Research Article | Submit Manuscript

Turkish Journal of Electromechanics and Energy

ISSN-2547-975X

Measuring the Efficiency of Wind Power Plants Using Data Envelopment Analysis: A Case Study from TURKEY

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Received: 16 November 2019; Revised: 19 December 2019; Accepted: 24 December 2019; Published: 31 December 2019

Turk J Electrom Energ Vol.: 4 No: 2 Page: 19-32 (2019)

SLOI: http://www.sloi.org/

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ABSTRACT **Energy is an important sector with great investments and strategic importance. Wind power plants (WPPs) have the most in-demand from the capacity of renewable energy sources in Turkey, where licensing, installation and commissioning processes can be performed relatively easily. According to the Republic of Turkey's Ministry of Energy and Natural Resources, the installed capacity of Turkey as of mid-2019 is 90.421 MW. The distribution of this installed capacity was obtained from various resources: 31.4% hydraulic energy, 29.0% natural gas, 22.4% coal, 8.0% wind, 6.0% solar, 1.5% geothermal and 1.7% from other sources. Efficiency studies on wind energy are important for directing investments correctly and evaluating national wealth. By increasing the efficiency of existing facilities, more electrical energy will be produced, and the average number of people whose energy demand are met will increase. This study aimed to determine the effectiveness of the existing 99 WPPs in Turkey, using the Data Envelopment Analysis (DEA) method. In this way, instead of investing in a new WPP, factors that contribute to ineffectiveness can be discussed by identifying inactive facilities. The efficiencies of WPPs were calculated using input-oriented CCR (Charnes, Cooper and Rhodes) and BCC (Banker, Charnes, Cooper) DEA models. The model results were compared, and the effectiveness of WPPs was investigated. The results revealed that only six plants were relatively effective according to the CCR model, while 18 plants were relatively effective according to the BCC model.**

Keywords: Renewable Energy, Wind Power Plant, Efficiency Analysis, Data Envelopment Analysis

Cite this article: Ş. Emeç, T. Adar, G. Akkaya, E. Kiliç Delice, Measuring the Efficiency of Wind Power Plants Using Data Envelopment Analysis: A Case Study from TURKEY, Turkish Journal of Electromechanics & Energy, 4(2), 19-32, (2019).

1. INTRODUCTION

Wind power is a natural, renewable, clean and infinite energy source. Its source is the sun: a small amount of the energy that the sun emits to the world turns into wind energy. Concentrated air flow occurs due to differences in temperature and pressure resulting from non-homogeneous heating of the earth's surface and atmosphere by the sun. If an air mass heats up more than its current state, it rises above the atmosphere. With the rise of that air mass, the same volume of cold air mass settles in its place. The displacement of these air masses is called wind. In other words, wind is the air flow from a high pressure center to a low pressure center due to pressure differences between two adjacent pressure zones [1].

Wind power plants (WPP) convert the kinetic energy of moving air into mechanical energy and then into electrical energy through wind turbines. These facilities do not have external dependence, a shortage of raw materials, or a negative impact on nature and human health. They require little space for installation [2]. The best way to increase the effectiveness of WPPs, which have an average life of 20 years, is to reduce operating costs or to maximize the energy produced. The share of electricity production of WPPs in Turkey is about 7.40% (as of July 2019) [3].

One important factor in the completion of Turkey's economic and social development is energy production. However, currently, Turkey is experiencing a rapid increase in demand for both primary energy sources and electrical energy. In order to meet the increasing energy demand, investments in the energy field and the number of installed facilities have also increased, as Turkey has been dependent on external sources in terms of both primary energy sources and as secondary energy in electricity generation [4]. As of July 2019, there are 183 WPPs operational in Turkey [3].

Although Turkey has high wind potential, it is not sufficient to depend only on it. The efficiency of the existing facilities must be increased, and more electricity should be produced.

Wind energy is increasingly becoming popular in recent years. Efficiency studies on wind energy are important for directing investment correctly. Also, it is important for in the national treasure [5]. The aim of this study was to determine the effectiveness of the existing 99 WPPs using the data envelopment analysis (DEA) method. Thus, instead of establishing new WPPs, the reasons for ineffectiveness can be investigated by identifying inactive facilities. Investment can then be directed to the right area, and more electricity can be generated by the WPPs. For this purpose, the efficiencies of WPPs were calculated using input-oriented CCR (Charnes, Cooper and Rhodes) and BCC (Banker, Charnes, Cooper) models of the DEA methodology. The model results were compared and the effectiveness of WPPs was investigated.

There are many studies in different fields related to energy in the literature, including the estimation of energy production capacity [6], the control of a photovoltaic installation with batteries [7], power/energy optimized management for a PV-battery interfaced to a smart grid [8], and the control of the electric vehicle using sustainable energy [9]. Studies related to WPPs have looked at plant location selection [10-14], wind turbine selection [15-19], the prediction of energy production [20-24] and efficiency analysis.

Several studies related to efficiency analysis in WPPs have also utilized the DEA method. Saglam [25] aimed to find the causes of inefficiencies by performing a two-stage performance evaluation of WPPs in Texas. In the first stage of the analysis, input- and output-oriented DEA models were applied to evaluate the efficiency of 95 large utility-scale wind farms with three input and two output variables. In the second stage, Saglam attempted to determine the factors causing inefficiency using a Tobit regression model. The Tobit regression model showed that elevation of the site, rotor diameter, hub height, and brand of turbine had significant contributions to the relative efficiency scores of the wind farms, and the age of turbine had a negative impact on the productivity of the wind farms.

In another study in the US, Saglam [26] applied a two-stage DEA to assess the relative effectiveness of the wind power performances of 39 states quantitatively for electricity generation. Both input- and output-oriented CCR and BCC models were applied to four input and six output variables. A Tobit regression model was used to determine the variables affecting productivity.

Saglam [27] also applied DEA to evaluate the relative efficiency of 236 large utility-scale wind farms quantitatively. Input- and output-oriented CCR and BCC models were applied to three input and three output variables. Tobit regression models were developed for the second stage of the analysis in order to investigate the effects of the characteristics of wind turbine technologies. The DEA results showed that two out of three of WPPs were operating efficiently.

Wu et al. [28] analyzed the efficiency of 42 large-scale WPPs in China using a two-stage analysis. In the first stage, wind farm productivity scores were determined using DEA. Sensitivity analysis was conducted to verify the robustness of the productivity results. In the second stage, a Tobit regression was used to investigate the relationship between productivity scores and environmental variables outside wind farm control. According to the results, all wind farms were operating at an acceptable level. However, 50% of the wind farms invested heavily in installed capacity, and approximately 48% had the potential to save electricity. The most important factors affecting the efficiency of WPPs were determined to be installed power and wind power density.

In another study, the DEA model was applied to measure the efficiency of WPPs in Turkey with three inputs and two outputs [5]. The power plants were divided into seven layers by context-dependent DEA approach, which allowed decision-making units to be grouped according to their efficiency levels. The results obtained were also interpreted in terms of geographical regions where the plants are located. It was concluded that the power plants in the Aegean region generally operated effectively or close to effectively.

Eroglu and Seckiner analyzed the performance comparisons of turbines using data obtained from existing data collection systems in wind farms [29]. The DEA method was used to evaluate the total factor efficiency obtained by the Malmquist Index to compare the two-year production performance of wind turbines in a wind farm and examine changes in detailed performance. They used operation data of a current wind farm in Turkey for the years 2013 and 2014 in their study. As a result, low performance turbines were identified, and the reasons for performance losses were interpreted.

Emre ve Omurgulsen [30] aimed to measure the efficiency values of WPPs in the Marmara Region using DEA methodology. Input and output variables included installation and connection costs of generation units and annual generation value, mean annual income and return on investment, respectively. The results of this study indicated problems related to effective use in the majority of power plants with different installation and connection costs and capacity and production amounts in WPP capacity samples in the Marmara Region.

Sarıca and Or [31] performed an efficiency analysis of thermal, hydro and WPPs using the DEA method. In addition, the relationships between productivity scores and various input and output factors were investigated.

As it can be noted, there are quite a few studies on the efficiency analysis of WPP using the DEA method. These studies include differences in the number of WPP to which efficiency analysis is applied, input and output variables used, city or country where the study is applied, and DEA models used.

In the current study, an efficiency analysis was performed using the DEA method for 99 WPPs installed in Turkey. The efficiency of the WPPs was calculated using input-oriented CCR and BCC models, and the results were compared. In accordance with this purpose, values of installed power, production capacity (year), and the amount of wind turbine were used as input variables. Electricity generation amount (year), the average number of people whose energy needs are met, and sale price to the grid were used as output variables. Using input-oriented CCR and BCC models, the efficiency of WPPs was calculated, and the results were compared.

The remainder of this study is organized as follows: in section 2, DEA and input-oriented BCC and CCR models are explained. Then, an efficiency analysis application is made for the 99 WPPs in Turkey. In sections 3 and 4, the results obtained are interpreted, and conclusions are drawn.

2. EXPERIMENTAL

In this section, the DEA method is explained first. Then, two different models used in DEA, namely the input-oriented CCR and input-oriented BCC models, are explained. Finally, the efficiency analysis performed using these methods for WPPs in Turkey is described.

2.1. Data Envelopment Analysis (DEA)

Data envelopment analysis is a linear programming-based method that can measure the relative effectiveness of decision-making units when there are multiple inputs and outputs with different units of measurement. The basis of DEA was Farrell's 1957 study [32]. Charnes, Cooper and Rhodes further developed Farrell's concept of relative technical efficiency and developed an analysis method that allowed multiple inputs or outputs to be reduced to a single input or output. This analysis method developed by Charnes et al. in 1978 under a fixed return assumption is referred to as CCR [33]. A different model of DEA called BCC, based on a variable return on a scale basis, was developed by Banker et al. in 1984 [34].

The CCR and BCC models used in DEA can be created in two different ways as input- and output-oriented. If there is little or no control over the inputs, an output-oriented model is created; likewise, if there is little or no control over the outputs, an input-oriented model should be established. Input-oriented models attempt to use the minimum input to produce the existing output [35]. Since we examined the total efficiency of the WPPs in the current study and attempted to determine the efficiency score, the input-oriented CCR and input-oriented BCC models, which could obtain the current output using minimum input, were used [36]:

<u>Input-oriented CCR Model:</u>

$$Enk\ \theta_k - \varepsilon \sum_{i=1}^{m} S_i^- - \varepsilon \sum_{r=1}^{s} S_r^+ \tag{1}$$

$$S_i^- = \theta_k X_{ik} - \sum_{j=1}^{n} X_{ij}\lambda_{jk} \qquad i=1,...,m \tag{2}$$

$$S_r^+ = \sum_{j=1}^{n} Y_{rj}\lambda_{jk} - Y_{rk} \qquad r=1,...,s \tag{3}$$

$$\lambda_{jk}, S_i^-, S_r^+ \geq 0 \qquad j=1,...,n \tag{4}$$

<u>Input-oriented BCC Model:</u>

$$Enk\ \theta_k \tag{5}$$

$$S_i^- = \theta_k X_{ik} - \sum_{j=1}^{n} X_{ij}\lambda_{jk} \qquad i=1,...,m \tag{6}$$

$$S_r^+ = \sum_{j=1}^{n} Y_{rj}\lambda_{jk} - Y_{rk} \qquad r=1,...,s \tag{7}$$

$$\sum_{j=1}^{n} \lambda_{jk} = 1 \qquad j=1,...,n \tag{8}$$

$$\lambda_{jk}, S_i^-, S_r^+ \geq 0 \qquad \forall i,j,r \tag{9}$$

Y_{rj} : the r[th] output of WPP$_j$

X_{ij} : the i[th] input of WPP$_j$

λ_{jk} : the model variables

S_i^- : the value of slack for the i[th] input

S_i^+ : the value of slack for the r[th] output

θ_k : the efficiency in input orient $(0 \leq \theta_k \leq 1)$

ε : a very small number

If both of the following conditions are met, WPP is regarded as efficient.

1. $\theta_k = 1$
2. All slack variables (S_i^-, S_i^+) are zero.

2.2.Application

In this study, an efficiency analysis of 99 WPPs in Turkey was performed using input-oriented CCR and BCC models.

The input variables used in the models included installed power and production capacity. Installed power is the maximum capacity that a power plant can meet or an electric network can carry. It is the maximum capacity carried by an installation. The unit was taken as MWe. Production capacity is the total amount of energy the plant can produce annually. The unit considered is GWh. The amount of wind turbine, on the other hand is in piece.

Output variables used in the models included power generation amount and the number of persons whose average energy needs are met. Power generation amount (in GWh) is the total amount of energy generated annually by the power plant. The number of persons whose average need are met represented the capacity of power plants to generate energy to meet the electricity needs of a certain number of people. Sale price to the grid; 1 kWh electricity sales price to the grid ($).

Input and output values were determined for each WPP plant. Some of these are shown in Table 1 and Table 2 [37]. All of these are shown in Appendix A. Because of data privacy, the names of the power plants are coded with numbers. Regional data are available for power plants.

Table 1. Input Values of WPPs

WPP No	*Installed Power (Mwe)*	*Generation capacity /annual (GWh)*	*The amount of wind turbine (Piece)*
1	240	820.277	169
2	200	604.1	81
.	.	.	.
.	.	.	.
.	.	.	.
98	7	24.5	3
99	6	21	3

Table 2. Output Values of WPPs

WPP No	*Power Generated/annual GWh*	*Number of Persons Whose Average Need are met*	*Sale price to grid ($/1 kWh)*
1	511	154.478	0.0858
2	239	72.233	0.0778
.	.	.	.
.	.	.	.
.	.	.	.
98	16	4.974	0.079
99	7	2.221	0.073

A model of input-oriented CCR by using equation (1-4) and BCC by using equation (5-9) was established for each WPP to measure efficiency. CCR model for WPP 1 is presented as follows equations:

For A WPP 1;

$$\text{Min} \quad \theta_1 - \varepsilon^*(s_1^- + s_2^- + s_3^- + s_4^+ + s_5^+ + s_6^+) \qquad (10)$$

$$240\theta_1 - 240\lambda_1 - 200\lambda_2 - \ldots - 7\lambda_{98} - 6\lambda_{99} - s_1^- = 0 \qquad (11)$$

$$820.277\theta_1 - 820.277\lambda_1 - 604.1\lambda_2 - \ldots - 24.5\lambda_{98} - 21\lambda_{99} - s_2^- = 0 \qquad (12)$$

$$169\theta_1 - 169\lambda_1 - 81\lambda_2 - \ldots - 3\lambda_{98} - 3\lambda_{99} - s_3^- = 0 \qquad (13)$$

$$511\lambda_1 + 239\lambda_2 + \ldots + 16\lambda_{98} + 7\lambda_{99} - s_4^+ = 511 \qquad (14)$$

$$154.478\lambda_1 + 72.233\lambda_2 + \ldots + 4.974\lambda_{98} + 2.221\lambda_{99} - s_5^+ = 154.478 \qquad (15)$$

$$0.0858\lambda_1 + 0.0778\lambda_2 + \ldots + 0.079\lambda_{98} + 0.073\lambda_{99} - s_6^+ = 0.0858 \qquad (16)$$

$$s_1^-, s_2^-, s_3^-, s_4^+, s_5^+, s_6^+, \lambda_j \geq 0, \qquad j = 1,2,\ldots,99 \quad (17)$$

3. RESULTS

In this section, the results obtained through DEA are discussed. The models of input-oriented CCR and BCC for each WPP were studied using a GAMS package program. Some of the results obtained are shown in Table 3 and Table 4. All data are provided in Appendix B and Appendix C. When the results of 99 WPP plants were examined, six plants (power plants numbered 74, 76, 95, 97, 98, and 99) were determined to be relatively effective, according to the CCR model. In contrast, 18 plants (power plants numbered 1, 3, 4, 5, 11, 15, 25, 37, 42, 57, 59, 63, 74, 76, 95, 97, 98, and 99) were found to be are relatively effective, according to the BCC model.

The efficiency values of the effective WPPs, according to the CCR model, are shown in Figure 1. In the graph, the efficiency values of 43.43% of WPPs were in the range of 0.7–0.9 while the efficiency of 7.07% of the plants fell below 0.5, and only the 6.06% of the plants were efficient. The efficiency values of the effective WPPs, according to the BCC model, are shown in Figure 2. In the graph, efficiency values of 44% of the WPPs were in the range of 0.7–0.9, but the efficiency 6% of WPPs fell below 0.5, and 18% of the plants were regarded as efficient. The reason why the results of the two models are different is the scales of the models. The analysis of returns to scale state can provide improvement directions and suggestions for WPPs to achieve reasonable resource allocation. The return values of the sectors can be used to guide the future improvement of energy efficiency.

As can be seen in Table 3, the primary reason why WPP 1 is ineffective is due to the number of people whose average energy needs must be met. Therefore, the number of people whose energy needs must be met should be increased by 0.16% in order to make the power plant efficient. Currently, WPP 1 meets the needs of 154,478 people as is. If WPP 1 is able to meet the energy needs of 154,722 people, it will become efficient.

As seen in Table 4, the amount of power generation should be improved by 4.2% for WPP 2. This means that the amount of power generation for WPP 2 is normally 239 (GWh). The plant does not work effectively as it is required to be. If the amount of power generation of WPP 2 is increased by 4.2% (10.143 GWh). The power plant will be relatively effective.

Table 3. GAMS results of WPPs for CCR

CCR Model		
WPP	*θ*	*Si*
1	0.583	3.343 - 52.970 - 243.693 0.308
2	0.370	10.143 - 8.867 - 131.941 0.106
. . .	. . .	. . .
98	1	- - - - -
99	1	- - - - -

Table 4. GAMS results of WPPs for BCC

BCC Model		
WPP	*θ*	*Si*
1	1	- - - - - -
2	0.475	12.417 - 2.350 - - -
. . .	. . .	. . .
98	1	- - - - -
99	1	- - - - -

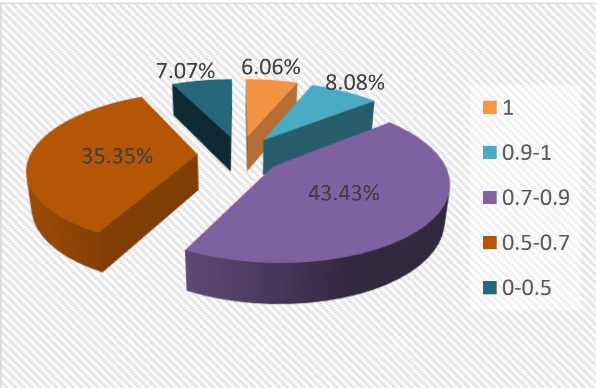

Fig. 1. Efficiency values of WPPs for CCR model.

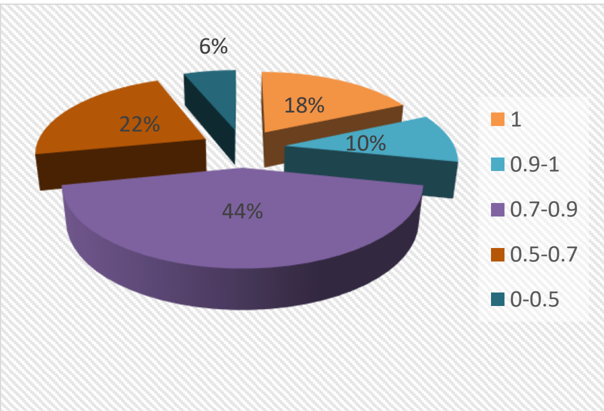

Fig. 2. Efficiency values of WPPs for BCC model.

4. CONCLUSION

This study has attempted to show how WPPs' relative efficiencies can be measured using the DEA method and how efficiency comparisons can be performed without requiring any assumptions.

The efficiencies of WPPs, which make up 10.81% of Turkey's total installed power, were measured using input-oriented CCR and BCC models in this study. In application, CCR and BCC models were facilitated separately for 99 WPPs, and the models were solved using a GAMS package program. The results revealed that 6.06% of the 99 WPPs were relatively effective, according to the CCR model, while 18% of the 99 WPPs were relatively effective, according to the BCC model. These results revealed how WPP inefficiency was related to an insufficiency of installed power and the amount of wind turbine. Therefore, inefficient WPPs can be made relatively effective by increasing the amount of wind turbine.

In addition to providing information to decision makers about the performance of the plants, these analyses may serve as a guideline for policy making in the energy sector in terms of identifying the efficiency value of individual plants.

Future studies may include additional calculations and compare the results for output-oriented BCC and output-oriented CCR output models. In this study, the efficiencies of WPP plants were measured, but it is possible to calculate the efficiency value for different power plant types.

Acknowledgement

Initial version of this paper was presented at the 3rd International Conference on Advanced Engineering Technologies (ICADET) 2019, Bayburt, Turkey.

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Biographies

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Appendix A: Input and Output Values of WPPs

WPP No	*Installed power (Mwe)*	*Generation capacity /annual (GWh)*	*The amount of wind turbine (Piece)*	*Power Generated/annual GWh*	*Number of persons whose average need was met*	*Sale price to grid ($/1kWh)*
1	240	820.277	169	511	154478	0,0858
2	200	604.1	81	239	72233	0.0778
3	168	588.5	70	317	95917	0.0858
4	143	606.375	52	376	113608	0.0778
5	135	510	54	389	117482	0.073
6	128	414.873	63	192	58138	0.0778
7	120	420	46	267	80697	0.073
8	120	420	46	277	83566	0.073
9	114	332	43	285	86078	0.073
10	93	325.5	30	201	60579	0.073
11	93	325.5	29	284	85695	0.073
12	87	304.5	29	230	69497	0.073
13	85	198.05	34	102	30765	0.0778
14	77	270.9	30	163	49175	0.0778
15	76	273	31	241	72913	0.073
16	75	199.275	26	113	34107	0.0778
17	73	184.179	29	169	50955	0.073
18	72	216	36	167	50541	0.073
19	67	234.418	28	145	43784	0.0858
20	63	228	29	95	28710	0.073
21	61	164.93	25	137	41403	0.0778
22	60	192.895	19	102	30898	0.087
23	60	156.5	27	93	28223	0.073
24	60	163.65	20	137	41325	0.079
25	60	233	24	201	60585	0.073
26	56	184.514	55	124	37390	0.073
27	56	154.1	51	98	29697	0.073
28	55	165	18	119	35937	0.073
29	54	166.177	48	110	33188	0.073
30	54	210	60	138	41704	0.073
31	53	183.75	22	93	28215	0.087
32	52	162	23	122	36826	0.073
33	51	179.2	16	114	34351	0.079
34	50	171.162	19	90	27047	0.073
35	50	152.587	16	129	38955	0.0778
36	50	216.814	20	158	47878	0.0778
37	50	175	16	174	52677	0.0778
38	50	182.632	16	140	42444	0.0778
39	50	175	16	124	37594	0.0778
40	50	165	20	132	39781	0.0778
41	48	135	16	116	35086	0.073
42	46	161	20	123	37054	0.087
43	45	151.61	20	125	37875	0.0778
44	44	154	32	93	28119	0.087
45	43	151.17	19	127	38393	0.0778
46	42	147	14	71	21381	0.087
47	42	147	15	81	24612	0.087
48	42	83.66	40	72	21901	0.073
49	41	140	18	79	23756	0.073
50	39	180	13	93	28231	0.073
51	39	150	16	95	28640	0.0778
52	38	101.29	12	77	23377	0.073
53	36	100.66	13	44	13306	0.078
54	36	126.144	18	92	27644	0.073
55	35	144.375	13	98	29580	0.0778
56	35	104.279	12	85	25749	0.073
57	34	147	14	126	38001	0.073

58	33	115.5	14	97	29325	0.0858
59	32	112.7	14	94	28383	0.087
60	32	122.462	15	91	27582	0.073
61	31	99.41	15	62	18725	0.073
62	30	105	10	54	16285	0.0778
63	30	150	12	108	32636	0.079
64	30	105	12	93	28216	0.073
65	30	102.59	15	79	23735	0.073
66	30	73.2	27	70	21044	0.073
67	30	91.6	13	81	24548	0.073
68	29	96	15	81	24604	0.073
69	28	51.322	9	44	13370	0.073
70	278	100.35	12	64	19391	0.073
71	28	90.227	12	52	15584	0.087
72	28	72.27	13	39	11785	0.073
73	28	96.25	19	84	25490	0.073
74	27	36	12	31	9312	0.0778
75	27	100.066	14	71	21414	0.073
76	27	94.5	9	101	30581	0.0778
77	25	87.5	10	69	20768	0.073
78	25	82.287	11	56	16967	0.0778
79	24	85	12	57	17102	0.073
80	24	83.005	12	56	16978	0.073
81	24	105.117	12	69	20800	0.073
82	22	75.6	9	35	10549	0.087
83	20	83.2	8	58	17500	0.073
84	20	80	8	45	13641	0.073
85	20	70.08	10	62	18788	0.081
86	20	38	8	30	9160	0.0778
87	20	62	10	45	13614	0.073
88	19	58.867	8	31	9287	0.0778
89	19	67	12	49	14876	0.081
90	16	58.561	6	39	11782	0.0858
91	15	47.66	18	42	12615	0.073
92	11	67	6	32	9625	0.073
93	10	40	5	23	6909	0.0778
94	10	34.273	4	22	6778	0.073
95	10	35	7	29	8704	0.081
96	9	31.537	5	15	4456	0.073
97	7	24.528	4	15	4652	0.087
98	7	24.5	3	16	4974	0.079
99	6	21	3	7	2221	0.073

Appendix B: GAMS results of WPPs for CCR

WPP	*θ*	*Si*	*WPP*	*θ*	*Si*	*WPP*	*θ*	*Si*	*WPP*	*θ*	*Si*
1	0.583	3.343	31	0.486	-	61	0.617	-	91	0.939	-
		-			-			-			-
		52.970			1.848			1.339			9.689
		-			0.112			-			-
		243.693			-			14.138			48.424
		0.308			-			-			-
2	0.370	10.143	32	0.705	3.674	62	0.567	1.086	92	0.948	-
		-			-			3.801			27.024
		8.687			5.335			-			-
		-			-			-			-
		131.941			113.426			135.547			56.252
		0.106			0.021			-			-
3	0.504	-	33	0.635	2.032	63	0.962	-	93	0.853	-
		0.252			7.117			42.307			4.242
		7.062			-			1.925			-
		-			-			-			-
		64.950			166.168			64.475			136.377
		0.158			0.009			0.004			-
4	0.705	-	34	0.495	-	64	0.832	-	94	0.835	0.174
		75.915			-			-			-
		3.174			0.922			1.637			-
		-			-			0.183			0.033
		238.099			198.461			-			-
		0.212			-			-			-
5	0.77	-	35	0.791	5.065	65	0.736	-	95	1	-
		28.886			-			-			-
		6.933			1.161			2.934			-
		-			-			-			-
		300.267			103.901			168.800			-
		0.227			0.022			-			-
6	0.433	4.099	36	0.845	-	66	0.929	2.430	96	0.716	-
		-			35.351			-			0.004
		10.171			2.818			15.565			-
		0.013			0.127			-			-
		-			-			124.481			170.447
		0.07			0.044			-			-
7	0.595	-	37	0.969	1.938	67	0.844	-	97	1	-
		-			6.783			-			-
		3.569			-			1.949			-
		-			-			0.122			-
		145.842			7.099			-			-
		0.133			0.056			-			-
8	0.617	-	38	0.781	1.561	68	0.807	-	98	1	-
		-			11.423			-			-
		3.702			-			3.934			-
		-			0.180			0.248			-
		304.663			-			-			-
		0.14			0.03			-			-
9	0.803	15.375	39	0.691	1.383	69	0.907	5.600	99	1	-
		-			4.840			-			-
		9.141			-			-			-
		-			0.162			0.166			-
		214.921			-			-			-
		0.147			0.018			-			-
10	0.597	1.791	40	0.749	1.764	70	0.629	154.536			
		6.269			-			-			
		-			3.208			-			
		-			-			-			
		280.218			186.248			-			
		0.082			0.024			-			
11	0.873	5.286	41	0.804	7.580	71	0.61	1.357			
		18.326			-			-			
		-			2.527			-			
		-			-			-			
		295.139			36.733			157.863			
		0.146			0.016			-			
12	0.707	-	42	0.715	-	72	0.585	-			
		-			-			-			
		-			3.336			0.044			
		-			-			-			
		142.901			188.208			-			
		0.104			0.008			-			
13	0.482	13.692	43	0.772	1.068	73	0.83	-			

		-			-			-
		7.295			4.293			7.796
		-			0.090			0.159
		118.782			-			-
		7.70E-04			0.019			-
14	0.563	-	44	0.578	-	74	1	-
		-			-			
		2.364			9.066			-
		-			-			-
		178.495			19.661			-
		0.048			-			-
15	0.848	-	45	0.799	-	75	0.729	-
		5.934			1.933			4.057
		4.804			3.861			2.500
		-			-			-
		57.505			60.337			59.601
		0.113			0.02			-
16	0.531	9.584	46	0.506	-	76	1	-
		-			0.969			-
		3.725			3.392			-
		-			-			-
		107.386			179.279			-
		0.009			-			-
17	0.859	17.065	47	0.54	0.003	77	0.768	-
		-			-			-
		9.838			-			0.040
		-			0.168			-
		215.188			-			98.023
		0.057			-			-
18	0.723	7.441	48	0.836	9.466	78	0.694	-
		-			-			-
		11.161			24.059			0.536
		-			0.411			-
		23.624			-			-
		0.056			-			-
19	0.579	-	49	0.54	-	79	0.681	-
		0.155			-			0.681
		3.303			1.591			0.907
		-			-			-
		119.416			147.793			118.553
		0.026			-			-
20	0.402	-	50	0.641	0.036	80	0.681	-
		2.878			28.017			-
		3.206			-			1.755
		-			0.231			-
		54.307			-			-
		1.78E-04			-			-
21	0.777	10.397	51	0.656	-	81	0.8	-
		-			8.852			16.889
		7.222			1.678			1.960
		-			-			-
		78.158			118.265			66.023
		0.028			-			-
22	0.5	2.156	52	0.731	3.476	82	0.545	0.221
		-			-			149.799
		-			-			-
		0.015			0.240			-
		-			-			-
		-			-			-
23	0.558	8.164	53	0.469	3.587	83	0.831	-
		-			-			10.958
		6.563			-			-
		0.218			-			-
		-			37.854			69.756
		-			-			-
24	0.783	10.373	54	0.686	-	84	0.677	-
		-			0.099			6.760
		3.458			3.979			-
		-			-			-
		156.158			209.173			36.375
		0.027			-			-
25	0.895	-	55	0.751	-	85	0.894	-
		20.598			16.429			0.064
		3.582			0.857			1.762
		-			-			-

		274.218			89.633			-
		0.082			-			-
26	0.629	2.189	56	0.773	1.708	86	0.934	1.999
		-			-			-
		23.534			0.411			-
		-			0.075			0.188
		154.990			-			-
		0.023			-			-
27	0.595	6.950	57	0.991	-	87	0.763	-
		-			27.739			-
		21.631			2.642			0.759
		0.080			-			-
		-			149.554			-
		0.003			0.024			-
28	0.675	5.302	58	0.799	-	88	0.62	1.356
		-			-			-
		1.542			1.703			-
		-			-			-
		94.079			30.386			157.959
		0.019			-			-
29	0.619	4.163	59	0.798	-	89	0.779	-
		-			-			0.377
		19.927			1.694			3.115
		-			-			-
		118.040			59.450			-
		0.012			-			-
30	0.683	-	60	0.777	-	90	0.799	0.075
		14.347			9.482			2.309
		28.693			3.432			-
		-			0.081			-
		79.941			-			-
		0.033			-			-

Appendix C: GAMS results of WPPs for BCC

WPP	θ	Si	WPP	θ	Si	WPP	θ	Si	WPP	θ	Si
1	1	-	31	0.633	1.219	61	0.626	-	91	0.959	-
					4.265			-			-
		-			-			0.989			9.503
		-			0.441			-			-
		-			-			5.988			39.038
		-			-			0.006			0.007
2	0.475	12.417	32	0.726	3.787	62	0.568	1.106	92	0.976	-
		-			-			3.871			27.805
		2.350			5.691			-			-
		-			-			-			-
		-			111.384			136.835			64.887
		-			0.005			6.6353E-4			0.007
3	1	-	33	0.667	2.123	63	1	-	93	0.863	-
					7.426			-			4.316
		-			-			-			-
		-			-			-			-
		-			178.196			-			124.138
		-			-			-			0.002
4	1	-	34	0.499	-	64	0.838	-	94	0.859	0.152
					-			-			-
		-			0.607			1.615			-
		-			-			0.150			-
		-			191.691			-			3.271
		-			0.005			0.005			0.006
5	1	-	35	0.822	5.262	65	0.744	-	95	1	-
					-			-			-
		-			1.462			2.616			-
		-			-			-			-
		-			101.178			161.370			-
		-			-			0.006			-
6	0.497	4.505	36	0.900	-	66	0.937	1.018	96	0.765	-
		-			37.636			-			0.028
		9.231			3.522			14.972			0.827
		0.118			0.145			-			-
		-			-			117.871			212.111
		-			-			0.005			0.005
7	0.721	-	37	1	-	67	0.851	-	97	1	-
		-			-			-			-
		6.123			-			1.919			-

		0.349			-			0.091			-
		-			-			-			-
		72659E-4			-			0.005			-
8	0.752	-	38	0.797	1.521	68	0.814	-	98	1	-
		-			7.909			-			-
		6.428			-			3.998			-
		-			0.193			0.206			-
		27.855			-			-			-
		3.0545E-4			-			0.005			-
9	0.987	19.025	39	0.701	0.768	69	0.922	5.325	99	1	-
		-			2.688			-			-
		13.145			0.169			-			-
		0.265			-			0.120			-
		-			-			-			-
		-			-			0.005			-
10	0.651	-	40	0.780	1.838	70	0.637	156.117			
		-			-			-			
		0.343			3.626			-			
		-			-			-			
		202.418			183.233			14.896			
		0.004			-			0.005			
11	1	-	41	0.822	7.755	71	0.730	1.624			
		-			-			-			
		-			2.722			0.071			
		-			-			-			
		-			35.274			182.519			
		-			0.005			-			
12	0.826	-	42	1	-	72	0.597	-			
		-			-			-			
		1.346			-			-			
		0.036			-			-			
		-			-			6.818			
		0.002			-			0.006			
13	0.483	13.716	43	0.799	1.104	73	0.837	-			
		-			-			-			
		7.317			4.661			7.898			
		-			0.098			0.116			
		118.685			-			-			
		-			-			0.005			
14	0.601	-	44	0.725	8.8998E-5	74	1	-			
		-			-			-			
		3.091			9.326			-			
		-			0.121			-			
		172.466			-			-			
		-			-			-			
15	1	-	45	0.828	-	75	0.738	-			
		-			2.004			4.106			
		-			4.240			2.160			
		-			-			-			
		-			57.808			51.583			
		-			-			0.006			
16	0.541	9.766	46	0.792	8.403	76	1	-			
		-			29.401			-			
		3.906			-			-			
		-			-			-			
		106.219			92.975			-			
		-			-			-			
17	0.920	18.292	47	0.827	6.555	77	0.778	-			
		-			22.938			-			
		11.166			-			-			
		-			0.446			-			
		208.575			-			190.890			
		0.005			-			0.006			
18	0.774	7.976	48	0.844	8.119	78	0.697	-			
		-			-			-			
		12.551			23.544			0.585			
		-			0.433			-			
		17.205			-			-			
		0.005			0.005			0.001			
19	0.812	0.883	49	0.545	-	79	0.692	-			
		-			-			0.692			
		-			1.260			0.528			
		0.258			-			-			
		-			140.371			109.722			
		-			0.006			0.007			

20	0.405	-	50	0.650	0.184	80	0.691	-
		2.899			28.915			-
		2.924			-			1.647
		-			0.199			-
		47.917			-			-
		0.005			0.005			0.006
21	0.814	10.885	51	0.656	-	81	0.810	-
		-			8.856			17.109
		7.890			1.662			1.611
		-			-			-
		74.658			117.917			57.889
		-			2.6667E-4			0.006
22	0.828	13.504	52	0.738	3.530	82	0.726	2.586
		33.092			-			8.316
		-			-			-
		0.411			0.203			-
		-			-			110.848
		-			0.005			-
23	0.562	6.744	53	0.471	1.180	83	0.843	-
		-			-			11.133
		5.852			-			-
		0.239			-			-
		-			77.060			79.573
		0.005			4.6163E-4			0.006
24	0.840	11.123	54	0.691	-	84	0.691	-
		-			0.100			6.907
		3.922			3.688			-
		-			-			-
		165.949			202.375			40.563
		-			0.005			0.006
25	1	-	55	0.751	-	85	0.894	-
		-			16.432			0.064
		-			0.849			1.764
		-			-			-
		-			89.458			-
		-			1.3333E-4			-
26	0.650	2.262	56	0.779	0.958	86	0.942	1.172
		-			-			-
		24.523			-			-
		-			0.072			0.162
		152.753			-			-
		0.005			0.005			5.6032E-4
27	0.597	6.279	57	1	-	87	0.778	-
		-			-			-
		21.346			-			0.606
		0.091			-			-
		-			-			-
		0.005			-			0.006
28	0.693	5.445	58	0.974	1.5067E-4	88	0.625	-
		-			-			-
		1.748			0.320			-
		-			0.022			-
		92.329			-			173.591
		0.005			-			0.001
29	0.628	4.223	59	1	-	89	0.780	-
		-			-			0.383
		20.300			-			3.185
		-			-			-
		117.164			-			-
		0.005			-			-
30	0.707	-	60	0.783	-	90	0.996	2.292
		-			9.559			10.552
		28.509			3.444			-
		0.006			0.045			-
		-			-			113.671
		0.002			0.005			-