Measuring Efficiency of Power Plants in Israel by Data Envelopment Analysis

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Abstract—**An application of data envelopment analysis (DEA) for measuring and evaluating the operating efficiency of power plants in the Israeli Electric Corporation (IEC) is presented. Emphasis is placed on the process of screening the list of potential input and output factors and determining the most relevant ones. Special attention is given to the qualitative factor concerning air pollution, which is here treated as a categorical variable. The incorporation of 'standard data' is examined and the results are analyzed.**

I. INTRODUCTION

THE electricity-generating industry at large, and utility companies in particular, have been at the focus of attention for productivity–efficiency measurement for at least three decades. This was motivated by several factors. First, most of these companies are publicly owned and as such are subject to regulations that enforce productivity evaluations. Second, the costs associated with the construction and operation of the electricity-generating facilities constitute a significant portion of the GNP in most developed countries. With so much at stake, even small improvements may result in large monetary benefits.

Applications of conventional efficiency measurement methods, e.g., Seitz [20], Rowsome [18], Färe *et al.* [9], and Douglas [8] to the electricity-generating industry were met with considerable difficulties. These stemmed from the multiple input, multiple output character of the problem as well as from the qualitative nature of some of the relevant factors. Also, the assumption of efficient performance for all 'surviving' units in the market (common in many traditional econometric studies) does not hold due to the heavy presence of regulation on one hand and (direct and indirect) government subsidies on the other.

Some of the measurement and evaluation difficulties encountered earlier are overcome when data envelopment analysis (DEA) is employed as the efficiency measurement vehicle. This methodology (developed in Charnes *et al.* [6]) has been applied in a wide variety of public sector environments to evaluate the performance of decision-making units (DMU's) such as municipal courts (Lewin *et al.* [14]), schools (Charnes *et al.* [7]), Air-Force maintenance units (Roll *et al.* [16]), and hospitals (Sherman [21]). A recent review of public sector applications of DEA is given in Ganley and Cubbin [10], and additional application areas can be found in the comprehensive bibliography compiled by Seiford [19].

In the area of electrical power, DEA has been applied mainly to the distribution aspects of the operations. Thomas [22] applied DEA for the Texas Utility Commission (TUC) to evaluate electrical cooperatives in Texas. These cooperatives engage mainly in the distribution of electrical power and not in its generation. Thomas drew his motivation from the need of the TUC to audit the cooperatives. Thus, the desired outcome from his study was a selection of the most appropriate cooperatives to be audited. A similar DEA study was done by Hjalmarsson and Veiderpass [13] for a Swedish electrical distribution study. The area of electrical generation, on the other hand, received less attention in DEA. The only published report describes an example used by Banker [1] in a context of developing a theoretical extension to DEA.

DEA and the other efficiency measurement techniques mentioned above are comparative in nature. Consequently, they are difficult to perform in Israel, where a single utility company provides electricity for the entire country. Unlike similar-size utility companies elsewhere, the Israel Electric Corporation (IEC) is virtually isolated from other potential sources of electrical energy. Due to Israel's unique geopolitical situation in the Middle East, the IEC cannot purchase excess capacity from neighboring countries in cases when the demand it faces exceeds the supply it is able to provide. Furthermore, the IEC must keep additional fuel inventory and idle generation power ready at all times to meet contingency operations plans in case of a sudden surge in demand due to a military conflict. This amounts to some built-in technical inefficiency in the IEC system. Thus, the circumstances under which the IEC operates are such that it is unlikely to find similar utility companies abroad to which it can be compared.

This paper reports on a multiperiod application of DEA to evaluate the performance of the power plants operated by the IEC. Conducted with real data taken over almost seven years (1981–1987), the experiment described here implemented, for the first time, innovative ideas that were presented earlier only as theoretical developments. First, the application followed the procedure suggested by Golany and Roll [11]. Second, it is the first reported attempt to apply a DEA model with categorical

This paper is dedicated by the surviving coauthors to the honor of their long-time mentor, colleague, and friend, Professor Yaakov Roll, who passed away in May 1993.

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TABLE I
POWER PLANT SITES

Site	Generating Units	Installed Capacity (MW)
Haifa	4	430
Hadera	4	1400
Tel-Aviv	4	530
Ashdod	9	1210

variables to real data. Finally, it pioneered an attempt to incorporate standard data into DEA as proposed by Golany and Roll [12].

The IEC employs standard financial and accounting procedures to evaluate the performance of its power plants as well as its other divisions. These generally involve a 'line-by-line' comparison for each activity of the actual expenditures with last year (or last quarter) expenditures and with the budgeted (or planned) expenditures. Only measured expenses enter these types of evaluations. Other evaluations, such as the routine measurement of air pollution, are made independently of the former evaluations. An important objective of the experiment described below was to provide the planning and analysis department of the IEC with an instrument that could evaluate performance across a multitude of activities, including some qualitative aspects of performance that are not measured directly by dollars.

II. DMU'S AND FACTORS

The DMU's chosen for analysis and efficiency monitoring in the IEC application were the four power-plant sites that were operating in Israel in the late 1980's. Time was measured by quarters, in accordance with managerial practices at IEC (e.g., with respect to budget planning and review). Following the rationale used in constructing the 'window analysis' in Charnes *et al.* [4], we considered each power plant in a different quarter as a separate entity. In this way, we ensured a sufficiently large number of observed DMU's for DEA. Also, this definition of DMU's allowed an analysis of performance trends across time—an issue of tremendous importance to the IEC management. This choice of DMU's followed conventional considerations for meaningful comparisons (see Golany and Roll [11]), requiring a number of similar units, all using similar types of inputs to produce similar kinds of outputs, but which possess (to some extent) decision making ability. Table I lists the sites and their (nominal) generating capacities. Data were collected for 25 quarters—September '81 to November '87—and periods of missing data were omitted. This resulted in a total of 87 DMU's.

The selection of factors to enter the efficiency analysis was carried out in two stages. First, a long list of candidate factors (outputs and inputs) was compiled. These factors could, in general, be grouped under the following headings:

1) Site-specific factors, e.g., average age of equipment, meteorological conditions, etc.
2) Operation-specific factors, e.g., power generated, availability, fuel consumption, etc.
3) Managerial factors, such as organizational structure, labor input, etc.

Altogether, 58 possible factors were defined (some of them were alternative definitions of the same attribute). The next step was to examine the various factors and to choose from them the ones to enter into the DEA model. Three filtering processes were applied at this stage:

A. A Preliminary Judgmental Process

This was carried out by a team of experts, created from members of the operations management group in the IEC. They scrutinized closely the various factors and reduced the list to 12 factors to be further examined. Criteria for choosing factors were the relevance to efficiency rating of power-plant operation, as well as the availability of reliable and sufficient data. In some instances it was recommended to redefine previously proposed factors or use surrogates that better fulfilled the criteria mentioned above. The team also indicated their preferences among the remaining factors at this stage. Table II lists these factors along with brief descriptions.

It should be noted that the deviation factors (#3 and #4) were transformed by taking their reciprocals before entering the DEA. This was done to maintain consistency in the desired changes of outputs (see, for example, the treatment of similar 'negative' outputs in Charnes *et al.* [4]).

B. Regression Analyses

The factors remaining after the first screening process were analyzed for correlation between pairs. The resulting correlation matrix is given in Table III. This analysis identified potentially redundant factors, where a high correlation was found between pairs of inputs or pairs of outputs (e.g., the strong correlation between installed capacity and fuel consumption—both being typical inputs). In some cases, it is not clear whether a particular factor should be viewed as an input or an output. By examining the correlation between such factors and other factors that are clearly defined as either inputs or outputs we gain a better understanding of their role (see Golany and Roll [11]).

C. Preliminary DEA Analyses

The CCR ratio model (Charnes *et al.* [6], see Appendix) was used to help in the selection of factors and to identify outputs and inputs. The CCR model was run with various mixes of outputs and inputs. Some of these contained only one output and several inputs, so that the effects of inputs on this

TABLE II
OUTPUTS AND INPUTS

Outputs	Description
1 Generated Power	Gross megawatt hours (MWH) generated, both for distribution and for internal use.
2 Operational Availability	The proportion of time in which units in the site were operational (excluding planned maintenance).
3 Deviation from Load	Power generation and distribution is planned centrally, specifying loads on each site. Local management is expected to adhere closely to this plan. The measurement unit used for DEA was the reciprocal of the deviations count.
4 Deviation from Operational Parameters	Each load level is associated with a set of optimal operational parameters. Deviations from these parameters are continuously recorded, and a composite index calculated. Again, the measurement unit used for DEA was the reciprocal of the deviations count.
5 SO_2 Emissions	Pollutant emissions (mainly SO_2) are monitored at constant time intervals. The emission index reflects the number of times pollutants exceed specified levels.
Inputs	
6 Installed Capacity	The installed (nominal) capacity of all units in a site.
7 Fuel Consumption	Physical quantities of fuel consumed per period.
8 Internal Power	The amount of energy consumed within the site (for electrically powered equipment etc.) .
9 Capital	All expenses incurred in developing the site, e.g., construction, equipment and installation.
10 Manpower	Shift operators, maintenance crews, lab technicians, administrative staff etc., as well as labor (e.g. for maintenance work) obtained from the central units of IEC (measured in man-hours).
11 Miscellaneous Expenses	All non-labor expenses, such as materials, spares, sub-contractors, taxes etc.
12 Fuel Stock	A sizable amount of money is tied up in fuel stocks. It is IEC policy that sites determine, to some extent, these stock levels.

TABLE III
CORRELATION AMONG FACTORS

Factor	1	2	3	4	5	6	7	8	9	10	11	12
1		.43	-.13	.80	.53	**.88**	**.99**	.72	.65	**.40**	.11	.47
2			.045	.19	.32	**.28**	**.44**	.33	.18	**.11**	.04	.06
3				.45	-.03	-.23	-.12	-.21	-.09	-.16	.19	-.36
4					.29	**.73**	**.81**	.62	-.07	**.39**	.11	.44
5						**.37**	**.49**	.44	.19	**.15**	-.01	.07
6							.87	.91	.57	.62	.08	.50
7								.90	.65	.48	.12	.54
8									.46	.57	.06	.57
9										.39	-.04	.44
10											.42	.35
11												-.07
12												

output could be better observed. This factor selection process continued until acceptable formulations were obtained. The criteria used for locating such formulations (e.g., the number of efficient units, mean and variance of efficiency scores, etc.) followed those used in Roll *et al.* [16]. These criteria are set to examine how well the models distinguish (efficiency wise) among the DMU's, taking the approach that a large variance in the distribution of efficiency scores enables better ranking. Similarly, a lower minimal efficiency score, a larger number of score groups and a smaller percentage of efficient DMU's better serve the purposes of efficiency analysis.

At the end of the screening procedure the following seven factors were finally chosen (the numbers correspond to Table II):

Outputs	Inputs
1. Generated Power	6. Installed Capacity
2. Operational Availability	7. Fuel Consumption
4. Deviation from Operational Parameters	10. Manpower
5. SO_2 Emissions	

TABLE IV
SUMMARY OF RESULTS BY CATEGORICAL LEVELS

Category Level	No. of DMUs	No. improved to Level 2	No. improved to level 3	No. of Efficient DMUs
1	14	-	5	6
2	23	-	12	11
3	50	-	-	23
Total	87	-	17	40

Observing again Table III we see that the factors above are associated with various levels of correlation coefficients. While fuel consumption is highly correlated to the generated power, its relation to the SO_2 emissions is not as strong. In particular, manpower is only weakly correlated to any of the outputs. This implies that there are DMU's with large manpower values and relatively small outputs—suggesting the possibility of identifying relatively more efficiency gaps associated with this input than with other inputs.

III. MODEL FORMULATION

DEA can be applied by means of several alternative model formulations (see Charnes and Cooper [5]), hence, a selection among these had to be made. First, the BCC model (Banker *et al.* [2], see Appendix) was considered. The reason was the obvious differences in scale of operations between the small plants (Haifa and Tel-Aviv) and the large ones (Hadera and Ashdod). The BCC model offers a distinction between scale and technical efficiencies and, thus, it can differentiate between the various sources of inefficiency. However, the final list of factors for the model contained a measure of air pollution, a discrete variable that represents a controllable output. Since this factor is actually measured and treated as a categorical variable by the IEC authorities, it was decided to adopt an extension of the BCC model that includes explicit consideration of ordinal categorical variables. The extension (see Appendix) is based on a model developed by Kamakura [14] and modified by Rousseau and Semple [17].

The specific formulation used to represent the categorical output of SO_2 emissions in our case employs three levels that are coded by means of two dummy binary indicators:

{1, 1} 'Good': acceptable emissions—no more than one instance of violating specified emission standards in a quarter,

{1, 0} 'Medium': intermediate level of emissions—between 2 and 4 violation instances,

{0, 0}'Bad': unacceptable emissions—5 or more violation instances.

A basic feature of the categorical DEA model is that the relative evaluation of a DMU is restricted according to its categorical affiliation. The model guarantees that improvements in the categorical output can be indicated only in a sequential manner. Thus, a DMU with unacceptable emissions, {0, 0}, can be projected 'upwards' to the efficient positions of {1, 0} or {1,1}. Similarly, a DMU with medium emissions {1, 0} can be compared with other DMU's in its category or in the better category {1, 1} but not to DMU's in the lower category {0, 0}.

IV. RUNS AND OUTCOMES

The DEA model was applied to the 87 observations representing the power-plant sites in the different quarters. The model was applied in stages for each of the three categorical levels as summarized in Table IV.

In total, the model was run eight times in different versions (see the Appendix):

Run 1: Using model (3a) we identified 5 DMU's out of the 14 in the lowest level as candidates for improvement to the second level.

Run 2: Using model (3b), with W_{01} set to 1, we determined that the same 5 DMU's can be projected up to the highest level.

Run 3: Using model (3c) and assuming a projection onto the third categorical level, i.e., setting W_{01} and W_{02} to 1, we determined the relative efficiency of these 5 DMU's with respect to all other input and output factors.

Run 4: Using model (3c) and assuming no change in the categorical level, we determined the relative efficiency of the remaining 9 DMU's in the first level with respect to all other input and output factors.

Run 5: Using model (3b) we identified 12 DMU's out of the 23 in the second level as candidates for improvement to the first level.

Run 6: Using model (3c) and assuming a projection onto the third categorical level, i.e., setting W_{02} to 1, we determined the relative efficiency of these 9 DMU's with respect to all other input and output factors.

Run 7: Using model (3c) and assuming no change in the categorical level, we found that all the remaining 11 DMU's in the second level were efficient with respect to the other input and output factors.

Run 8: Using model (3c) and assuming no change in the categorical level, we determined the relative efficiency of the DMU's in the first level with respect to the other input and output factors.

The aggregate results, in terms of the four sites and the four quarters, are presented in Tables V and VI.

TABLE V
Analysis by Site

Plant No.	Name	No. of DMUs	No. of Efficient DMUs$^{(*)}$	No. of Appearances in Efficient Facets
1	Haifa	25	21 (5,5,4,7)	126
2	Hadera	12	8 (3,2,3,0)	19
3	Tel-Aviv	25	6 (2,1,1,2)	16
4	Ashdod	25	4 (2,0,1,1)	50
Total		87	39	214

TABLE VI
Analysis by Quarter

Quarter No.	Months	No. of DMUs	No. of Efficient DMUs	No. of Appearances in Efficient Facets
1	12,1,2	21	12	101
2	3,4,5	21	8	12
3	6,7,8	21	9	36
4	9,10,11	24	10	73
Total		87	39	222

TABLE VII
Dual Variable Indicating Returns to Scale

	Haifa	Hadera	Tel-Aviv	Ashdod	Total
No. of observations	25	12	25	25	87
Mean	-2.49	0.238	0.440	0.285	NA
Median	-0.28	0.128	0.476	0.258	NA
Standard deviation	2.038	0.106	0.113	0.024	NA
Positive observations	7	10	20	25	62
Negative observations	18	2	5	0	25
Min value	-51.06	-0.073	-0.687	0.149	-51.06
Max value	1.152	1.239	1.986	0.643	1.986

The Haifa power plant, which is the smallest and oldest of the four units, turned out to be on the efficiency frontier more often than any other plant. Furthermore, its presence there has influenced the efficiency rating of most other units in most time periods—as can be seen from the count of its appearances in efficient facets used to evaluate other units. To explain this phenomenon, we explored whether different returns to scale are present in the analyzed data. This was done by observing optimal values of the dual variable corresponding to the convexity constraint in model (3c). Banker *et al.* [2] stated that this value can be interpreted to indicate returns to scale. However, Chang and Guh [3] showed that this interpretation may sometimes be misleading as a result of alternate optima. Our results, summarized in Table VII, confirm the latter finding. We observe large variances as well as different signs for the optimal dual variables corresponding to the same power plant. Nevertheless, the mean and median values for each plant may provide some evidence of a situation in which the Haifa plant is operating at an area of increasing returns to scale while all other plants operate at various degrees of decreasing returns to scale.

A potential drawback of treating power plants in different quarters as different units involves possible seasonal effects. Strong seasonal effects might refute the premise of comparing 'like units' and force the inclusion of a seasonal indicator in the input-output list. This question may be investigated by observing the cross-reference to quarters in Table V and the information in Table VI. The distribution of the efficient units among the quarters is almost uniform with the exception of the first quarter (winter), which has slightly more efficient units than the other quarters. Also, the distribution of efficient performance for every site among the four quarters (given in parentheses in Table V) is almost identical, with the exception of Hadera and Ashdod, which never turned out to be efficient in the fall and spring seasons, respectively. However, the small number of efficient observations for these two plants—seven and four,, respectively–does not allow for a solid conclusion. Table VI shows that the winter and fall quarters appeared more often in the facets of inefficient DMU's than the other two quarters. This may be explained by steps taken by the IEC to level the demand for electricity and match it as much as possible with capacity. On the supply side, during the winter quarter (when demand peaks) there are no scheduled shutdowns. Demand is affected by higher prices at peak hours. Also, massive consumption by large customers (e.g., the pumping of water from the Sea of Galilee through the pipeline that takes the water south to the Negev desert) is scheduled mainly in the spring (second quarter), which otherwise would have been associated with relatively low demand. The analysis could not be expanded to evaluate the efficiency of the sites for each quarter separately because of the limited number of observations for each quarter. However, with more observations it probably would be useful to continue exploring this issue.

A detailed evaluation, based on the DEA outcomes, was prepared for every site and quarter (i.e., for each of the 87 DMU's). An example, applying to DMU 85, is shown in Table VIII. DMU 85 was in the lowest categorical level. It was identified through the first two runs as having the potential to improve to the highest level, and the results shown in Table VIII correspond to its evaluation in Run 3. Consequently, all three efficient DMU's in its facet are associated with category $\{1, 1\}$.

The bottom part of Table VIII compares the input-output values of DMU 85 with those of its efficient facet. Similar comparisons are offered in Table IX. DMU 3, at the top of Table IX, was associated with the lowest categorical level. However, its evaluation in the first run revealed no potential improvement in the categorical factor. Next, when it was evaluated in Run 4, the model selected a facet of five efficient DMU's, three at the same categorical level, and one in each of the higher levels. Notice that the convex combination of the values of these five DMU's served as a potential 'Value if efficient' for DMU 3 with the exception of the categorical level in which its original value stayed unchanged. The next DMU in Table IX, DMU 83, is an example for units that were improved from level $\{1, 0\}$ to level $\{1, 1\}$ and the last DMU, DMU 78, is an example for DMU's whose original value was $\{1, 1\}$.

An interesting question that arises when multiperiod DEA applications are run with duplication of units across time is whether a DMU is more commonly compared to itself in its best periods, or to other DMU's. Table X shows that the former was generally the case. Haifa, the smallest plant, was compared only with itself; Hadera, the largest plant, was compared mostly to itself. Tel-Aviv and Ashdod, in the few quarters when they were efficient, appeared in their own facets quite extensively. This phenomenon may allow the IEC to set efficiency improvement targets for an inefficient unit either on the basis of its entire facet or by relating the inefficient unit only to the facet members which are associated with the same site. Targets set through the latter approach will fall short of those set under the former approach but may be more acceptable in the environment in which the IEC operates.

Additional insight into the performance of the DMU's over time may be gained through Table XI. While the ratio of efficient units to the number of DMU's in each of the seven years fluctuates between 0.333–0.5 (with no apparent trend), the average efficiency rating across all years is very stable (with, perhaps, a slight trend upward in the last three years). The implications for the IEC were that the various productivity improvement activities that were tried during these years failed to result in significant improvement in the overall operations of the power plants.

V. EXPERIMENT WITH STANDARD DATA

A potential shortcoming of DEA is the strictly relative efficiency measures it provides. DEA identifies the best DMU's within the group being analyzed, marks them as efficient, and compares all other DMU's to these efficient ones. In reality, however, it may happen that DMU's forming the 'efficient frontier' are themselves lagging in efficiency behind some known 'standard.' This issue is addressed by Golany and Roll [12].

However, establishing standards in DEA environments may be a difficult task for several reasons. Two prominent ones among these are:

a) A strong interdependence between factors (outputs and inputs) is typical of many situations where DEA is applied. DEA analyzes the various factors collectively. It follows that appropriate standards must not be constructed separately for each input or output dimension but rather jointly so as to describe particular scenarios.
b) DEA recognizes that different combinations of the relevant factors can be considered as efficient. To be consistent with this approach, several suitably spread-out multidimensional standards should be constructed, to which the analyzed group can be 'fairly' compared.

Following this reasoning, one 'standard' DMU was constructed for each of the four sites. Data for these standards were taken from several sources:

- Manufacturer specifications for capacity
- Government regulations for pollutant emissions
- IEC standards for power generation, fuel consumption, and man-hours
- IEC management objectives for operational deviations and availability.

For most of the factors, an effort was made to use achievable levels of performance as the standards. For example, government regulations require the pollutant indicator to adhere to the 'good' $\{1, 1\}$ state, which was achieved by some power plants in some quarters. Fuel consumption was based on a separate multiyear engineering study which examined this issue and developed certain standards. However, in some cases we have

TABLE VIII
An Illustrative Efficiency Summary Table

Efficiency Summary - DMU No. 85 (Hadera , 4/87)

Efficiency Score : 0.988

	Actual Value	Slack Value	Value if Efficient (*)
Outputs			
Generation (MWH)	1935474	0	1958981
Availability (%)	71.64	12.5	85.01
Deviations	216.2	0.014	52.94
SO_2 Emissions I	0	1	1
SO_2 Emissions II	0	1	1
Inputs			
Capacity (MW)	1400	98.11	1301.9
Fuel Consump.	463403	0	463403
Manhours	233483	0	233483

DMUs in the Efficient Facet and their actual output-input values

DMU no.	6	41	73
DMUS Names	Ashdod	Hadera	Hadera
Quarter	1/82	1/85	1/87
Lambda Values	.522	.371	.107
Generation (MWH)	1699200	2258730	2190445
Availability (%)	80.35	94.20	75.93
Deviations	34.5	116.5	187.2
SO_2 Emissions I	1	1	1
SO_2 Emissions II	1	1	1
Capacity (MW)	1212	1400	1400
Fuel Consump.	397212	538941	524215
Manhours	249850	226286	178628

deliberately chosen nonachievable levels to ensure that the frontier generated by the 'standard units' will be strictly above the relative frontier. Nevertheless, even for these factors the selection of values was not arbitrary. For example, values for operational availability were taken as 100% (which is the theoretical upper bound in this dimension).

Applying the same DEA model as before, but with a set of 91 DMU's (87 observed and 4 standard points), brought about an average decrease of 1 percentage point in the efficiency scores of the compared DMU's. Likewise, a drop in the proportion of efficient DMU's (from 45% to 31%) was observed. Most of the effect occurred at the smaller sites (Haifa and Tel-

TABLE IX
COMPARISON TABLES: INEFFICIENT DMU'S VERSUS THEIR EFFICIENT FACETS

Efficiency Summary - DMU No. 3 (Ashdod , 4/81) Efficiency Score : 0.957

Comparison Table with Efficient DMUs in Facet

DMU name (no.)	Ashdod (3)	Ashdod (12)	Tel-Aviv (35)	Hadera (77)	Hadera (81)	Haifa (84)
Quarter	4/81	3/82	3/84	2/87	3/87	4/87
Lambda values		0.458	0.065	0.323	0.031	0.122
Generation (MWH)	1704424	1791049	585021	2432070	2549914	477544
Availability (%)	85.89	85.86	80.72	97.26	94.83	88.32
Deviations	35.92	79.08	6.54	77.33	112.08	13.83
SO_2 Emissions I	0	0	1	0	0	1
SO_2 Emissions II	0	0	0	0	0	1
Capacity (MW)	1212	1212	528	1400	1400	432
Fuel Consump.	401266	367480	145973	587837	621257	116326
Manhours	229442	229552	121134	157684	321295	475727

Efficiency Summary - DMU No. 83 (Ashdod , 3/87) Efficiency Score : 0.960

Comparison Table with Efficient DMUs in Facet

DMU name (no.)	Ashdod (83)	Ashdod (18)	Haifa (25)	Haifa (56)
Quarter	3/87	1/83	4/83	1/86
Lambda values		.788	.208	.004
Generation (MWH)	1165442	1432285	406760	239717
Availability (%)	67.21	81.13	69.22	60.49
Deviations	51.7	40.84	37.44	27.89
SO_2 Emissions I	1	1	1	1
SO_2 Emissions II	0	1	1	1
Capacity (MW)	1212	1212	432	432
Fuel Consump.	283459	334278	95020	55395
Manhours	211281	233027	129583	167933

Efficiency Summary - DMU No. 78 (Hadera , 2/87) Efficiency Score : 0.974

Comparison Table with Efficient DMUs in Facet

DMU name (no.)	Hadera (78)	Ashdod (18)	Haifa (25)	Haifa (56)
Quarter	2/87	1/83	4/83	1/86
Lambda values		0.016	0.319	0.665
Generation (MWH)	303611	1432285	406760	239717
Availability (%)	55.96	81.13	69.22	60.49
Deviations	35.83	40.84	37.44	27.89
SO_2 Emissions I	1	1	1	1
SO_2 Emissions II	1	1	1	1
Capacity (MW)	528	1212	432	432
Fuel Consump.	72426	334278	95020	55395
Manhours	156723	233027	129583	167933

Aviv), where efficiency scores dropped by 1%–5%. The scores for the larger sites (Ashdod and Hadera) were hardly affected by adding standards to the analysis. This may be explained in part by the fact that the latter sites are the newer ones, and that in a way they served as a framework for constructing the standards.

VI. DISCUSSION

A case study of using DEA for efficiency assessments has been presented, highlighting several aspects of this approach. One aspect is the careful and systematic selection of factors to enter the analysis. In this process, several combinations of factors, differing both in content and in number, were compared. The well known phenomenon of a correlation between the number of factors and the level of efficiency scores was observed. The larger the number of outputs and inputs in the analysis, the more inefficiency can be 'explained' and the higher the resultant efficiency scores. Thus, a balance has to be struck between an appropriate representation of all important factors and keeping the overall number low enough so that a meaningful analysis is possible.

TABLE X
FACET COMPOSITION FOR INEFFICIENT DMU'S

Plant No.	Name	No. of DMUs	No. of Ineff. DMUs	No. of Appearances in Eff. Facets			
				Haifa	Hadera	Tel-Aviv	Ashdod
1	Haifa	25	4	29	0	0	0
2	Hadera	12	4	2	14	0	4
3	Tel-Aviv	25	19	55	1	15	18
4	Ashdod	25	21	40	4	1	28
Total		87	48	126	19	16	50

TABLE XI
EFFICIENCY PERFORMANCE ACROSS TIME

year	81	82	83	84	85	86	87
no. of DMUs	3	12	12	12	16	16	16
no. of eff. DMUs	1	6	4	5	7	8	8
% of eff. DMUs	33.3	50	33.3	41.6	43.7	50	50
Average eff. rating	.975	.983	.982	.989	.980	.981	.987

A second issue involved selecting a particular DEA model from among the available candidates. Considerations in the case reported here were differences in DMU size and the presence of a 'categorical' factor. In addition, the effects of introducing standards into the analysis were examined. Outcomes with this modification pointed to a larger latent potential for efficiency improvement. It was also found that a more careful construction of standards (with particular regard to the larger sites) may be necessary.

An important issue in efficiency analyses is presenting the various outcomes in a way that serves best the purpose of such analyses. This is of particular importance with DEA studies, where a wide array of outcomes can be obtained. Each array of data illuminates the situation analyzed from a different angle, and may serve different aspects of efficiency control. To gain the understanding and support of decision makers one has to find ways of presenting the information in an attractive and concise manner. This topic, which has received very little attention in the DEA literature, is crucial to the success of future DEA implementations. It is hoped that the range of tables offered in this paper will help future practitioners in designing their presentations.

Finally, this study demonstrated to the IEC management the importance of instituting efficiency analyses as a continuous procedure within their organization, alongside other management control tools. This was the first time that an overall approach to the measurement of performance in the power plants was tried in the IEC. As a result of the study, the company has initiated an effort to define and monitor an array of managerial indicators in most of its divisions. In the 'Operations' division (which oversees the activities of the power plants) the measures selected for this study were adopted by the company as the ones desired for long-time monitoring. Another outcome of the study was an effort initiated by the IEC to systematically collect data on the same parameters from power plants abroad, which may serve for future comparisons. Thus, although there are no immediate plans to activate an on-going DEA evaluation of the power plants, the study did generate a major drive within the IEC to look for better means and measures that will lead to enhancing the performance of its operating units.

APPENDIX

Notation

Z_0	intensity factor indicating maximal possible increase of all outputs of the analyzed DMU_0.
Y_{rj}	the value of the r^{th} output of the j^{th} DMU, $r = 1, \ldots, s$.
X_{ij}	the value of the i^{th} input of the j^{th} DMU, $i = 1, \ldots, m$.
λ_j	'weight' of the j^{th} DMU in evaluating DMU_0.
ε	a non-Archimedean infinitesimal.
s_r^+, s_i^-	slack variables.
$W_{\delta j}$	a 0–1 category indicator for the j^{th} DMU, $\delta = 1, \ldots, \Delta - 1$.
t_δ	an auxilary variable, $\delta = 1, \ldots, \Delta - 1$.
Δ	number of categories.

A. The CCR Model

$$\text{Max } Z_0 + \varepsilon \cdot \left[\sum_{i=1}^{m} s_i^- + \sum_{r=1}^{s} s_r^+\right] \tag{1}$$

s.t.

$$Z_0Y_{r0} - \sum_{j=1}^{n} Y_{rj}\lambda_j - s_r^+ = 0, r = 1, \ldots, s$$

$$\sum_{j=1}^{n} X_{ij}\lambda_j + s_i^- = X_{i0}, i = 1, \ldots, m$$

$$\lambda_j, s_i^-, s_r^+ \geq 0$$

B. The BCC Model

$$\text{Max } Z_0 + \varepsilon \cdot \left[\sum_{i=1}^{m} s_i^- + \sum_{r=1}^{s} s_r^+\right] \tag{2}$$

s.t.

$$Z_0Y_{r0} - \sum_{j=1}^{n} Y_{rj}\lambda_j - s_r^+ = 0, r = 1, \ldots, s$$

$$\sum_{j=1}^{n} X_{ij}\lambda_j + s_i^- = X_{i0}, i = 1, \ldots, m$$

$$\sum_{j=1}^{n} \lambda_j = 1$$

$$\lambda_j, s_i^-, s_r^+ \geq 0$$

C. The Rousseau and Semple Model

We present below a procedure based on the model developed by Rousseau and Semple [17] and here applied to the IEC application. The procedure assigns absolute priority to improvements in the categorical output dimension over all other input and output factors. After finding the maximal improvement in the categorical dimension, an ordinary BCC model is used to find the maximal potential improvement in the other dimensions. Three model formulations (corresponding to the three categorical levels) are used. For DMU's in the lowest categorical level we solve (3a) to see whether they can be improved to the medium level.

$$\text{Max } t_1 \tag{3a}$$

s.t.

$$\sum_{j=1}^{n} Y_{rj} \cdot \lambda_j - s_r^+ = Y_{r0}, r = 1, \ldots, s$$

$$\sum_{j=1}^{n} X_{ij} \cdot \lambda_j + s_i^- = X_{i0}, i = 1, \ldots, m$$

$$\sum_{j=1}^{n} W_{\delta j} \cdot \lambda_j - t_\delta = W_{\delta 0}, \delta = 1, \ldots, 2$$

$$\sum_{j=1}^{n} \lambda_j = 1$$

$$t_\delta, \lambda_j, s_i^-, s_r^+ \geq 0.$$

For DMU's in the second level, as well as DMU's of the lowest level for which $t_1* = 1$, we solve (3b) to see if improvements to the highest level are possible.

$$\text{Max } t_2 \tag{3b}$$

s.t.

$$\sum_{j=1}^{n} Y_{rj} \cdot \lambda_j - s_r^+ = Y_{r0}, r = 1, \ldots, s$$

$$\sum_{j=1}^{n} X_{ij} \cdot \lambda_j + s_i^- = X_{i0}, i = 1, \ldots, m$$

$$\sum_{j=1}^{n} W_{\delta j} \cdot \lambda_j - t_\delta = W_{\delta 0}, \delta = 1, \ldots, 2$$

$$\sum_{j=1}^{n} \lambda_j = 1$$

$$t_\delta, \lambda_j, s_i^-, s_r^+ \geq 0$$

Notice that when (3b) is run for DMU's that belong to the lowest categorical level, but that were identified through (3a) as being able to improve their performance to (at least) the medium level, W_{10} is set to 1.

Finally, we solve model (3c) for DMU's in the highest possible categorical level, as well as for DMU's of the other categorical levels that were identified through (3a) and (3b) as capable of reaching the highest level. The solution to (3c) identifies for these DMU's the largest possible improvement in all other input–output factors.

$$\text{Max } Z_0 + \varepsilon \cdot \left[\sum_{i=1}^{m} s_i^- + \sum_{r=1}^{S} s_r^+\right] \tag{3c}$$

s.t.

$$Z_0 \cdot Y_{r0} - \sum_{j=1}^{n} Y_{rj} \cdot \lambda_j - s_r^+ = 0, r = 1, \ldots, s$$

$$\sum_{j=1}^{n} X_{ij} \cdot \lambda_j + s_i^- = X_{i0}, i = 1, \ldots, m$$

$$\sum_{j=1}^{n} W_{\delta j} \cdot \lambda_j - t_\delta = W_{\delta 0}, \delta = 1, \ldots, 2$$

$$\sum_{j=1}^{n} \lambda_j = 1$$

$$t_\delta, \lambda_j, s_i^-, s_r^+ \geq 0.$$

Again, when (3c) is run for DMU's that belong to the lower categorical levels but that were identified through (3a) or (3b) as being able to improve their performance to the highest level, W_{10} and W_{20} are set to 1.

DMU_0 is efficient if and only if $Z_0 = 1$ and all slacks are equal to zero. The efficiency score reported in this study is equal to the reciprocal of Z_0 $(1/Z_0)$.

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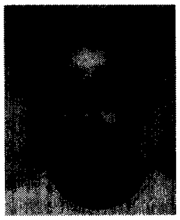

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