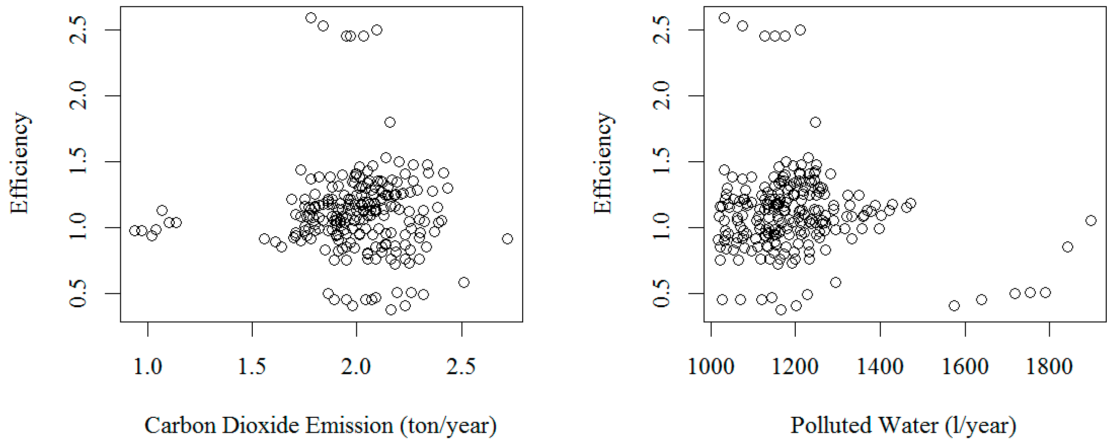

Figure 3. Scatter plots for super-efficiency levels and pollutant emissions.

Similarly, Figure 4 also presents a scatterplot panel of efficiency levels, but now against cost structure variables. Figure 4 clearly shows that inefficient energy generation prevailed when Angolan thermal plants presented a lower KL ratio, meaning that they are labor intensive, and had a higher cost–asset ratio, which means that they have higher operating costs in comparison to the value of their assets. As regards the lower KL ratios, the state-controlled operation of Angolan thermal plants may explain the excessive number of highly paid employees in relation to the size/scale of the plant. On the other hand, higher cost–asset ratios may reflect the operation of older, smaller, poorly maintained plants. With this cost structure in mind, the adoption of costly technologies for controlling CO_2 emissions may be enhanced by opportunities that emerge from rebalancing KL and cost–asset ratios. This is necessary because adopting carbon capture devices would certainly increase the cost to asset ratio. Therefore, labor expenses should be rightsized first in order to open room in cost expenditure before adopting such an antipollutant measure.

Firstly, an adequate equilibrium between a rightsized labor force and the intensity of capital seems to be the cornerstone for improving efficiency levels while simultaneously controlling the discharge of undesirable outputs as a byproduct of the energy generation process. The drop in oil prices imposed strong budgetary restrictions upon the Angolan economy causing the classical conflict between labor and capital to increase with respect to scarce resource allocation. Secondly, with respect to the capital investments required for controlling carbon dioxide emissions, it is deemed necessary to apprehend how economically feasible these investments are for a thermal plant and how they impact relevant ratios such as the capital–labor and the cost–asset ratios. As a matter of fact, thermal energy generation is one of the biggest causers of the greenhouse effect on a worldwide basis. Except for CO_2, all other emissions from a thermal plant can be mitigated with the technology available at a feasible cost (http://www.brighthubengineering.com/power-plants/57788-power-plant-emissions/). This happens because carbon dioxide is an unavoidable part of the thermal generation process. Therefore, systems for capturing carbon dioxide emissions consists of a costly alternative for reducing pollutant emissions in the context of the investments required for building up and/or renovating a thermal plant (U.S. Department of Energy (DOE) and U.S. National Energy Technology Laboratory (NETL). 2010. DOE/NETL Carbon Dioxide Capture and Storage RD&D Roadmap. http://www.netl.doe.gov/File%20Library/Research/Carbon%20Seq/Reference%20Shelf/CCSRoadmap.pdf), but they are often economically feasible in newer plants.

These results are confirmed by the bootstrapped regression trees presented in Figures 5 and 6. While Figure 5 depicts the bootstrapped regression tree structure and its thresholds at each tree node, Figure 6 shows the most impacting variables in terms of overall increase in the Mean Squared Errors (MSE). The interpretation of a regression tree is very straightforward in terms of allowing the decision-maker to segment the results. For example, the first branch of the tree presented in Figure 5 states that "if labor cost is lower than 0.33 and capacity cost is lower than 0.80, and KL ratio is lower than 1.37, then the average plant efficiency is 0.962 (almost weak-efficient)". The other branches read similarly. Both figures suggest that capacity cost and labor cost are the most impacting variables on Angolan thermal power plant efficiency.

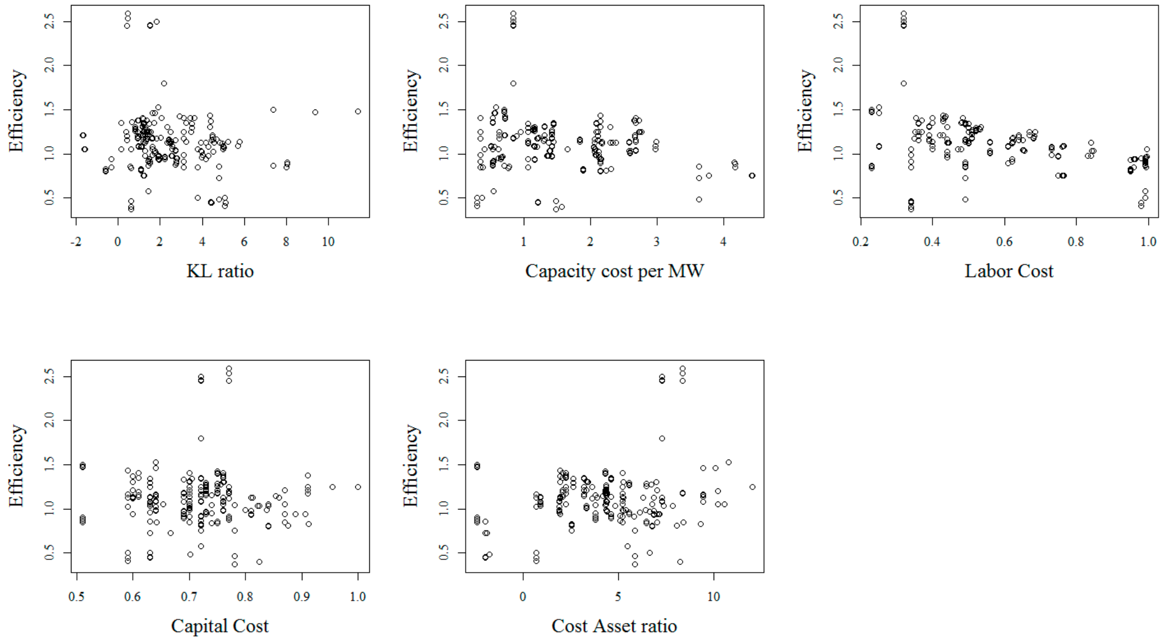

Figure 4. Scatter plots for super-efficiency levels and cost structure variables.

Policy implications for Angolan thermal plants suggest the need for a better training of the workforce, downsizing of personnel in order to keep labor costs under control, and investing in carbon capture equipment. Since it is expensive and impacts the plant's capacity cost, such equipment can be acquired by rebalancing the KL equilibrium in Angolan plants so that total operating costs are kept under control. There are, however, technological limits to adopting such measures, which are revealed by the capital cost. Lower values of capacity cost, often related to older amortized plants, may present physical constraints to the deployment of newer carbon capture technologies. In such cases, efficiency improvements may be confined to the traditional conversion from diesel to combined cycle gas, which has already occurred in some Angolan thermal plants.

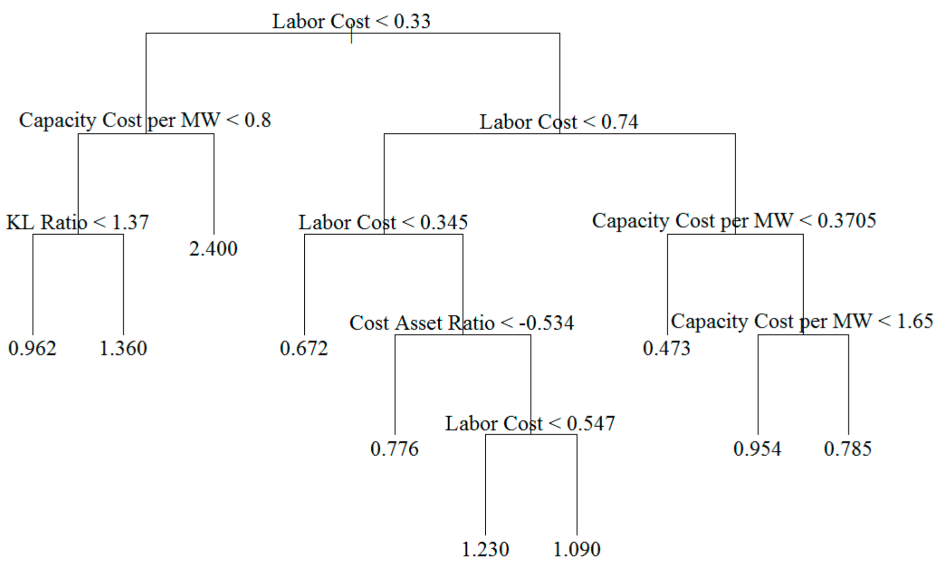

Figure 5. Bootstrapped regression tree thresholds.

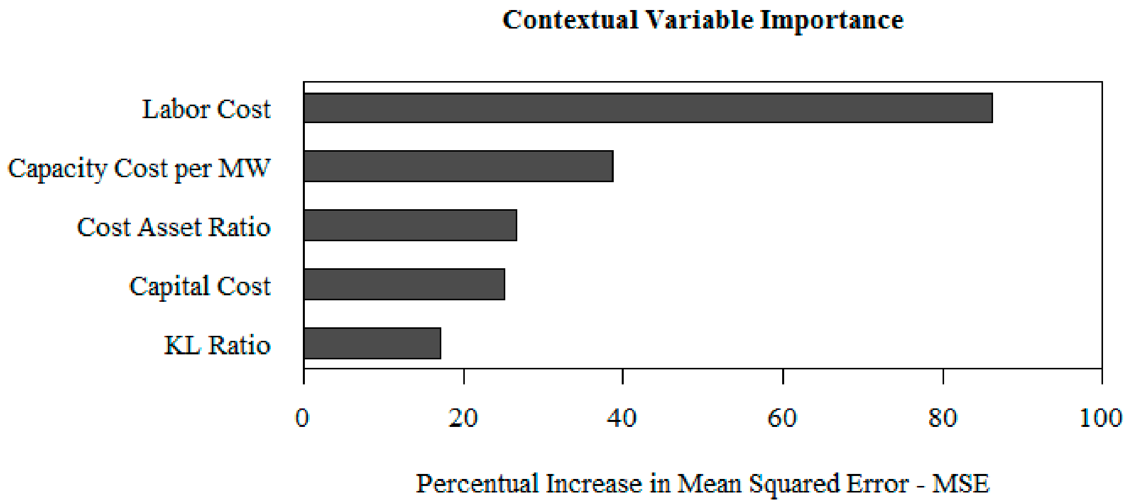

Figure 6. Relative importance of the cost structure variables for efficiency generation in thermal plants.

7. Conclusions

This research assessed the thermal plants in Angola in terms of their energetic efficiency by jointly applying a novel super-efficiency DEA model that handles undesirable outputs and bootstrapped regression trees that discriminate productive technologies based on cost structure variables. This novel super-efficiency model makes it possible to capture subtle productivity variations in a state-owned industry where managerial practices tend to be quite similar over the course of time. This paper gives insights on how the technological patterns or productive technologies of thermal energy generation are reflected in the cost structure variables of each plant by means of efficiency levels, which constitutes a relatively novel approach not only in the energy efficiency strand, but also on infrastructure efficiency.

Efficiency levels were computed based on three outputs (energy production, carbon dioxide emissions, and discharged polluted water) and on five inputs (fuel, investment, labor costs, plant capacity, and number of employees). The findings suggest that efficiency levels of fuel consumption and undesirable emissions included are mostly affected by the capacity cost and the labor cost, which are the reflex of rightsizing and training the workforce in parallel with adopting expensive carbon capture devices. Specifically with respect to the pattern of pollutant emissions/discharges, CO_2 emissions appear to be more impacted by the technological pattern of the power plant than the level of discharged polluted water, which may suggest that carbon capture technologies have evolved and can be deployed faster than technologies for recycling water in the energy generation productive processes.

Limitations of this research are related to the very nature of case studies built on the evidence of single countries. Although these results cannot be generalized to other countries with different regulatory regimes, some useful lessons for conducting similar research in other countries have been learned. It may be advisable to focus on capital, labor, and operating expenses and their countervailing forces while seeking opportunities for adopting antipollutant technologies. Further research should confirm these results in other environments.

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Appendix A. Angolan Thermal Plants Dataset

DMU	Year	Energy Production (MWh)	CO_2 Emission (Tons Per Year)	Polluted Water (Liters Per Year)	Capacity (MW)	Number of Employees	Employee Cost Per Year (Log)	Fuel Cost Per Year (Log)	Investment Cost (Log)	KL Ratio (Log)	Capacity Cost per MW (Log)	Labor Cost Per Year (Log)	Capital Cost Per Year (Log)	Cost–Asset Ratio (Log)	Fuel_Type
Central Termica de Xitoto Novo	2016	106.000	2.000	1232.614	70.000	45.000	2.768	9.714	16.660	3.100	0.340	0.354	0.700	5.230	Diesel
Central Termica de Xitoto Antigo	2016	10.000	2.412	1245.006	8.000	40.000	2.773	7.901	13.030	3.630	2.670	0.400	0.610	2.070	Diesel
Central Termica do Aeroporto	2016	10.000	2.392	1270.162	8.000	23.000	2.714	10.156	17.597	2.730	2.676	0.656	0.822	4.838	Diesel
Central Termica de Arimba	2016	40.600	2.372	1257.516	35.000	15.000	2.704	9.962	17.221	2.200	0.674	0.996	0.730	6.664	Diesel
Central Termica de Anexo SE	2016	30.000	2.432	1254.758	20.000	30.000	2.774	10.241	17.709	0.790	1.162	0.534	0.762	6.982	Diesel
Central Termica de Kileva	2016	45.600	2.338	1250.716	30.000	69.000	2.764	6.737	10.710	11.408	0.700	0.230	0.510	−2.420	Diesel
Central Termical do Lobito	2016	20.000	2.318	1228.670	5.000	31.000	2.721	7.713	12.706	4.810	3.620	0.490	0.702	−1.748	Diesel
Central Termica de Biopio	2016	117.000	2.296	1238.282	15.000	46.000	2.750	12.128	21.506	0.630	1.648	0.340	0.870	10.592	Diesel
Central Termica do Cunene	2016	15.000	2.296	1234.144	5.000	20.000	2.729	8.151	13.572	1.180	3.770	0.766	0.720	2.540	Diesel
Central Termica Do Kuando Kubango	2016	30.000	2.256	1270.162	10.000	16.000	2.721	11.894	21.067	−0.590	2.310	0.950	0.912	9.340	Diesel
Central Termica do Benfica	2016	50.400	2.232	1282.926	35.000	34.000	2.801	8.449	14.098	1.154	0.530	0.484	0.760	2.250	Diesel
Central Termica do Cuito	2016	10.000	2.212	1268.818	7.000	42.000	2.743	11.039	19.334	1.566	2.762	0.370	1.000	2.250	Diesel
Central Termica do Moxico	2016	40.000	2.176	1250.726	30.000	23.000	2.759	12.352	21.945	0.920	0.950	0.686	0.770	12.058	Diesel
Central Termica de Cazenga	2016	40.000	2.156	1246.388	30.000	50.000	2.773	41.401	17.928	2.160	0.830	0.320	0.720	7.280	Combined Cycle Gas
Central Termica do Caminho de Ferro de Luanda	2016	96.800	2.136	1231.272	50.000	65.000	2.788	10.674	18.560	1.902	0.580	0.250	0.640	10.784	Diesel
Central Termica do Morro Bento	2016	30.000	2.112	1232.224	15.000	32.000	2.752	9.152	15.552	1.210	1.440	0.490	0.720	4.630	Diesel
Central Termica do Morro da Luz	2016	34.800	2.092	1245.008	10.000	25.000	2.747	7.872	12.996	5.770	2.166	0.624	0.600	1.940	Diesel
Central Termica KM9	2016	15.000	2.092	1246.398	10.000	35.000	2.748	11.582	20.416	2.330	2.374	0.446	0.860	7.300	Diesel
Central Termica Benfica	2016	20.000	1.136	1247.778	17.000	18.000	2.723	11.272	19.821	1.270	1.388	0.846	0.840	7.850	Diesel
Central Termica Praia do Bispo	2016	35.000	2.074	1249.168	20.000	15.000	2.671	10.939	19.207	−0.330	1.060	0.964	0.906	7.162	Diesel
Central Termica dos Quarteis	2016	30.000	2.052	1246.548	30.000	37.000	2.781	9.445	16.110	2.936	0.716	0.436	0.750	4.340	Diesel
Central Termica Boavista I	2016	32.000	2.252	1255.880	15.000	30.000	2.728	9.084	15.440	1.380	1.410	0.510	0.730	4.356	Diesel
Central Termica Boavista II	2016	20.000	2.192	1237.996	10.000	45.000	2.785	8.881	14.976	1.704	2.080	0.360	0.720	3.180	Diesel
Central Termica Boavista III	2016	22.600	2.148	1259.340	16.000	42.000	2.796	8.700	14.605	1.160	1.304	0.390	0.700	3.404	Diesel
Central Termica Kassaki	2016	10.000	2.128	1290.828	8.000	28.000	2.752	7.878	13.003	5.214	2.580	0.560	0.630	0.930	Diesel
Central Termica CEEF	2016	15.000	2.106	1396.924	10.000	20.000	2.681	10.064	17.447	1.640	2.082	0.730	0.838	6.434	Diesel
Central Termica do Bengo	2016	32.200	2.086	1472.140	18.000	25.000	2.747	8.937	15.128	2.008	1.218	0.624	0.690	4.418	Diesel
Central Termica do Uige	2016	20.000	2.128	1402.332	15.000	20.000	2.727	8.179	13.632	5.710	1.420	0.764	0.640	1.890	Diesel
Central Termica Banza Congo	2016	20.000	2.086	1368.170	10.000	35.000	2.734	7.444	12.154	4.820	2.060	0.440	0.590	0.680	Diesel
Central Termica Soyo	2016	110.600	2.402	1898.212	70.000	15.000	2.704	42.215	18.404	3.760	0.402	0.996	0.654	10.232	Combined Cycle Gas
Central Termica Landana	2016	30.200	2.386	1462.912	20.000	30.000	2.708	10.406	18.105	2.490	1.060	0.500	0.854	4.204	Diesel
Central Termica Malongo	2016	45.000	2.720	1333.350	40.000	15.000	2.698	9.183	15.667	1.420	0.544	0.990	0.720	5.854	Diesel
Central Termica de Xitoto Novo	2015	93.000	1.940	1197.222	70.000	45.000	2.763	9.711	16.660	3.100	0.340	0.352	0.700	5.230	Diesel
Central Termica de Xitoto Antigo	2015	10.000	2.341	1209.258	8.000	40.000	2.773	7.901	13.030	3.430	2.670	0.400	0.610	2.070	Diesel
Central Termica do Aeroporto	2015	10.000	2.321	1233.691	8.000	23.000	2.709	9.705	16.701	2.730	2.673	0.653	0.781	4.319	Diesel
Central Termica de Arimba	2015	40.300	2.301	1221.408	35.000	15.000	2.701	9.808	16.914	2.200	0.662	0.993	0.730	6.127	Diesel
Central Termica de Anexo SE	2015	30.000	2.361	1218.729	20.000	30.000	2.770	10.124	17.479	0.790	1.156	0.532	0.756	6.721	Diesel
Central Termica de Kileva	2015	42.800	2.269	1214.803	30.000	69.000	2.764	6.737	10.710	9.384	0.700	0.230	0.510	-2.420	Diesel
Central Termical do Lobito	2015	20.000	2.249	1193.390	5.000	31.000	2.721	7.388	12.055	4.810	3.620	0.490	0.666	-1.874	Diesel
Central Termica de Biopio	2015	103.500	2.228	1202.726	15.000	46.000	2.750	11.052	19.354	0.630	1.564	0.340	0.825	8.231	Diesel

DMU	Year	Energy Production (MWh)	CO_2 Emission (Tons Per Year)	Polluted Water (Liters Per Year)	Capacity (MW)	Number of Employees	Employee Cost Per Year (Log)	Fuel Cost Per Year (Log)	Investment Cost (Log)	KL Ratio (Log)	Capacity Cost per MW (Log)	Labor Cost Per Year (Log)	Capital Cost Per Year (Log)	Cost–Asset Ratio (Log)	Fuel_Type
Central Termica do Cunene	2015	15.000	2.228	1198.707	5.000	20.000	2.725	8.149	13.572	1.180	3.770	0.763	0.720	2.540	Diesel
Central Termica Do Kuando Kubango	2015	30.000	2.188	1233.691	10.000	16.000	2.721	11.128	19.535	-0.590	2.230	0.950	0.876	8.065	Diesel
Central Termica do Benfica	2015	45.200	2.166	1246.088	35.000	34.000	2.797	8.447	14.098	0.642	0.530	0.482	0.760	2.250	Diesel
Central Termica do Cuito	2015	10.000	2.146	1232.384	7.000	42.000	2.743	10.534	18.324	1.453	2.741	0.370	0.955	2.250	Diesel
Central Termica do Moxico	2015	40.000	2.113	1214.813	30.000	23.000	2.754	11.657	20.559	0.920	0.890	0.683	0.770	10.219	Diesel
Central Termica de Cazenga	2015	40.000	2.093	1210.599	30.000	50.000	2.773	41.401	17.928	1.840	0.830	0.320	0.720	7.280	Combined Cycle Gas
Central Termica do Caminho de Ferro de Luanda	2015	88.400	2.073	1195.916	50.000	65.000	2.788	10.434	18.080	1.756	0.565	0.250	0.640	10.127	Diesel
Central Termica do Morro Bento	2015	30.000	2.051	1196.842	15.000	32.000	2.752	8.990	15.228	1.210	1.440	0.490	0.705	4.630	Diesel
Central Termica do Morro da Luz	2015	32.400	2.031	1209.259	10.000	25.000	2.744	7.861	12.978	4.970	2.163	0.622	0.600	1.940	Diesel
Central Termica KPM9	2015	15.000	2.031	1210.609	10.000	35.000	2.741	10.815	18.889	2.330	2.332	0.443	0.810	6.295	Diesel
Central Termica Benfica	2015	20.000	1.103	1211.949	17.000	18.000	2.720	11.030	19.340	1.270	1.379	0.843	0.825	7.370	Diesel
Central Termica Praia do Bispo	2015	35.000	2.012	1213.299	20.000	15.000	2.669	10.747	18.826	-0.330	1.060	0.962	0.888	7.111	Diesel
Central Termica dos Quarteis	2015	30.000	1.991	1210.754	30.000	37.000	2.774	9.408	16.043	2.073	0.713	0.433	0.750	4.340	Diesel
Central Termica Boavista I	2015	31.000	2.186	1219.820	15.000	30.000	2.728	9.084	15.440	1.380	1.410	0.510	0.730	4.353	Diesel
Central Termica Boavista II	2015	20.000	2.126	1202.448	10.000	45.000	2.785	8.881	14.976	1.462	2.080	0.360	0.720	3.180	Diesel
Central Termica Boavista III	2015	21.300	2.084	1223.180	16.000	42.000	2.796	8.689	14.582	1.160	1.302	0.390	0.700	3.362	Diesel
Central Termica Kassaki	2015	10.000	2.064	1253.764	8.000	28.000	2.752	7.878	13.003	4.567	2.580	0.560	0.630	0.930	Diesel
Central Termica CEEF	2015	15.000	2.043	1356.812	10.000	20.000	2.681	9.634	16.587	1.640	2.076	0.730	0.799	5.402	Diesel
Central Termica do Bengo	2015	31.100	2.023	1429.870	18.000	25.000	2.744	8.849	14.954	1.814	1.204	0.622	0.690	4.409	Diesel
Central Termica do Uige	2015	20.000	2.064	1362.066	15.000	20.000	2.724	8.178	13.632	5.000	1.420	0.762	0.640	1.890	Diesel
Central Termica Banza Congo	2015	20.000	2.023	1328.885	10.000	35.000	2.734	7.444	12.154	4.665	2.060	0.440	0.590	0.680	Diesel
Central Termica Soyo	2015	100.300	2.331	1843.706	70.000	15.000	2.701	39.646	17.122	3.760	0.381	0.993	0.642	8.441	Combined Cycle Gas
Central Termica Landana	2015	30.100	2.318	1420.906	20.000	30.000	2.708	9.961	17.214	2.490	1.060	0.500	0.812	3.907	Diesel
Central Termica Malongo	2015	45.000	2.510	1295.065	40.000	15.000	2.698	9.154	15.610	1.420	0.542	0.990	0.720	5.467	Diesel
Central Termica de Xitoto Novo	2014	80.000	1.880	1161.830	70.000	45.000	2.757	9.708	16.660	3.100	0.340	0.350	0.700	5.230	Diesel
Central Termica de Xitoto Antigo	2014	10.000	2.270	1173.510	8.000	40.000	2.773	7.901	13.030	3.230	2.670	0.400	0.610	2.070	Diesel
Central Termica do Aeroporto	2014	10.000	2.250	1197.220	8.000	23.000	2.705	9.256	15.806	2.730	2.670	0.650	0.740	3.800	Diesel
Central Termica de Arimba	2014	40.000	2.230	1185.300	35.000	15.000	2.698	9.653	16.608	2.200	0.650	0.990	0.730	5.590	Diesel
Central Termica de Anexo SE	2014	30.000	2.290	1182.700	20.000	30.000	2.766	10.008	17.250	0.790	1.150	0.530	0.750	6.460	Diesel
Central Termica de Kileva	2014	40.000	2.200	1178.890	30.000	69.000	2.764	6.737	10.710	7.360	0.700	0.230	0.510	-2.420	Diesel
Central Termical do Lobito	2014	20.000	2.180	1158.110	5.000	31.000	2.721	7.062	11.403	4.810	3.620	0.490	0.630	-2.000	Diesel
Central Termica de Biopio	2014	90.000	2.160	1167.170	15.000	46.000	2.750	10.033	17.316	0.630	1.480	0.340	0.780	5.870	Diesel
Central Termica do Cunene	2014	15.000	2.160	1163.270	5.000	20.000	2.721	8.147	13.572	1.180	3.770	0.760	0.720	2.540	Diesel
Central Termica Do Kuando Kubango	2014	30.000	2.120	1197.220	10.000	16.000	2.721	10.391	18.060	-0.590	2.150	0.950	0.840	6.790	Diesel
Central Termica do Benfica	2014	40.000	2.100	109.250	35.000	34.000	2.792	8.445	14.098	0.130	0.530	0.480	0.760	2.250	Diesel
Central Termica do Cuito	2014	10.000	2.080	195.950	7.000	42.000	2.743	10.035	17.326	1.340	2.720	0.370	0.910	2.250	Diesel
Central Termica do Moxico	2014	40.000	2.050	1178.900	30.000	23.000	2.750	10.961	19.173	0.920	0.830	0.680	0.770	8.380	Diesel
Central Termica de Cazenga	2014	40.000	2.030	1174.810	30.000	50.000	2.773	41.401	17.928	1.520	0.830	0.320	0.720	7.280	Combined Cycle Gas
Central Termica do Caminho de Ferro de Luanda	2014	80.000	2.010	1160.560	50.000	65.000	2.788	10.194	17.600	1.610	0.550	0.250	0.640	9.470	Diesel
Central Termica do Morro Bento	2014	30.000	1.990	1161.460	15.000	32.000	2.752	8.828	14.904	1.210	1.440	0.490	0.690	4.630	Diesel

DMU	Year	Energy Production (MWh)	CO_2 Emission (Tons Per Year)	Polluted Water (Liters Per Year)	Capacity (MW)	Number of Employees	Employee Cost Per Year (Log)	Fuel Cost Per Year (Log)	Investment Cost (Log)	KL Ratio (Log)	Capacity Cost per MW (Log)	Labor Cost Per Year (Log)	Capital Cost Per Year (Log)	Cost–Asset Ratio (Log)	Fuel_Type
Central Termica do Morro da Luz	2014	30.000	1.970	1173.510	10.000	25.000	2.741	7.850	12.960	4.170	2.160	0.620	0.600	1.940	Diesel
Central Termica KM9	2014	15.000	1.970	1174.820	10.000	35.000	2.734	10.069	17.404	2.330	2.290	0.440	0.760	5.290	Diesel
Central Termica Benfica	2014	20.000	1.070	1176.120	17.000	18.000	2.716	10.790	18.865	1.270	1.370	0.840	0.810	6.890	Diesel
Central Termica Praia do Bispo	2014	35.000	1.950	1177.430	20.000	15.000	2.667	10.556	18.444	-0.330	1.060	0.960	0.870	7.060	Diesel
Central Termica dos Quarteis	2014	30.000	1.930	1174.960	30.000	37.000	2.767	9.371	15.975	1.210	0.710	0.430	0.750	4.340	Diesel
Central Termica Boavista I	2014	30.000	2.120	1183.760	15.000	30.000	2.728	9.084	15.440	1.380	1.410	0.510	0.730	4.350	Diesel
Central Termica Boavista II	2014	20.000	2.060	1166.900	10.000	45.000	2.785	8.881	14.976	1.220	2.080	0.360	0.720	3.180	Diesel
Central Termica Boavista III	2014	20.000	2.020	1187.020	16.000	42.000	2.796	8.678	14.560	1.160	1.300	0.390	0.700	3.320	Diesel
Central Termica Kassaki	2014	10.000	2.000	1216.700	8.000	28.000	2.752	7.878	13.003	3.920	2.580	0.560	0.630	0.930	Diesel
Central Termica CEEF	2014	15.000	1.980	1316.700	10.000	20.000	2.681	9.207	15.732	1.640	2.070	0.730	0.760	4.370	Diesel
Central Termica do Bengo	2014	30.000	1.960	1387.600	18.000	25.000	2.741	8.760	14.780	1.620	1.190	0.620	0.690	4.400	Diesel
Central Termica do Uige	2014	20.000	2.000	1321.800	15.000	20.000	2.721	8.177	13.632	4.290	1.420	0.760	0.640	1.890	Diesel
Central Termica Banza Congo	2014	20.000	1.960	1289.600	10.000	35.000	2.734	7.444	12.154	4.510	2.060	0.440	0.590	0.680	Diesel
Central Termica Soyo	2014	90.000	2.260	1789.200	70.000	15.000	2.698	37.148	15.876	3.760	0.360	0.990	0.630	6.650	Combined Cycle Gas
Central Termica Landana	2014	30.000	2.250	1378.900	20.000	30.000	2.708	9.516	16.324	2.490	1.060	0.500	0.770	3.610	Diesel
Central Termica Malongo	2014	45.000	2.300	1256.780	40.000	15.000	2.698	9.125	15.552	1.420	0.540	0.990	0.720	5.080	Diesel
Central Termica de Xitoto Novo	2013	81.000	1.820	1138.600	70.000	45.000	2.728	9.694	16.660	3.100	0.340	0.340	0.700	5.230	Diesel
Central Termica de Xitoto Antigo	2013	11.000	2.200	1150.040	8.000	40.000	2.773	7.901	13.030	3.230	2.670	0.400	0.610	2.070	Diesel
Central Termica do Aeroporto	2013	11.000	2.180	1173.270	8.000	23.000	2.705	9.256	15.806	2.730	2.670	0.650	0.740	3.800	Diesel
Central Termica de Arimba	2013	41.000	2.160	1161.600	35.000	15.000	2.698	9.653	16.608	2.200	0.650	0.990	0.730	5.590	Diesel
Central Termica de Anexo SE	2013	31.000	2.220	1159.050	20.000	30.000	2.747	9.999	17.250	0.790	1.150	0.520	0.750	6.460	Diesel
Central Termica de Kileva	2013	40.000	2.140	1155.310	30.000	69.000	2.764	6.737	10.710	7.360	0.700	0.230	0.510	-2.420	Diesel
Central Termical do Lobito	2013	21.000	2.120	1134.950	5.000	31.000	2.721	7.062	11.403	4.810	3.620	0.490	0.630	-2.000	Diesel
Central Termica de Biopio	2013	91.000	2.090	1143.820	15.000	46.000	2.750	10.033	17.316	0.630	1.480	0.340	0.780	5.870	Diesel
Central Termica do Cunene	2013	16.000	2.090	1140.000	5.000	20.000	2.721	8.147	13.572	1.180	3.770	0.760	0.720	2.540	Diesel
Central Termica Do Kuando Kubango	2013	31.000	2.050	1173.270	10.000	16.000	2.721	10.349	17.976	-0.590	2.140	0.950	0.840	6.790	Diesel
Central Termica do Benfica	2013	41.000	2.030	1185.060	35.000	34.000	2.792	8.445	14.098	0.130	0.530	0.480	0.760	2.250	Diesel
Central Termica do Cuito	2013	11.000	2.010	1172.030	7.000	42.000	2.743	10.035	17.326	1.340	2.720	0.370	0.910	2.250	Diesel
Central Termica do Moxico	2013	41.000	1.990	1155.320	30.000	23.000	2.750	10.961	19.173	0.920	0.830	0.680	0.770	8.380	Diesel
Central Termica de Cazenga	2013	41.000	1.970	1151.320	30.000	50.000	2.773	41.401	17.928	1.520	0.830	0.320	0.720	7.280	Combined Cycle Gas
Central Termica do Caminho de Ferro de Luanda	2013	81.000	1.950	1137.350	50.000	65.000	2.788	10.194	17.600	1.610	0.550	0.250	0.640	9.470	Diesel
Central Termica do Morro Bento	2013	31.000	1.930	1138.230	15.000	32.000	2.752	8.828	14.904	1.210	1.440	0.490	0.690	4.630	Diesel
Central Termica do Morro da Luz	2013	31.000	1.910	1150.040	10.000	25.000	2.741	7.850	12.960	4.170	2.160	0.620	0.600	1.940	Diesel
Central Termica KPM9	2013	15.000	1.910	1151.320	10.000	35.000	2.734	10.069	17.404	2.330	2.290	0.440	0.760	5.290	Diesel
Central Termica Benfica	2013	21.000	1.040	1152.600	17.000	18.000	2.716	10.790	18.865	1.270	1.370	0.840	0.810	6.890	Diesel
Central Termica Praia do Bispo	2013	35.000	1.900	1153.880	20.000	15.000	2.667	10.556	18.444	-0.330	1.060	0.960	0.870	7.060	Diesel
Central Termica dos Quarteis	2013	31.000	1.880	1151.460	30.000	37.000	2.767	9.371	15.975	1.210	0.710	0.430	0.750	4.340	Diesel
Central Termica Boavista I	2013	31.000	2.060	1160.090	15.000	30.000	2.728	9.084	15.440	1.380	1.410	0.510	0.730	4.350	Diesel
Central Termica Boavista II	2013	21.000	2.000	1143.560	10.000	45.000	2.785	8.881	14.976	1.220	2.080	0.360	0.720	3.180	Diesel
Central Termica Boavista III	2013	21.000	1.960	1163.280	16.000	42.000	2.796	8.678	14.560	1.160	1.300	0.390	0.700	3.320	Diesel
Central Termica Kassaki	2013	11.000	1.940	1192.370	8.000	28.000	2.752	7.853	12.953	3.920	2.570	0.560	0.630	0.930	Diesel
Central Termica CEEF	2013	16.000	1.920	1290.370	10.000	20.000	2.681	9.207	15.732	1.640	2.070	0.730	0.760	4.370	Diesel
Central Termica do Bengo	2013	31.000	1.900	1359.850	18.000	25.000	2.725	8.752	14.780	1.620	1.190	0.610	0.690	4.400	Diesel

DMU	Year	Energy Production (MWh)	CO_2 Emission (Tons Per Year)	Polluted Water (Liters Per Year)	Capacity (MW)	Number of Employees	Employee Cost Per Year (Log)	Fuel Cost Per Year (Log)	Investment Cost (Log)	KL Ratio (Log)	Capacity Cost per MW (Log)	Labor Cost Per Year (Log)	Capital Cost Per Year (Log)	Cost–Asset Ratio (Log)	Fuel_Type
Central Termica do Uige	2013	21.000	1.940	1295.360	15.000	20.000	2.708	8.170	13.632	4.290	1.420	0.750	0.640	1.890	Diesel
Central Termica Banza Congo	2013	21.000	1.900	1263.810	10.000	35.000	2.734	7.444	12.154	4.510	2.060	0.440	0.590	0.680	Diesel
Central Termica Soyo	2013	91.000	2.190	1753.420	70.000	15.000	2.698	37.148	15.876	3.760	0.360	0.990	0.630	6.650	Combined Cycle Gas
Central Termica Landana	2013	31.000	2.180	1351.320	20.000	30.000	2.708	9.516	16.324	2.490	1.060	0.500	0.770	3.610	Diesel
Central Termica Malongo	2013	46.000	2.230	1231.640	40.000	15.000	2.698	8.981	15.264	1.420	0.530	0.990	0.720	5.080	Diesel
Central Termica de Xitoto Novo	2012	81.000	2.260	1115.830	70.000	45.000	2.728	9.694	16.660	3.100	0.340	0.340	0.700	5.240	Diesel
Central Termica de Xitoto Antigo	2012	11.000	1.780	1127.040	8.000	40.000	2.773	9.730	16.688	2.540	2.980	0.400	0.700	5.230	Diesel
Central Termica do Aeroporto	2012	11.000	2.160	1149.810	8.000	23.000	2.689	7.859	13.030	4.460	2.670	0.640	0.610	2.070	Diesel
Central Termica de Arimba	2012	41.000	2.140	1138.370	35.000	15.000	2.688	9.243	15.799	2.780	0.610	0.980	0.740	3.800	Diesel
Central Termica de Anexo SE	2012	31.000	2.120	1135.870	20.000	30.000	2.747	9.623	16.498	1.250	1.130	0.520	0.730	5.590	Diesel
Central Termica de Kileva	2012	40.000	2.180	1132.200	30.000	69.000	2.764	10.045	17.325	0.590	0.770	0.230	0.750	6.460	Diesel
Central Termical do Lobito	2012	21.000	2.090	1112.250	5.000	31.000	2.721	6.677	10.634	8.020	4.170	0.490	0.510	-2.420	Diesel
Central Termica de Biopio	2012	91.000	2.070	1120.950	15.000	46.000	2.750	7.045	11.340	4.400	1.200	0.340	0.630	-2.000	Diesel
Central Termica do Cunene	2012	16.000	2.050	1117.200	5.000	20.000	2.721	9.999	17.277	1.190	4.430	0.760	0.780	5.870	Diesel
Central Termica Do Kuando Kubango	2012	31.000	2.050	1149.810	10.000	16.000	2.721	8.129	13.536	1.070	1.880	0.950	0.720	2.540	Diesel
Central Termica do Benfica	2012	41.000	2.010	1161.360	35.000	34.000	2.792	10.363	17.934	-1.600	0.610	0.480	0.840	6.790	Diesel
Central Termica do Cuito	2012	11.000	1.990	1148.590	7.000	42.000	2.743	8.447	14.151	0.940	2.660	0.370	0.760	2.250	Diesel
Central Termica do Moxico	2012	41.000	1.970	1132.220	30.000	23.000	2.750	9.974	17.199	1.180	0.630	0.680	0.910	2.250	Diesel
Central Termica de Cazenga	2012	41.000	1.950	1128.290	30.000	50.000	2.773	43.891	19.173	0.430	0.830	0.320	0.770	8.380	Combined Cycle Gas
Central Termica do Caminho de Ferro de Luanda	2012	81.000	1.930	1114.600	50.000	65.000	2.788	10.394	18.000	1.100	0.500	0.250	0.720	7.280	Diesel
Central Termica do Morro Bento	2012	31.000	1.910	1115.470	15.000	32.000	2.752	10.208	17.664	2.400	1.840	0.490	0.640	9.470	Diesel
Central Termica do Morro da Luz	2012	31.000	1.900	1127.040	10.000	25.000	2.741	8.788	14.835	1.480	2.150	0.620	0.690	4.630	Diesel
Central Termica KPM9	2012	15.000	1.880	1128.290	10.000	35.000	2.734	7.817	12.900	4.360	2.150	0.440	0.600	1.940	Diesel
Central Termica Benfica	2012	21.000	1.880	1129.550	17.000	18.000	2.716	10.079	17.442	2.540	1.350	0.840	0.760	5.290	Diesel
Central Termica Praia do Bispo	2012	35.000	1.020	1130.800	20.000	15.000	2.667	10.730	18.792	1.910	1.160	0.960	0.810	6.890	Diesel
Central Termica dos Quarteis	2012	31.000	1.860	1128.430	30.000	37.000	2.767	10.518	18.270	-1.700	0.700	0.430	0.870	7.060	Diesel
Central Termica Boavista I	2012	31.000	1.840	1136.890	15.000	30.000	2.728	9.351	15.975	1.590	1.420	0.510	0.750	4.340	Diesel
Central Termica Boavista II	2012	21.000	2.020	1120.690	10.000	45.000	2.785	9.094	15.403	0.390	2.110	0.360	0.730	4.350	Diesel
Central Termica Boavista III	2012	21.000	1.960	1140.020	16.000	42.000	2.796	8.886	14.976	1.290	1.300	0.390	0.720	3.180	Diesel
Central Termica Kassaki	2012	11.000	1.920	1168.520	8.000	28.000	2.752	8.656	14.560	1.730	2.600	0.560	0.700	3.320	Diesel
Central Termica CEEF	2012	16.000	1.900	1264.560	10.000	20.000	2.681	7.830	12.978	4.990	2.060	0.730	0.630	0.930	Diesel
Central Termica do Bengo	2012	31.000	1.880	1332.650	18.000	25.000	2.725	9.228	15.732	0.950	1.150	0.610	0.760	4.370	Diesel
Central Termica do Uige	2012	21.000	1.860	1269.460	15.000	20.000	2.708	8.703	14.697	1.900	1.420	0.750	0.690	4.400	Diesel
Central Termica Banza Congo	2012	21.000	1.900	1238.530	10.000	35.000	2.734	8.151	13.568	3.970	2.120	0.440	0.640	1.890	Diesel
Central Termica Soyo	2012	91.000	1.860	1718.350	70.000	15.000	2.698	29.350	11.977	5.060	0.290	0.990	0.590	0.680	Combined Cycle Gas
Central Termica Landana	2012	31.000	2.140	1324.300	20.000	30.000	2.708	8.032	13.356	3.480	1.060	0.500	0.630	2.620	Diesel
Central Termica Malongo	2012	46.000	2.140	1207.010	40.000	15.000	2.698	9.511	16.324	2.730	0.530	0.990	0.770	3.790	Diesel
Central Termica de Xitoto Novo	2011	85.000	1.700	1064.500	70.000	45.000	2.728	9.694	16.660	3.130	0.340	0.340	0.700	5.240	Diesel
Central Termica de Xitoto Antigo	2011	13.000	2.050	1075.200	8.000	40.000	2.773	9.702	16.632	2.570	2.970	0.400	0.700	5.230	Diesel
Central Termica do Aeroporto	2011	13.000	2.030	1096.920	8.000	23.000	2.689	7.835	12.981	4.490	2.660	0.640	0.610	2.070	Diesel
Central Termica de Arimba	2011	46.000	2.010	1086.000	35.000	15.000	2.688	9.243	15.799	2.810	0.610	0.980	0.740	3.800	Diesel
Central Termica de Anexo SE	2011	36.000	2.070	1083.620	20.000	30.000	2.747	9.623	16.498	1.280	1.130	0.520	0.730	5.590	Diesel
Central Termica de Kileva	2011	44.000	1.990	1080.120	30.000	69.000	2.764	9.932	17.100	0.620	0.760	0.230	0.750	6.460	Diesel

DMU	Year	Energy Production (MWh)	CO_2 Emission (Tons Per Year)	Polluted Water (Liters Per Year)	Capacity (MW)	Number of Employees	Employee Cost Per Year (Log)	Fuel Cost Per Year (Log)	Investment Cost (Log)	KL Ratio (Log)	Capacity Cost per MW (Log)	Labor Cost Per Year (Log)	Capital Cost Per Year (Log)	Cost–Asset Ratio (Log)	Fuel_Type
Central Termical do Lobito	2011	24.000	1.970	1061.090	5.000	31.000	2.721	6.677	10.634	8.050	4.170	0.490	0.510	-2.420	Diesel
Central Termica de Biopio	2011	100.000	1.950	1069.380	15.000	46.000	2.750	7.045	11.340	4.430	1.200	0.340	0.630	-2.000	Diesel
Central Termica do Cunene	2011	18.000	1.950	1065.810	5.000	20.000	2.708	9.993	17.277	1.220	4.430	0.750	0.780	5.870	Diesel
Central Termica Do Kuando Kubango	2011	34.000	1.910	1096.920	10.000	16.000	2.721	8.129	13.536	1.100	1.880	0.950	0.720	2.540	Diesel
Central Termica do Benfica	2011	45.000	1.890	1107.940	35.000	34.000	2.792	10.363	17.934	-1.570	0.610	0.480	0.840	6.790	Diesel
Central Termica do Cuito	2011	12.000	1.870	1095.750	7.000	42.000	2.743	8.421	14.098	0.970	2.650	0.370	0.760	2.250	Diesel
Central Termica do Moxico	2011	45.000	1.860	1080.130	30.000	23.000	2.735	9.967	17.199	1.210	0.630	0.670	0.910	2.250	Diesel
Central Termica de Cazenga	2011	45.000	1.840	1076.390	30.000	50.000	2.773	43.891	19.173	0.460	0.830	0.320	0.770	8.380	Combined Cycle Gas
Central Termica do Caminho de Ferro de Luanda	2011	89.000	1.820	1063.330	50.000	65.000	2.788	10.394	18.000	1.130	0.500	0.250	0.720	7.280	Diesel
Central Termica do Morro Bento	2011	34.000	1.800	1064.150	15.000	32.000	2.752	10.208	17.664	2.430	1.840	0.490	0.640	9.470	Diesel
Central Termica do Morro da Luz	2011	35.000	1.780	1075.190	10.000	25.000	2.741	8.788	14.835	1.510	2.150	0.620	0.690	4.630	Diesel
Central Termica KPM9	2011	16.000	1.780	1076.390	10.000	35.000	2.711	7.806	12.900	4.390	2.150	0.430	0.600	1.940	Diesel
Central Termica Benfica	2011	23.000	0.970	1077.590	17.000	18.000	2.704	10.008	17.313	2.570	1.340	0.830	0.760	5.290	Diesel
Central Termica Praia do Bispo	2011	38.000	1.760	1078.790	20.000	15.000	2.667	10.730	18.792	1.940	1.160	0.960	0.810	6.890	Diesel
Central Termica dos Quarteis	2011	34.000	1.750	1076.520	30.000	37.000	2.743	10.507	18.270	-1.660	0.700	0.420	0.870	7.060	Diesel
Central Termica Boavista I	2011	35.000	1.920	1084.590	15.000	30.000	2.728	9.351	15.975	1.620	1.420	0.510	0.750	4.340	Diesel
Central Termica Boavista II	2011	23.000	1.860	1069.140	10.000	45.000	2.785	9.094	15.403	0.420	2.110	0.360	0.730	4.350	Diesel
Central Termica Boavista III	2011	24.000	1.820	1087.580	16.000	42.000	2.796	8.886	14.976	1.320	1.300	0.390	0.720	3.180	Diesel
Central Termica Kassaki	2011	12.000	1.800	1114.770	8.000	28.000	2.752	8.628	14.504	1.770	2.590	0.560	0.700	3.320	Diesel
Central Termica CEEF	2011	17.000	1.790	1206.390	10.000	20.000	2.681	7.798	12.915	5.020	2.050	0.730	0.630	0.930	Diesel
Central Termica do Bengo	2011	34.000	1.770	1271.350	18.000	25.000	2.725	9.228	15.732	0.980	1.150	0.610	0.760	4.370	Diesel
Central Termica do Uige	2011	23.000	1.800	1211.060	15.000	20.000	2.708	8.703	14.697	1.930	1.420	0.750	0.690	4.400	Diesel
Central Termica Banza Congo	2011	24.000	1.770	1181.560	10.000	35.000	2.734	8.151	13.568	4.000	2.120	0.440	0.640	1.890	Diesel
Central Termica Soyo	2011	100.000	2.040	1639.300	70.000	15.000	2.688	29.330	11.977	5.090	0.290	0.980	0.590	0.680	Combined Cycle Gas
Central Termica Landana	2011	34.000	2.040	1263.380	20.000	30.000	2.708	8.032	13.356	3.510	1.060	0.500	0.630	2.620	Diesel
Central Termica Malongo	2011	85.000	1.610	1151.490	40.000	15.000	2.698	9.511	16.324	2.760	0.530	0.990	0.770	3.790	Diesel
Central Termica de Xitoto Novo	2010	13.000	1.640	1021.920	70.000	45.000	2.728	9.694	16.660	3.120	0.340	0.340	0.700	5.240	Diesel
Central Termica de Xitoto Antigo	2010	13.000	1.990	1032.190	8.000	40.000	2.773	9.702	16.632	2.560	2.970	0.400	0.700	5.230	Diesel
Central Termica do Aeroporto	2010	46.000	1.970	1053.040	8.000	23.000	2.689	7.729	12.768	4.480	2.660	0.640	0.600	2.070	Diesel
Central Termica de Arimba	2010	36.000	1.950	1042.560	35.000	15.000	2.688	9.243	15.799	2.800	0.610	0.980	0.740	3.800	Diesel
Central Termica de Anexo SE	2010	39.600	2.010	1040.270	20.000	30.000	2.747	9.623	16.498	1.270	1.130	0.520	0.730	5.590	Diesel
Central Termica de Kileva	2010	24.000	1.930	1036.920	30.000	69.000	2.764	9.818	16.872	0.610	0.760	0.230	0.740	6.460	Diesel
Central Termical do Lobito	2010	100.000	1.910	1018.640	5.000	31.000	2.721	6.664	10.608	8.040	4.160	0.490	0.510	-2.420	Diesel
Central Termica de Biopio	2010	18.000	1.890	1026.610	15.000	46.000	2.750	7.045	11.340	4.420	1.200	0.340	0.630	-2.000	Diesel
Central Termica do Cunene	2010	34.000	1.890	1023.180	5.000	20.000	2.708	9.973	17.238	1.210	4.420	0.750	0.780	5.870	Diesel
Central Termica Do Kuando Kubango	2010	45.000	1.850	1053.040	10.000	16.000	2.721	8.129	13.536	1.090	1.880	0.950	0.720	2.540	Diesel
Central Termica do Benfica	2010	12.000	1.840	1063.620	35.000	34.000	2.771	10.353	17.934	-1.580	0.610	0.470	0.840	6.790	Diesel
Central Termica do Cuito	2010	45.000	1.820	1051.920	7.000	42.000	2.743	8.421	14.098	0.960	2.650	0.370	0.760	2.250	Diesel
Central Termica do Moxico	2010	45.000	1.800	1036.930	30.000	23.000	2.735	9.967	17.199	1.200	0.630	0.670	0.910	2.250	Diesel
Central Termica de Cazenga	2010	89.000	1.780	1033.330	30.000	50.000	2.773	43.891	19.173	0.450	0.830	0.320	0.770	8.380	Combined Cycle Gas
Central Termica do Caminho de Ferro de Luanda	2010	34.000	1.760	1020.790	50.000	65.000	2.788	10.394	18.000	1.120	0.500	0.250	0.720	7.280	Diesel

DMU	Year	Energy Production (MWh)	CO_2 Emission (Tons Per Year)	Polluted Water (Liters Per Year)	Capacity (MW)	Number of Employees	Employee Cost Per Year (Log)	Fuel Cost Per Year (Log)	Investment Cost (Log)	KL Ratio (Log)	Capacity Cost per MW (Log)	Labor Cost Per Year (Log)	Capital Cost Per Year (Log)	Cost–Asset Ratio (Log)	Fuel_Type
Central Termica do Morro Bento	2010	35.000	1.750	1021.590	15.000	32.000	2.752	10.208	17.664	2.420	1.840	0.490	0.640	9.470	Diesel
Central Termica do Morro da Luz	2010	16.000	1.730	1032.190	10.000	25.000	2.725	8.780	14.835	1.500	2.150	0.610	0.690	4.630	Diesel
Central Termica KPM9	2010	23.000	1.730	1033.340	10.000	35.000	2.711	7.698	12.685	4.380	2.150	0.430	0.590	1.940	Diesel
Central Termica Benfica	2010	38.000	0.940	1034.480	17.000	18.000	2.704	10.008	17.313	2.560	1.340	0.830	0.760	5.290	Diesel
Central Termica Praia do Bispo	2010	34.000	1.710	1035.630	20.000	15.000	2.657	10.724	18.792	1.930	1.160	0.950	0.810	6.890	Diesel
Central Termica dos Quarteis	2010	35.000	1.690	1033.460	30.000	37.000	2.743	10.507	18.270	-1.670	0.700	0.420	0.870	7.060	Diesel
Central Termica Boavista I	2010	23.000	1.860	1041.210	15.000	30.000	2.728	9.351	15.975	1.610	1.420	0.510	0.750	4.340	Diesel
Central Termica Boavista II	2010	24.000	1.800	1026.370	10.000	45.000	2.785	9.094	15.403	0.410	2.110	0.360	0.730	4.350	Diesel
Central Termica Boavista III	2010	12.000	1.770	1044.070	16.000	42.000	2.796	8.828	14.861	1.310	1.290	0.390	0.720	3.180	Diesel
Central Termica Kassaki	2010	17.000	1.750	1070.180	8.000	28.000	2.752	8.628	14.504	1.760	2.590	0.560	0.700	3.320	Diesel
Central Termica CEEF	2010	34.000	1.730	1158.130	10.000	20.000	2.681	7.798	12.915	5.010	2.050	0.730	0.630	0.930	Diesel
Central Termica do Bengo	2010	23.000	1.710	1220.500	18.000	25.000	2.725	9.160	15.595	0.970	1.140	0.610	0.760	4.370	Diesel
Central Termica do Uige	2010	24.000	1.750	1162.620	15.000	20.000	2.708	8.703	14.697	1.920	1.420	0.750	0.690	4.400	Diesel
Central Termica Banza Congo	2010	100.000	1.710	1134.300	10.000	35.000	2.734	8.045	13.356	3.990	2.120	0.440	0.630	1.890	Diesel
Central Termica Soyo	2010	34.000	1.980	1573.730	70.000	15.000	2.688	29.330	11.977	5.080	0.290	0.980	0.590	0.680	Combined Cycle Gas
Central Termica Landana	2010	28.000	1.980	1212.840	20.000	30.000	2.708	8.032	13.356	3.500	1.060	0.500	0.630	2.620	Diesel
Central Termica Malongo	2010	45.000	1.560	1105.430	40.000	15.000	2.698	9.511	16.324	2.750	0.530	0.990	0.770	3.790	Diesel

Appendix B. Complete Ranking of DMUs

DMU	Phase I	ψ_o^{2010}	ψ_o^{2011}	ψ_o^{2012}	ψ_o^{2013}	ψ_o^{2014}	ψ_o^{2015}	ψ_o^{2016}	Phase II	Rank	DMU Location	DMU Name	DMU Capacity (MW)
1	1.0825	0.85	0.9169	0.991	0.9904	1.1773	1.2453	1.4068	-	15	Namibe	Xitoto Novo	70
2	1.226	1.0524	1.0915	1.1361	1.1345	1.3469	1.4104	1.4101	-	23	Namibe	Xitoto Antigo	8
3	1.1193	1.212	1.1884	1.155	1.1546	1.0444	1.043	1.0376	-	16	Namibe	Aeroporto	8
4	0.9546	0.951	0.9517	0.9519	0.9569	0.9418	0.9601	0.9691	-	8	Lubango	Arimba	35
5	1.2801	1.2981	1.2805	1.2627	1.2614	1.2819	1.2762	1.3001	-	29	Lubango	Anexo SE	20
6	1.1208	0.8338	0.8427	0.8585	0.8632	1.4997	1.4707	1.4769	-	17	Benguela	Kileva	30
7	0.7757	0.9064	0.8848	0.8521	0.8524	0.7232	0.7245	0.4868	-	4	Benguela	Lobito	5
8	0.5208	0.448	0.4514	0.4534	0.4622	0.3726	0.4035	1.0545	-	1	Benguela	Biópio	15
9	0.7547	0.7534	0.7539	0.7544	0.7547	0.755	0.7555	0.756	-	3	Cunene	Cunene	5
10	0.8143	0.8274	0.8181	0.806	0.8002	0.8108	0.8104	0.8275	-	5	Cuando-Cubango	Kuando Kubango	10
11	1.1904	1.0509	1.0534	1.057	1.0557	1.3517	1.3566	1.4074	-	19	Huambo	Benfica	35
12	1.3248	1.3825	1.3823	1.3827	1.3812	1.2493	1.2456	1.2496	-	31	Bié	Cuito	7
13	1.2069	1.2522	1.2149	1.1736	1.1742	1.1858	1.2014	1.2459	-	21	Moxico	Moxico	30
14	2.3954	2.5889	2.5306	2.4504	2.453	2.4537	2.4937	1.7977	-	32	Luanda	Cazenga	30
15	1.2533	1.0851	1.0762	1.0779	1.0769	1.4617	1.4639	1.5313	-	26	Luanda	Caminho de Ferro de Luanda	50
16	1.23	1.1608	1.1517	1.1362	1.1366	1.3331	1.337	1.3543	-	24	Luanda	Morro Bento	15
17	1.0105	0.8956	0.9149	0.9376	0.9395	1.1263	1.121	1.1387	-	9	Luanda	Morro da Luz	10
18	1.2566	1.4324	1.3648	1.3078	1.3084	1.129	1.1311	1.1228	-	27	Luanda	KM9	10
19	1.0157	0.9742	0.9769	0.9786	0.9822	1.1277	1.0333	1.0371	-	10	Luanda	Benfica	17
20	0.9266	0.9355	0.9364	0.9374	0.9399	0.8488	0.9435	0.9448	-	7	Luanda	Praia do Bispo	20
21	1.2979	1.2124	1.2143	1.2135	1.2143	1.4004	1.4049	1.4252	-	30	Luanda	Quarteis	30
22	1.2056	1.1773	1.18	1.176	1.1753	1.2183	1.2474	1.2648	-	20	Luanda	Boavista I	15
23	1.2693	1.1584	1.1972	1.2448	1.245	1.35	1.3436	1.3463	-	28	Luanda	Boavista II	10
24	1.236	1.1493	1.1675	1.2084	1.2086	1.3093	1.3064	1.3022	-	25	Luanda	Boavista III	16
25	1.0691	1.0057	1.0181	1.0335	1.0315	1.1312	1.1309	1.133	-	14	Luanda	Kassaki	8
26	1.0321	1.0818	1.0726	1.0513	1.0508	0.9891	0.9892	0.9897	-	12	Luanda	CEEF	10
27	1.1248	1.0936	1.0876	1.0811	1.0822	1.1697	1.1743	1.1852	-	18	Bengo	Bengo	18
28	1.0236	0.973	0.975	0.9772	0.9791	1.0796	1.09	1.0914	-	11	Uige	Uige	15
29	1.0657	0.9578	0.9868	1.0278	1.028	1.1666	1.1657	1.1274	-	13	Zaire	Banza Congo	10
30	0.6098	0.4069	0.4487	0.5	0.5055	0.5055	0.85	1.0524	-	2	Zaire	Soyo	70
31	1.2169	1.3405	1.296	1.245	1.2438	1.1195	1.1252	1.1483	-	22	Cabinda	Landana	20
32	0.8512	0.9106	0.8922	0.8718	0.866	0.9213	0.5817	0.9149	-	6	Cabinda	Malongo	40

References

1. Eser, P.; Singh, A.; Chokani, N.; Abhari, R. Effect of increased renewables generation on operation of thermal power plants. *Appl. Energy* **2016**, *164*, 723–732. [CrossRef]
2. Faraway, J.J. *Extending the Linear Model with R: Generalized Linear, Mixed Effects and Nonparametric Regression Models*; Chapman & Hall/CRC: Boca Raton, FL, USA, 2006.
3. Chien, C.F.; Chen, W.C.; Lo, F.Y.; Lin, Y.C. A case study to evaluate the productivity change of the thermal power plants of the Taiwan power company. *IEEE Trans. Energy Conserv.* **2007**, *22*, 680–688. [CrossRef]
4. Yao, X.; Guo, C.; Shao, S.; Jiang, Z. Total-factor CO_2 emission performance of China's provincial industrial sector: A meta-frontier non-radial Malmquist index approach. *Appl. Energy* **2016**, *184*, 1142–1153. [CrossRef]
5. Wang, Y.-S.; Xie, B.-C.; Shang, L.-F.; Li, W.-H. Measures to improve the performance of China's thermal power industry in view of cost efficiency. *Appl. Energy* **2013**, *112*, 1078–1086. [CrossRef]
6. Lin, B.; Yang, L. Efficiency effect of changing investment structure on China's power industry. *Renew. Sustain. Energy Rev.* **2014**, *39*, 403–411. [CrossRef]
7. Barros, C.P.; Wanke, P. Efficiency in Angolan thermal power plants: Evidence from cost structure and pollutant emissions. *Energy* **2017**, *130*, 129–143. [CrossRef]
8. Wanke, P.; Barros, C.P. Efficiency thresholds and cost structure in Senegal airports. *J. Air Transp. Manag.* **2017**, *58*, 100–112. [CrossRef]
9. Park, S.U.; Lesourd, J.B. The efficiency of conventional fuel power plants in South Korea: A comparison of parametric and non-parametric approaches. *Int. J. Prod. Econ.* **2000**, *63*, 59–67. [CrossRef]
10. Lam, P.L.; Shiu, A. A data envelopment analysis of the efficiency of China's thermal power generation. *Util. Policy* **2001**, *10*, 75–83. [CrossRef]
11. Sarica, K.; Or, I. Efficiency assessment of Turkish power plants using data envelopment analysis. *Energy* **2007**, *32*, 1484–1499. [CrossRef]
12. Barros, C.P.; Peypoch, N. Technical efficiency of thermoelectric power plants. *Energy Econ.* **2008**, *30*, 3118–3127. [CrossRef]
13. Nakano, M.; Managi, S. Regulatory reforms and productivity: An empirical analysis of the Japanese electricity industry. *Energy Policy* **2008**, *36*, 201–209. [CrossRef]
14. Sozen, 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]
15. Liu, C.H.; Lin, S.J.; Lewis, C. Evaluation of thermal power plant operational performance in Taiwan by data envelopment analysis. *Energy Policy* **2010**, *38*, 1049–1058. [CrossRef]
16. Rezaee, M.J.; Moini, A.; Makui, A. Operational and non-operational performance evaluation of thermal power plants in Iran: A game theory approach. *Energy* **2012**, *38*, 96–103. [CrossRef]
17. Rezaee, M.J. Using Shapley value in multi-objective data envelopment analysis: Power plants evaluation with multiple frontiers. *Int. J. Electr. Power Energy Syst.* **2015**, *69*, 141–149. [CrossRef]
18. Shrivastava, N.; Sharma, S.; Chauhan, K. Efficiency assessment and benchmarking of thermal power plants in India. *Energy Policy* **2012**, *40*, 159–176. [CrossRef]
19. Sueyoshi, T.; Goto, M. DEA environmental assessment of coal fired power plants: Methodological comparison between radial and non-radial models. *Energy Econ.* **2012**, *34*, 1854–1863. [CrossRef]
20. Du, L.; Mao, J. Estimating the environmental efficiency and marginal CO_2 abatement cost of coal-fired power plants in China. *Energy Policy* **2015**, *85*, 347–356. [CrossRef]
21. Ghosh, R.; Kathuria, V. The effect of regulatory governance on efficiency of thermal power generation in India: A stochastic frontier analysis. *Energy Policy* **2016**, *89*, 11–24. [CrossRef]
22. Yan, D.; Lei, Y.; Li, L.; Song, W. Carbon emission efficiency and spatial clustering analyses in China's thermal power industry: Evidence from the provincial level. *J. Clean. Prod.* **2017**, *156*, 518–527. [CrossRef]
23. Wu, Y.; Ke, Y.; Xu, C.; Xiao, X.; Hu, Y. Eco-efficiency measurement of coal-fired power plants in China using super efficiency data envelopment analysis. *Sustain. Cities Soc.* **2018**, *36*, 157–168. [CrossRef]
24. See, K.F.; Coelli, T. An analysis of factors that influence the technical efficiency of Malaysian thermal power plants. *Energy Econ.* **2012**, *34*, 677–685. [CrossRef]
25. Munisamy, S.; Arabi, B. Eco-efficiency change in power plants: Using a slacks-based measure for the meta-frontier Malmquist–Luenberger productivity index. *J. Clean Prod.* **2015**, *105*, 218–232. [CrossRef]

26. Mahmoudi, R.; Emrouznejad, A.; Khosroshahi, H.; Khashei, M.; Rajabi, P. Performance evaluation of thermal power plants considering CO_2 emission: A multistage PCA, clustering, game theory and data envelopment analysis. *J. Clean. Prod.* **2019**, *223*, 641–650. [CrossRef]
27. Wei, X.; Zhang, N. The shadow prices of CO_2 and SO_2 for Chinese Coal-fired Power Plants: A partial frontier approach. *Energy Econ.* **2020**, *85*, 104576. [CrossRef]
28. Emrouznejad, A.; Yang, G. A survey and analysis of the first 40 years of scholarly literature in DEA: 1978–2016. *Socio-Econ. Plan. Sci.* **2018**, *61*, 4–8. [CrossRef]
29. Fernández, D.; Pozo, C.; Folgado, R.; Jiménez, L.; Guillén-Gosálbez, G. Productivity and energy efficiency assessment of existing industrial gases facilities via data envelopment analysis and the Malmquist index. *Appl. Energy* **2018**, *212*, 1563–1577. [CrossRef]
30. Charnes, A.; Clark, C.T.; Cooper, W.W.; Golany, B. A developmental study of data envelopment analysis in measuring the efficiency of maintenance units in the U.S. air forces. *Ann. Oper. Res.* **1985**, *2*, 95–112. [CrossRef]
31. Färe, R.; Grosskopf, S. *Intertemporal Production Functions with Dynamic DEA*; Kluwer Academic Publishers: Boston, MA, USA, 1996.
32. Nemoto, J.; Goto, M. Dynamic data envelopment analysis: modeling intertemporal behavior of a firm in the presence of productive inefficiencies. *Econ. Lett.* **1999**, *64*, 51–56. [CrossRef]
33. Thompson, R.G.; Dharmapala, P.S.; Thrall, R.M. Linked-cone DEA profit ratios and technical efficiency with application to Illinois coal mines. *Int. J. Prod. Econ.* **1995**, *39*, 99–115. [CrossRef]
34. Jahanshahloo, G.R.; Soleimani-damaneh, M.; Reshadi, M. On the Pareto (dynamically) efficient paths. *Int. J. Comput. Math.* **2006**, *83*, 629–633. [CrossRef]
35. Silva, E.; Stefanou, S.E. Nonparametric dynamic efficiency measurement: Theory and application. *Am. J. Agric. Econ.* **2007**, *89*, 398–419. [CrossRef]
36. Soleimani-damaneh, M. An effective computational attempt in DDEA. *Appl. Math. Model.* **2009**, *33*, 3943–3948. [CrossRef]
37. Sam Park, K.; Park, K. Measurement of multi-period aggregative efficiency. *Eur. J Oper. Res.* **2009**, *193*, 567–580. [CrossRef]
38. Charnes, A.; Cooper, W.; Rhodes, E. Measuring the efficiency of decision making units. *Eur. J. Oper. Res.* **1978**, *2*, 429–444. [CrossRef]
39. Andersen, P.; Petersen, N.C. A procedure for ranking efficient units in data envelopment analysis. *Manag. Sci.* **1993**, *39*, 1261–1264. [CrossRef]
40. Mariano, E.B.; Gobbo, J.A., Jr.; Camioto, F.C.; Rebelatto, D.A.N. CO_2 emissions and logistics performance: A composite index proposal. *J. Clean Prod.* **2016**, *163*, 166–178. [CrossRef]
41. Ozkan, N.F.; Ulutas, B.H. Efficiency analysis of cement manufacturing facilities in Turkey considering undesirable outputs. *J. Clean Prod.* **2017**, *156*, 932–938. [CrossRef]
42. Scheel, H. Undesirable outputs in efficiency valuations. *Eur. J. Oper. Res.* **2001**, *132*, 400–410. [CrossRef]
43. Seiford, L.M.; Zhu, J. Modeling undesirable factors in efficiency evaluation. *Eur. J. Oper. Res.* **2002**, *142*, 16–20. [CrossRef]
44. Hadi-Vencheh, A.; Kazemi Matin, R.; Tavassoli Kajani, M. Undesirable factors in efficiency measurement. *Appl. Math. Comput.* **2005**, *63*, 547–552. [CrossRef]
45. EIA. How Much Does It Cost to Generate Electricity with Different Types of Power Plants? 2017. Available online: https://www.eia.gov/tools/faqs/faq.php?id=19&t=3 (accessed on 1 March 2018).
46. EIA. How Much Does It Cost to Build Different Types of Power Plants? 2018. Available online: https://www.eia.gov/tools/faqs/faq.php?id=487&t=3 (accessed on 7 July 2018).
47. Morgan, J.; Sonquist, J. Problems in the analysis of survey data and a proposal. *J. Am. Stat. Assoc.* **1963**, *58*, 415–434. [CrossRef]
48. Breiman, L.; Friedman, J.; Olshen, R.; Stone, C. *Classification and Regression Trees*; Wadsworth: Belmont, CA, USA, 1984.
49. James, G.; Witten, D.; Hastie, T.; Tibshirani, R. *An Introduction to Statistical Learning with Applications in R*; Springer: New York, NY, USA, 2013.
50. Opitz, D.; Maclin, R. Popular ensemble methods: An empirical study. *J. Artif. Intell. Res.* **1999**, *11*, 169–198. [CrossRef]
51. Polikar, R. Ensemble based systems in decision making. *IEEE Circuits Syst. Mag.* **2006**, *6*, 21–45. [CrossRef]

52. Torgo, L. *Data Mining with R: Learning with Case Studies*; CRC Press: Boca Raton, FL, USA, 2011.
53. Breiman, L. Bagging predictors. *Mach. Learn.* **1996**, *24*, 123–140. [CrossRef]
54. Ledolter, J. *Data Mining and Business Analytics with R*; Wiley: Hoboken, NJ, USA, 2013.