

Performance assessment and supply energy planning in Iranian wind power plants

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Abstract

Data envelopment analysis (DEA) is a mathematical programming approach for the performance basement of the production units from a production economic view. In this work, we analyze the performance of Iranian wind power plants (IWPPs) using DEA. In the second phase of the work, we utilize the inverse DEA approach as a valuable method for the future planning of IWPPs. In this step, we consider five different scenarios from a short-run up to a long-run planning for electricity production by renewable energy. In the short-run, we just need more capacity factor rather than capital. Although in the mid-run we do not presume capital extension, the result suggests this. In the end, in the long-run planning, extension in not only capacity factor but also more investment in the higher technologies is a requirement for reaching the desired electricity production.

Keywords: Wind power plant performance, Energy efficiency, Energy planning, Mathematical programming.

Introduction

Energy production and supply are vital issues for all societies from different views. Nowadays, any interruption in this sector is like a nightmare, and may have a non-compostable effect on other parts of the human life. Energy production, specifically electricity production, usually involves producing some emission as a by-product that affects human life from another angle. Therefore, having green electricity, namely electricity with no emissions, is also vital and essential. Environmental issues are becoming a more significant concern regarding the expansion of energy uses in different sectors. Non-renewable energy still is the most energy source, about 85%, in the world.

Consequently, the environmental impact of using nonrenewable energies has been focused on during the last decades. One of the most critical issues and concerns is achieving maximum energy production from a particular energy source. The growing electricity demand can be attributed to the economic structure, climate change, and technology structure. One of these key strategies and practices are identifying and measuring the efficiency of the environmental performance of electricity production firms [1].

Ref. [2] utilized a two stages DEA-Tobit regression model for efficiency analysis of 39 wind power plants in the US. They found that more than half of power plants were working efficiently, and newly

installed power plants are more expensive and less productive than the currently installed power

plants. Ref. [3] used the fuzzy TOPSIS method for evaluation and ranking, and consequently, site selection of wind power plants. Ref. [4] propped a double frontier network DEA for analysis and sustainable location of hybrid photovoltaic and wind power plants in Iran. Ref. [5] provided a systematic literature review of the Chinese wind power industry. They used a four-stage DEA approach to analyze wind power companies in terms of efficiency. They investigated the scale of enterprises, their nature, regions, and the downstream and upstream of their industrial chain in each stage. [6] proposed a meta frontier DEA model, and then developed a decomposition scheme for studying the sources of inefficiency in power generation. [7] performed a cost efficiency analysis and productivity analysis, and considered the environmental effects of Chinese power plants and found an approximate U-shaped effect of environmental regulation on productivity growth. [8] also performed a cost efficiency analysis of power plants in Bangladesh in order to identify the sources of inefficiencies. [9] proposed a stochastic cross efficiency DEA model for evaluating 32 thermal power plants.

The current article is the first attempt for performance assessment and planning based on the performance for IWPPs. The performance assessment and planning of IWPPs have not been investigated in the literature, based on the best knowledge of the author. We perform a two-phase analysis. In the first place, we perform an efficiency analysis and performance assessment of Iranian wind power pants (IWPPs). Secondly, we

accomplish a post-efficiency analysis for planning. In the first phase, we use the DEA approach for the efficiency analysis, and in the second phase, we utilize the inverse DEA approach for a short-run, mid-run, and a long-run planning of IWPPs. The primary result shows a high efficiency in the performance of IWPPs based on the data set gained from the RETScreen software, in the constant returns to scale and variable returns to scale case. We suggest more investigation regarding the fact the input-output data is estimated itself. The second phase of the analysis provides useful information for the future planning of IWPPs. In the short-run period, we may not need any extra capital for increasing the electricity production by the wind farms. The factor capacity is the key factor in this run. However, if we aim to produce more electricity by wind farms in the mid-run and long-run period of time and closing to the expected electricity levels out of renewable energy systems by the sixth national development, we need more investment for IWPPs.

The structure of this paper is as what follows. Section I reviews the relative literature in the performance assessment and planning of IWPPs. Section II describes the research method. Section III implements the efficiency analysis, and provides scenario-based planning for IWPPs. Section I reviews the relative literature for wind power plant assessment. Section II provides the research methodology of the study. Section III utilizes the methodology for the performance assessment and future planning of IWPPs.

2. Research Methodology

In this section, we describe the reach methodology that is used for both phases of our analysis.

2.1. DEA models

Assume that there are n DMUs using m dimensional input vector of $\mathbf{x}_j = (x_{1j}, x_{2j}, \dots, x_{mj}) \in \mathbb{R}_+^m$ to produce s dimensional output vector of $\mathbf{y}_j = (y_{1j}, y_{2j}, \dots, y_{sj}) \in \mathbb{R}_+^s$. The general production technology for the above input-output data is $T = \{(x, y) : x \text{ can produce } y\}$. Considering the input-output set, we can identify the following production technology:

$$T = \{(x, y) \mid x \geq \sum_{j=1}^n \lambda_j \mathbf{x}_j, y \leq \sum_{j=1}^n \lambda_j \mathbf{y}_j, \lambda \in \Lambda\}$$

where Λ specifies the returns to scale properties of the production. We used the following parameters in the current work:

- θ is the efficiency level of the power plant that is under evaluation.
 - $\lambda_j \quad 1 \leq j \leq n$ is the intensity variable associated with the j -th powerplant.
 - $\alpha_i \quad 1 \leq i \leq m = 2$ is the required level of i -th input for producing the desired output level that is electricity production.
- In the current study, we also used the following data:
- $x_{ij} \quad 1 \leq j \leq n = 31, 1 \leq i \leq m = 2$ is the i -th input of the j -th power plant that includes capacity factor and capital.
 - $y_{rj} \quad 1 \leq j \leq n = 31, 1 \leq r \leq s = 1$ is the output of the j -th power plant, which is electricity production.
 - $\beta_{rj} \quad 1 \leq j \leq n = 31, 1 \leq r \leq s = 1$ is the targeted output level of the j -th power plant that is electricity production that is expected to be produced.
 - γ is the improvement percentage of efficiency for estimating the required input level that can produce the desired output level of β .

Considering Farrell's distance measure of $\min \{\theta \mid (\theta x_k, y_k) \in T\}$ [10] for the production technology T , we get the following linear programming model for measuring the relative efficiency of DMU $_k$, i.e. the DMU under assessment:

$$\theta_o = \text{Min } \theta$$

$$s.t$$

$$\sum_{j=1}^n \lambda_j x_{ij} \leq \theta x_{io} \quad i = 1, 2, \dots, n \quad (1)$$

$$\sum_{j=1}^n \lambda_j y_{rj} \geq y_{ro} \quad r = 1, 2, \dots, s$$

$$\lambda \in \Lambda$$

See [11] for more description of the modelling properties of the above linear programming.

If we solve the above model for all DMUs, then we find the relative efficiency scores of all DMUs based on the observed input-output parameters.

Considering $\Lambda = \{\lambda_j : \lambda_j \geq 0, 1 \leq j \leq n\}$ in the above model yields to the well-known CCR model of [11] with constant returns to scale

properties, and considering

$$\Lambda = \{\lambda_j : \sum_{j=1}^n \lambda_j = 1, \lambda_j \geq 0, 1 \leq j \leq n\}$$

, we get the BBC model of [12] with variable returns to scale properties for the production technology, and having these two measures, we can find the scale efficiency of production units as the ratio of CCR-efficiency to the BCC-efficiency.

Definition 1. DMUo is (weakly) efficient if the optimal value of linear programming (2) is unity ($\theta_k = 1$).

The index of θ_k is the relative efficiency score of DMUK compared with other existing production units. The measure of $1 - \theta_k$ specifies the inefficiency or deficiency of this unit, and determines the percentage of wasted input level by this unit. If we multiply this index by the input values, then we find the wasted input of DMUK by $(1 - \theta_k) \mathbf{x}_k$. In other words, the latter measure determines the potential possibility of improvement for the unit under evaluation. This improvement path can be performed by target setting based on those production units that are performing well.

2.2. Inverse DEA models

In this sub-section, we go one step forward compared with the efficiency analysis. We know that having the input-output set, the DEA models seek the efficiency score of DMUs. In a quite different path, the inverse DEA models try to answer another question. Assume that DMUK

perturbs its output from y_{rk} to $\beta_{rk} = y_{rk} + \Delta y_{rk}$. The question is how much input is required for producing a new output level of DMUK with its current efficiency score of θ_k . This question is answered by the following multiple objective linear programming (MOLP) in the inverse DEA literature.

$$\text{Min}(\alpha_1, \alpha_2, \dots, \alpha_m)$$

s.t

$$\sum_{j=1}^n \lambda_j x_{ij} \leq \theta_k (x_{ik} + \Delta x_i) = \theta_k \alpha_i, \quad i = 1, 2, \dots, m$$

$$\sum_{j=1}^n \lambda_j y_{rj} \geq (y_{rk} + \Delta y_{rk}) = \beta_{rk}, \quad r = 1, 2, \dots, s \quad (2)$$

$$\lambda \in \Lambda$$

The readers are referred to [13] and [14] for more details about the inverse DEA modeling.

Definition 2. Suppose (λ, α) is a feasible solution MOLP model (2.2); if there is no feasible solution $(\bar{\lambda}, \bar{\alpha})$ for this model such that $\bar{\alpha} < \alpha$, then we say (λ, α) is a weak efficient solution of that model.

It is a well-known fact in the inverse DEA literature that weak efficient solutions of the MOLP model (2) preserve the efficiency score of DMUs (see, for instance, [15]).

The inverse DEA models are useful approaches for the policymaking and planning of production units. This approach determines the required input level for reaching a desired output with the current efficiency status. The current efficiency status plays an important role in the process of output setting and input estimation. The key factor is that we cannot expect an efficiency improvement for production units, at least in a short-run setting. Performance improvement involves many different issues in each production system, depending on the structure of the system. It becomes more complex when we deal with the performance of humans in a production system. However, the inverse DEA models are capable of considering performance improvement in the mid-run and long-run settings. To do this end, we can use the following inverse DEA model that considers the performance improvement for estimating required input that can produce the desired production:

$$\text{Min}(\alpha_1, \alpha_2, \dots, \alpha_m)$$

s.t

$$\sum_{j=1}^n \lambda_j x_{ij} \leq \gamma \theta_k (x_{ik} + \Delta x_i) = \gamma \theta_k \alpha_i, \quad i = 1, 2, \dots, m$$

$$\sum_{j=1}^n \lambda_j y_{rj} \geq (y_{rk} + \Delta y_{rk}) = \beta_k, \quad r = 1, 2, \dots, s \quad (3)$$

$$\lambda \in \Lambda$$

where γ is the improvement percentage of efficiency for estimating the required input level

that can produce the desired output level of β_k .

It is also a well-known fact in the inverse DEA literature that weak efficient solutions of the MOLP model (3) determine the minimum input level for producing desired outputs when the efficiency score of DMUs is improved by γ percentage (see, for instance, [15]). The MOLP models (2) and (3) are used for the short-run, mid-run, and long-run planning of IWPPs in the second phase of the analysis.

3. Efficiency analysis and planning of IWPPs

3.1. Efficiency analysis

In this section, we apply DEA, and inverse DEA approaches for the efficiency analysis and furthermore, planning of IWPPs. The capacity factor and capital are assumed as inputs, and electricity production is assumed as output in this analysis. Table I reports the statistical summary of the data. This dataset is an output of the RETScreen software for IWPP. In the first phase of the analysis, we perform DEA model (1) for the case of constant and variable returns to scale, and the results are reported in the second and the third column of Table II. The result show that most power plants are performing relatively efficient in both constant returns to scale and variable returns to scale cases. The fourth column of Table II reports the scale efficiency of power plants, and as we expect from the theory, we have a large-scale efficiency measure for most of the power plants. Although this report may be promising, it is essential to point out that these measures are relatively efficient, and the performance of these power plants are measured compared with each other. In a more comprehensive analysis, all electricity production systems could be considered in this analysis. On the other hand, only two power plants, namely P19 and P23, are found efficient for all three measures. However, the main focus of this

analysis is the inverse analysis and planning of IWPPs that is performed in the next sub-section.

Table 1. statistical summary of the input and output data.

	Capacity factor	Capital	Electricity production
Max	41.7	81.25	3.65
Min	23.5	66.25	2.06
Mean	27.14193548	73.08467742	2.37709677
StDev	2.867493004	3.24332441	0.25084117

Table 2. technical and scale efficiency of all power plants.

Power plant	CCR-efficiency	BCC-efficiency	Scale efficiency
P1	0.998557	1	0.998557
P2	0.998441	0.999399	0.999041
P3	0.997843	0.998062	0.99978
P4	0.998191	0.998238	0.999953
P5	0.985179	0.985867	0.999301
P6	0.997293	0.997568	0.999724
P7	0.998441	1	0.998441
P8	0.99836	1	0.99836
P9	0.998304	0.998694	0.999609
P10	0.998467	0.998474	0.999993
P11	0.996791	0.996811	0.99998
P12	0.997965	0.998108	0.999857
P13	0.999679	0.999759	0.99992
P14	0.998699	0.999332	0.999367
P15	0.997778	0.998108	0.99967
P16	0.999904	1	0.999904
P17	0.997855	0.997911	0.999943
P18	0.997855	0.997911	0.999943
P19	1	1	1
P20	0.99699	0.997004	0.999986
P21	0.997853	0.998108	0.999744
P22	0.99731	0.997558	0.999751
P23	1	1	1
P24	0.996908	0.9973	0.999607
P25	0.998391	0.998653	0.999738
P26	0.998292	0.998653	0.999639
P27	0.999237	0.99987	0.999367
P28	0.99893	0.999162	0.999768
P29	0.999115	1	0.999115
P30	0.997913	0.997913	0.999999
P31	0.998467	0.998474	0.999993

3.2. Inverse analysis and planning

In this sub-section, we perform a scenario-based inverse analysis for the planning of IWPPs. Based on the sixth national development, we should meet 5000 MWh of electricity production by renewable energy systems. However, we still have a long way to reach this aim since the current electricity production by renewable energy is about 840 MWh. Wind power plants play an essential role in renewable energy in Iran. This is due to the geographical location and high potential possibility of electricity production by wind farms in Iran. Based on the latest possible estimation of wind electricity production, there is a potential of producing 60000 MWh of electricity using wind

farms. 18000 MWh of this value is estimated as the minimum economic electricity production by wind farms in Iran [16]. Regarding the current electricity production of wind farms and the potential possible production of this type of renewable energy, we should enlarge and use this potential in the near future. In this sub-section, we analyze the required input values for different electricity production setting scenarios for IWPPs. In the first round, let us consider a five percent increment in the electricity production of wind farms. We are then interested in finding the required inputs for such an increment with the current status. This analysis is done using model (2). This analysis is performed for all power plants, and the required input levels are reported in the second and third columns of Table III.

TABLE I. required input levels for the short-run planning.

Power plant	First scenario		Second scenario	
	Input 1	Input 2	Input 2	Input 2
P1	1.175	0	2.35	0
P2	1.255	0	2.516615	0
P3	1.29	0	2.588811	0
P4	1.378886	0	2.757773	0
P5	1.338886	0	2.677773	0
P6	1.285	0	2.574934	0
P7	1.262306	0	2.525969	0
P8	1.378653	0	2.757305	0
P9	1.378731	0	2.757461	0
P10	1.344042	0	2.688085	0
P11	1.329042	0	2.658085	0
P12	1.379198	0	2.758396	0
P13	1.353886	0	2.707773	0
P14	1.343731	0	2.687461	0
P15	1.375267	0	2.754724	0
P16	1.393731	0	2.787461	0
P17	1.33912	0	2.678241	0
P18	1.33912	0	2.678241	0
P19	1.319042	0	2.638085	0
P20	1.369042	0	2.738085	0
P21	1.379354	0	2.758708	0
P22	1.374354	0	2.748708	0
P23	2.085	3312500	4.17	6625000
P24	1.328886	0	2.657773	0
P25	1.384354	0	2.768708	0
P26	1.377874	0	2.762365	0
P27	1.432004	0	2.86684	0
P28	1.307593	0	2.616566	0
P29	1.308731	0	2.617461	0
P30	1.339042	0	2.678085	0
P31	1.344042	0	2.688085	0

These columns show the required level of inputs, namely capital and capacity factors for producing the targeted electricity production by wind power plants. The main observation for the first scenario, i.e. 5% enlargement for electricity production, requires more capacity factors for power plants rather than just capital. 5% more electricity production requires 42.29 extra capacity factor in total. On the other side, P23 requires 3312500 more

capital to reach such an electricity enlargement. Recall P23 is one of two power plants that is performing at the optimal size of production compared with other power plants. In the next scenario, we expand the previous scenario by 15% and consider a 10% electricity production enlargement. The result of the required inputs is reported in the last two columns of Table III. We find almost the same result as the previous runs but with different values. This scenario requires 84.61 extra capacity factor in total, and P23 plays a vital role in absorbing the capital again. In mid-run planning, we expect a 100% increment in electricity production by wind power plants. The result of this scenario as the third scenario is reported in Table IV. Compared with the previous scenarios, we found that for the mid-run planning that expects more electricity production, we require extension not only in the capacity factor but also in the capital. This shows the importance of more investment in higher electricity production technology even in mid-run planning.

Table II. required input levels for the mid-run planning.

Power plant	Third scenario		Fourth scenario	
	Input 1	Input 2	Input 2	Input 2
P1	23.62175	0	117.9128	1.43E + 08
P2	25.24698	6237713	125.9409	1.66E + 08
P3	25.95108	7218446	129.4532	1.72E + 08
P4	27.53774	16031181	137.4132	1.91E + 08
P5	26.74406	13499249	133.4322	1.83E + 08
P6	25.8505	5649770	128.9515	1.69E + 08
P7	25.24698	9987713	125.9409	1.7E + 08
P8	27.52842	17891379	137.3853	1.92E + 08
P9	27.53153	17271313	137.3946	1.92E + 08
P10	26.84948	12575608	133.9484	1.83E + 08
P11	26.55185	11626134	132.4555	1.8E + 08
P12	27.55016	13550918	137.4505	1.88E + 08
P13	27.04169	14448723	134.9251	1.86E + 08
P14	26.83705	15055872	133.9112	1.85E + 08
P15	27.56045	9817264	137.4814	1.84E + 08
P16	27.82916	18220787	138.8875	1.95E + 08
P17	26.75337	11639051	133.4601	1.81E + 08
P18	26.75337	11639051	133.4601	1.81E + 08
P19	26.35342	10993151	131.4603	1.78E + 08
P20	27.34553	14158066	136.4366	1.87E + 08
P21	27.55637	12310786	137.4691	1.87E + 08
P22	27.45716	11994294	136.9715	1.86E + 08
P23	27.65558	12627278	137.9668	1.88E + 08
P24	27.66104	8885941	137.9831	1.84E + 08
P25	28.66689	10822702	143.0007	1.92E + 08
P26	26.15225	10355798	130.4568	1.76E + 08
P27	26.14258	12840431	130.4277	1.79E + 08
P28	26.75027	12259117	133.4508	1.82E + 08
P29	26.84948	12575608	133.9484	1.83E + 08
P30	27.65558	12627278	137.9668	1.88E + 08
P31	27.66104	8885941	137.9831	1.84E + 08

In fact, the main observation in this scenario compared with the short-run scenarios is that we need both capital and capacity factor expansion in the mid-run expansion planning. This highlights the possibility of capacity expansion without any extra capital for all power plants (except P23) in the short-run planning. All power plants demand both capital and capacity factors in this scenario, except P1. In the next scenario of the mid-run planning, we consider 500% enlargement for electricity production. The result of this scenario is reported in the last two columns of Table IV. This scenario requires 4220.313 extra factor capacity and $5.78E + 09$ extra capitals to reach the target electricity production. Despite the previous scenario, P1 demands the capital too, like all other power plants, in this scenario.

In the next run of the analysis, we perform a long expansion planning investigation for IWPPs. The result of this analysis is reported in Table V.

table III. Required input levels for the long-run planning.

Power plant	Fifth scenario		Sixth scenario	
	Input 1	Input 2	Input 2	Input 2
P1	447.8761	$6.68E + 08$	405.0238	$6E + 08$
P2	478.3698	$7.26E + 08$	432.5998	$6.53E + 08$
P3	491.7108	$7.47E + 08$	444.6644	$6.72E + 08$
P4	521.9774	$8.02E + 08$	472.034	$7.22E + 08$
P5	506.8406	$7.76E + 08$	458.346	$6.99E + 08$
P6	489.805	$7.43E + 08$	442.9409	$6.68E + 08$
P7	478.3698	$7.3E + 08$	432.5998	$6.57E + 08$
P8	521.8842	$8.03E + 08$	471.9493	$7.24E + 08$
P9	521.9153	$8.03E + 08$	471.9775	$7.23E + 08$
P10	508.7948	$7.78E + 08$	460.1134	$7.01E + 08$
P11	503.1185	$7.69E + 08$	454.9804	$6.92E + 08$
P12	522.1016	$7.99E + 08$	472.1469	$7.2E + 08$
P13	512.5169	$7.86E + 08$	463.479	$7.08E + 08$
P14	508.6705	$7.81E + 08$	460.0005	$7.03E + 08$
P15	522.2045	$7.96E + 08$	472.2405	$7.16E + 08$
P16	527.5916	$8.12E + 08$	477.1105	$7.32E + 08$
P17	506.9337	$7.75E + 08$	458.4307	$6.97E + 08$
P18	506.9337	$7.75E + 08$	458.4307	$6.97E + 08$
P19	499.3342	$7.62E + 08$	451.5584	$6.87E + 08$
P20	518.2553	$7.94E + 08$	468.6685	$7.15E + 08$

P21	522.1637	$7.98E + 08$	472.2034	$7.19E + 08$
P22	520.2716	$7.95E + 08$	470.4924	$7.16E + 08$
P23	792.3	$1.26E + 09$	716.4818	$1.14E + 09$
P24	503.0563	$7.7E + 08$	454.9239	$6.93E + 08$
P25	524.0558	$8.01E + 08$	473.9144	$7.22E + 08$
P26	524.1104	$7.98E + 08$	473.964	$7.18E + 08$
P27	543.1689	$8.28E + 08$	491.199	$7.46E + 08$
P28	495.5225	$7.56E + 08$	448.1114	$6.81E + 08$
P29	495.4258	$7.58E + 08$	448.0235	$6.83E + 08$
P30	506.9027	$7.75E + 08$	458.4024	$6.98E + 08$
P31	508.7948	$7.78E + 08$	460.1134	$7.01E + 08$

In the first part of this run, we consider no technology improvement and estimate the required inputs with the current status for reaching targeted electricity production. The first target is increasing the electricity production 12 times the current production. The results are reported in the first and the second column of Table V. In total, we require an extra unit of capacity factor and capital as 16030.98 and 24540010043, respectively. This shows that expansion in both capacity factor and capital is essential in this run. Although we consider a new technology development in the previous scenario of the long-run planning, we should expect to utilize more advanced and higher technology in this run. This is associated with the performance improvement of the power plants in the long-run planning. The following scenario of the long-run analysis deals with this case. We consider a 10% performance improvement for reaching the target electricity production of the previous scenario. The results are reported in the fourth and fifth columns of Table 5. We require 14497.12 extra units of capacity factor and 22103134130 extra units of capital in this case. Compared with the previous scenario, we require more capacity factors and less capital if we consider the technology improvement, and consequently, perform improvement in the planning process.

4. Conclusion

DEA and inverse DEA are two powerful and useful mathematical programming that can be used in the process of decision-making. The former can be used for performance measurement and efficiency analysis, while the latter is a powerful tool for planning based on performance. These two

approaches are used for the efficiency analysis and planning of IWPPs. We found rather high technical and scale efficiency for the IWPPs based on the dataset of the RETScreen software for renewable energy in Iran including IWPPs. Regarding the fact that this dataset is an output of estimation itself, we believe in the necessity of more investigation in this part of the analysis. The result of the second part of the analysis reveals vital insight and information for future planning and extension of IWPPs. This part highlighted the importance and necessity of more investment in the technology extension that has been used for electricity production by renewable energy, although we did not presume the technology improvement in the mid-run planning. Even in the mid-run planning scenario, we expected a 100% increment in electricity production by wind power plants; we need the extension not only in the capital but also in the capacity factor to reach the desired electricity level. While we need to extend IWPPs both in terms of capacity and technology in the mid-run and long-run, we need no extra investment in the new technology in the short-run and for producing more electricity with the current status of IWPPs. For the long-run planning, technological improvement is necessary, if decision-makers aim to reach the required level of electricity production by renewable energy.

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