



Optimal Allocation of Mega-solar Power Station using Integrated Input and Output-oriented models in Data Envelopment Analysis

S. Yokota¹, T. Kumano²

¹ Graduate School of Science and Technology
Meiji University
1-1-1, Higashi-mita Tama-ku, Kawasaki 214-8571(Japan)
Phone/Fax number:+81 090 5100 5932, e-mail: ce11094@meiji.ac.jp

² Professor, School of Science and Technology
Meiji University
Phone/Fax number:+81 44 934 7294, e-mail: kumano@isc.meiji.ac.jp

Abstract. In this paper, optimal allocation of mega-solar power station is studied using Data Envelopment Analysis (DEA). In Japan, A great attention is paid to natural energy. Especially, installation of a mega-solar station, which is a large photovoltaic power plant over 1MW, is beginning. In order to propose the optimal allocation, DEA method is applied in this research. Land cost, earthquake occurrence, transmission loss are used as inputs, and the amount of global solar radiation, and population density are used as outputs. The target locations are at 81 points in 5 prefectures of Chubu District in Japan. We perform ranking in consideration of input-oriented and output-oriented in BCC model, and successfully get solutions about the mega-solar optimal allocation.

Key words

Data Envelopment Analysis, Mega-solar, Sensitivity Analysis, Decision Making Unit, Linear Programming Problem

1. Introduction

A great earthquake occurred in the eastern Japan on March 11, 2011, and it fell into electric power shortages from the stop of the Fukushima nuclear power plant, etc. People have become intensively interested in electric power, and attentions are paid to natural energy, such as photovoltaic and wind power generation. Mega-solar is one of such targets that great efforts are made on. Verification tests carried out in Wakkanai city, Hokkaido [1] and Hokuto city, Yamanashi prefecture [2]. Quick and large penetration is expected.

However, in our country's small land area, since its installation has a limitation, they should be installed at appropriate locations in a rational and systematic manner. In installation of mega-solar, consideration on the safety in case of the natural disaster such as earthquakes is

important. Its installation cost is greatly affected by the land cost of the location point. Therefore, it is necessary to consider various factors such as the amount of global solar radiation etc. in the mega-solar optimal installation. In this paper, Data Envelopment Analysis (DEA) is used to solve this problem [3]. This method is a technique of making relative evaluation on the productivity of Decision Making Unit (DMU), such as companies and public entities. Many works have been done [4]-[8] which applied this DEA method to various fields. [7] and [8] applied it to the problem of the location optimization of solar heat plants and wind plants. In these studies, the efficiency of each plant in Iran was evaluated.

Yokota et al. [9] applied this technique to the problem of the optimal allocation of photovoltaic power plant for the first time. But, only the input-oriented of CCR model in DEA was evaluated. So we perform ranking taking advantage of the characteristic of three models, BCC model [10], input-oriented model, and output-oriented model [11] in this paper. Moreover, we increase the number of the studied points (DMUs). Solutions are obtained on the mega-solar optimal allocation problem for Chubu District 81 points in Japan.

2. DEA

A. CCR Model

DEA is a method based on linear programming, and the method of relatively evaluating the efficiency of DMU, such as a set of firms etc. Usually, when considering the problem of efficiency, it can be expressed with $(\text{efficiency}) = (\text{output}) / (\text{input})$. In this formula, the efficiency becomes higher when input value is smaller, and output value is larger. However, since the influences which each input gives to each output may differ if the number of input or output increases, it may be unable to

evaluate simply by the efficiency $\theta = (\text{sum of output}) / (\text{sum of input})$. By DEA, the maximum of the efficiency of each DMU can be calculated by applying weight so that each parameter may become advantageous. Moreover, as a fundamental idea, accepting the property of each DMU and not limiting the optimal solution to one, it allows enhancing efficiency in the form that is best for each DMU. Say DMU_j is the target of our evaluation out of n DMUs, the efficiency evaluation can be written to be

$$\frac{\sum_{r=1}^s u_r y_{rj}}{\sum_{i=1}^m v_i x_{ij}}$$

and what is necessary is just to solve the following fractional programming problem to know the most efficient status of operation.

$$\begin{aligned} & \max \frac{\sum_{r=1}^s u_r y_{rj}}{\sum_{i=1}^m v_i x_{ij}} \\ & \text{s.t. } \frac{\sum_{r=1}^s u_r y_{rk}}{\sum_{i=1}^m v_i x_{ik}} \leq 1 \quad (k=1,2,\dots,n) \quad (1) \\ & \quad u_r \geq 0 \quad (r=1,2,\dots,s) \quad v_i \geq 0 \quad (i=1,2,\dots,m) \end{aligned}$$

In the equation (1), y , x , u , and v express output values, input values, output weights, and input weights of each parameter, respectively. And s is the number of output data, m is the number of input data. In addition, k is the subscript given to all DMU which contain also except DMU_j made applicable to evaluation, and these inequality constraint need to be satisfied in all DMUs. If this objective function takes the value 1, j can be said to be the most efficient in that specific u_r and v_i . Since this equation (1) is developed by Charnes, Cooper, and Rhodes, it is called CCR model.

For simplicity, the additional condition

$$\sum_{i=1}^m v_i x_{ij} = 1$$

is considered in many cases, and this paper also follows this tradition. In this case, an optimization problem changes into the form of the following linear programming.

$$\begin{aligned} & \max \sum_{r=1}^s u_r y_{rj} \\ & \text{s.t. } \sum_{i=1}^m v_i x_{ij} = 1 \quad (2) \\ & \quad \frac{\sum_{r=1}^s u_r y_{rk}}{\sum_{i=1}^m v_i x_{ik}} \leq 1 \quad (k=1,2,\dots,n) \\ & \quad u_r \geq 0 \quad (r=1,2,\dots,s) \quad v_i \geq 0 \quad (i=1,2,\dots,m) \end{aligned}$$

The above equation (2) is called an input-oriented model. Changing this formula to the dual form, we can get equation (3).

$$\begin{aligned} & \min \theta_j \\ & \text{s.t. } \theta_j x_{ij} - \sum_{k=1}^n x_{ik} \lambda_k \geq 0 \quad (i=1,2,\dots,m) \quad (3) \\ & \quad y_{rj} - \sum_{k=1}^n y_{rk} \lambda_k \leq 0 \quad (r=1,2,\dots,s) \\ & \quad \lambda_k \geq 0 \quad (k=1,2,\dots,n) \end{aligned}$$

As can be easily understood by this formula, this model minimizes the value of input as much as possible, maintaining output level. On the other hand, an output-oriented model can be expressed as follows [11].

Table I. – Example of parameter

DMU	A	B	C	D	E
Input	3	4	2	1	3.5
Output	3	2	4	1	5

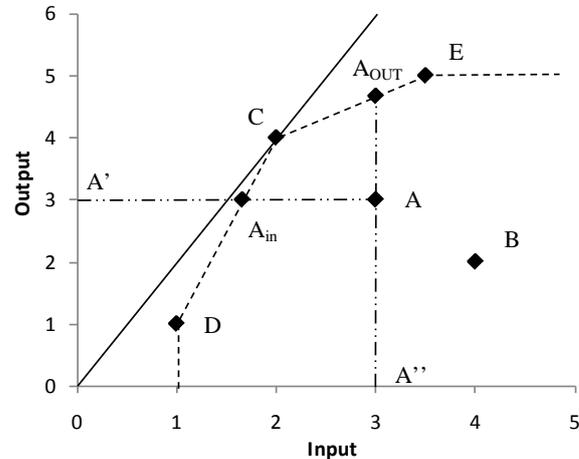


Fig. 1. Difference between CCR and BCC

$$\begin{aligned} & \max \phi_j \\ & \text{s.t. } x_{ij} - \sum_{k=1}^n x_{ik} \lambda_k \geq 0 \quad (i=1,2,\dots,m) \quad (4) \\ & \quad \phi_j y_{rj} - \sum_{k=1}^n y_{rk} \lambda_k \leq 0 \quad (r=1,2,\dots,s) \\ & \quad \lambda_k \geq 0 \quad (k=1,2,\dots,n) \end{aligned}$$

This model maximizes the value of output as much as possible, maintaining input level. In CCR model, the input-oriented efficiency value is equivalent to the output-oriented efficiency value. ($\theta_j = 1/\phi_j$)

B. BCC Model

The above CCR model is premised on the conditions of constant returns to scale. As opposed to this technique, Banker et al. [10] proposed BCC model, in which variable returns to scale. This type of system cannot be always run efficiently in large scale even if it is in highly efficient manners when small. Similarly, it cannot be always run efficiently in small scale even if it is in highly efficient manners when large. In BCC model, this variable return characteristic is modeled based on the real field activity. In the mathematical formulation, we should just add

$$\sum_{k=1}^n \lambda_k = 1 \quad (5)$$

to the constraint condition of equations (3) and (4).

The difference between CCR model and BCC model is illustrated in Fig. 1, where each DMU shown in Table I is marked by a black rhombus. In CCR model, the solid line

is called the efficient frontier, which implies the most efficient ratio between the input and the output. The dotted line (DCE) is the efficient frontier in BCC model. As shown here, DMUs evaluated as efficient by BCC model are not necessarily evaluated as efficient also by CCR model.

Moreover, in BCC model, the input-oriented efficiency differs from the output-oriented efficiency. In this example, the input-oriented efficiency is the length $A_{in} A'$ divided by the length AA' , whereas the output-oriented efficiency is the length $A_{out} A''$ divided by the length AA'' . They are $5/9$ and $14/9$, respectively.

C. SE-DEA Model

In DEA application results, the efficiency values of many DMUs sometimes become 1. This is no problem in mathematical sense, and is a theoretically sound consequence from the viewpoint of DEA for accepting the property of many DMUs. However, in the case of the present mega-solar point selection problem, this may lead to the problem that we cannot determine which candidate to choose. In order to narrow down the candidates out of result obtained by DEA, the following sensitivity analysis is applied.

$$\begin{aligned} & \min \theta_j \\ & s.t. \quad \theta_j x_{ij} - \sum_{\substack{k=1 \\ k \neq j}}^n x_{ik} \lambda_k \geq 0 \quad (i=1,2,\dots,m) \\ & \quad \sum_{\substack{k=1 \\ k \neq j}}^n y_{rk} \lambda_k \geq y_{rj} \quad (r=1,2,\dots,s) \\ & \quad \sum_{\substack{k=1 \\ k \neq j}}^n \lambda_k = 1 \\ & \quad \lambda_k \geq 0 \quad (k \neq j) \end{aligned} \quad (6)$$

The equation (6) is a sensitivity analysis by the input-oriented BCC model. The sensitivity analysis of the output-oriented BCC model should just add the equation (5) to the constraint condition of equation (4). ($k \neq j$) However, when this sensitivity analysis is conducted by BCC model, it sometimes becomes infeasible [12]. Some techniques are proposed for its improvement [13],[14]. In this study, we have tried to apply these techniques, but could not be solved. Therefore, the efficiency value of such DMUs are forced to be set to 1.0.

Finally, the following equation is used when performing ranking of each place[14]. The weighting factors w_θ and w_ϕ can take arbitrary value between 0 and 1 satisfying the condition $w_\theta + w_\phi = 1$. They are set to 0.5 in this research.

$$\begin{aligned} S_i &= w_\theta \theta_j + w_\phi \frac{1}{\phi_j} \\ S_o &= w_\theta \frac{1}{\theta_j} + w_\phi \phi_j \end{aligned} \quad (7)$$

3. Data

The mega-solar installation candidates are shown in Fig. 2, which are 81 points in Mie prefecture, Shizuoka prefecture, Aichi prefecture, Gifu prefecture, and Nagano prefecture

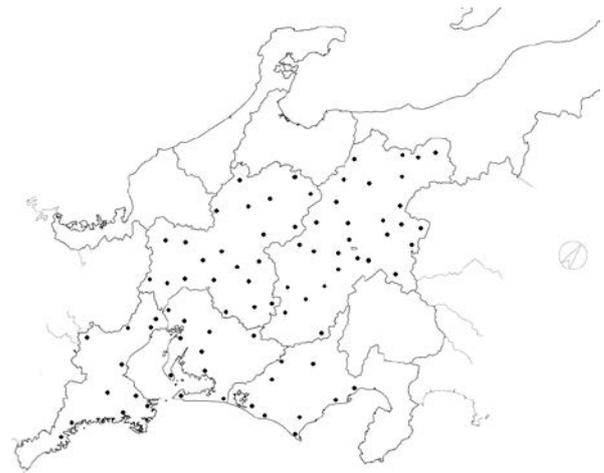


Fig. 2. Selected Location

of Japan (which are numbered below in random order). The amount of global solar radiation, population density, the land cost, the earthquake occurrence, and the transmission loss at each point are chosen as variables. Each data is explained below.

A. Global Solar Radiation

The amount of global solar radiation is important for choosing the area because it dominates the overall electric energy production. This data is recorded on METPV-3 of the New Energy and Industrial Technology Development Organization (NEDO), and is carried out based on the statistics in 1990~2003. Average value is newly computed from the amount of average year global solar radiation of these points. Since the larger amount of global solar radiation is favorable, it is considered as an output in DEA.

B. Population Density

Highly populated area is, in a sense, suitable for the mega-solar installation from the viewpoint of power flow distribution balance. Lager population density can be advantageous. Population density is obtained from the Ministry of Internal Affairs and Communications. This data is considered as an output in DEA from the above sense.

C. Land Cost

When installing mega-solar, the installation cost is one of the important parameters. Since this cost influenced by the land cost of each point greatly, the land cost in each place investigated. This data is obtained from the Ministry of Land, Infrastructure, Transport and Tourism. Since the lower land cost is advantageous, it is considered as an input in DEA.

D. Earthquake Occurrence

The mega-solar installation to the area where the

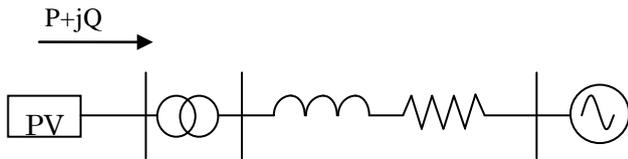


Fig. 3. Mega-solar System

Table II. – Line Constant

	ACSR(160mm ²)
R[Ω/km]	0.182
ωL[Ω/km]	0.502296

earthquake frequently occurs is not desirable, not only in the sense of safety but also in the sense of maintenance. The accumulated number of the earthquake occurrence (NE) and the data of the observation start year (SY) are obtained from the Meteorological Agency. The degree of earthquake frequency, which is NE divided by (2011-SY) is used to evaluate the earthquake occurrence. From the above viewpoint, this data is considered as an input in DEA.

E. Transmission Loss

We have to connect the mega-solar station to the grid, in order to supply electric power from it. Long distance transmission from mega-solar station gives rise to loss. Then, it assumed to the nearest substation assuming connection, the expected transmission loss is calculated. Since the lower transmission loss is better, this data is considered as an input in DEA.

To calculate this data, the distance from each site to its nearest substation is geographically measured. Since the main mega-solar installation area needs over 30000[m²] in Japan, required land area is set to 40000[m²].

To calculate the transmission loss, the mega-solar is assumed to be connected as shown in Fig. 3. The transmission loss is calculated on the basis of the maximum power generation, the day of the maximum solar radiation. The output from PV panel is set to 2.7[MW] by 100[kW]×27, and the loss of the panel is set to 0.155 [15]. It is assumed that the transformer capacity is 3000[kW] and a reactance value is 5.5[%]. Rated (nominal) voltage is 33[kV] and Frequency is 60[Hz]. A Line Constant is indicated in Table II [16]. The transmission loss at each place is computed from the above conditions, and the value is applied to DEA.

Table III shows the above five data, where all the numerical value shows a relative value on the basis of a maximum value. LP Solve is used in our calculations.

Table III. – Each Data

Point	Land Cost (p.u.)	Earth-quake Occurrence (p.u.)	Loss (p.u.)	Global Solar Radiation (p.u.)	Population Density (p.u.)
	v_1	v_2	v_3	u_1	u_2
DMU ₁	0.362	0.113	0.281	0.840	0.149
DMU ₂	0.345	0.140	0.184	0.891	0.218
DMU ₃	0.203	0.062	0.079	0.825	0.038
DMU ₄	0.166	0.118	0.318	0.855	0.026
DMU ₅	0.252	0.127	0.145	0.916	0.238
DMU ₆	0.254	0.083	0.188	0.808	0.039
DMU ₇	0.280	0.059	0.126	0.855	0.080
DMU ₈	0.222	0.023	0.027	0.833	0.031
DMU ₉	0.097	0.027	0.117	0.832	0.010
DMU ₁₀	0.180	0.113	0.281	0.839	0.013
DMU ₁₁	0.188	0.079	0.165	0.884	0.016
DMU ₁₂	0.667	0.147	0.226	0.827	0.148
DMU ₁₃	0.879	0.189	0.257	0.942	0.420
DMU ₁₄	0.110	0.082	0.211	0.811	0.002
DMU ₁₅	0.254	0.186	0.229	0.849	0.074
DMU ₁₆	0.141	0.085	0.111	0.974	0.078
DMU ₁₇	0.356	0.034	0.065	0.888	0.153
DMU ₁₈	0.770	0.112	0.064	0.942	0.345
DMU ₁₉	0.326	0.073	0.066	0.809	0.017
DMU ₂₀	0.096	0.110	0.099	0.804	0.004
DMU ₂₁	0.466	0.159	0.086	0.855	0.145
DMU ₂₂	1	0.233	0.097	0.922	1
DMU ₂₃	0.582	0.080	0.177	0.859	0.354
DMU ₂₄	0.615	0.228	0.074	0.841	0.186
DMU ₂₅	0.119	0.056	0.158	0.773	0.004
DMU ₂₆	0.615	0.186	0.279	0.839	0.230
DMU ₂₇	0.195	0.118	0.140	0.875	0.084
DMU ₂₈	0.529	0.075	0.098	0.860	0.213
DMU ₂₉	0.579	0.191	0.268	0.855	0.210
DMU ₃₀	0.233	0.086	0.124	0.942	0.051
DMU ₃₁	0.039	0.120	0.131	0.769	0.000
DMU ₃₂	0.262	0.123	0.137	0.812	0.005
DMU ₃₃	0.060	0.188	0.398	0.786	0.001
DMU ₃₄	0.457	0.085	0.520	0.838	0.069
DMU ₃₅	0.042	0.062	0.068	0.760	0.000
DMU ₃₆	0.030	0.076	0.580	0.767	0.001
DMU ₃₇	0.178	0.056	0.425	0.752	0.009
DMU ₃₈	0.397	0.126	0.124	0.801	0.009
DMU ₃₉	0.166	0.104	0.239	0.788	0.011
DMU ₄₀	0.350	0.131	0.208	0.784	0.010
DMU ₄₁	0.143	0.092	0.156	0.780	0.006
DMU ₄₂	0.097	0.220	0.113	0.785	0.018
DMU ₄₃	0.108	0.042	1	0.815	0.006
DMU ₄₄	0.184	0.064	0.129	0.811	0.029
DMU ₄₅	0.203	0.122	0.430	0.713	0.013
DMU ₄₆	0.104	0.103	0.076	0.815	0.016
DMU ₄₇	0.185	0.164	0.149	0.823	0.102
DMU ₄₈	0.238	0.132	0.116	0.819	0.196
DMU ₄₉	0.091	0.126	0.285	0.812	0.004
DMU ₅₀	0.474	0.180	0.132	0.896	0.302
DMU ₅₁	0.369	0.150	0.083	0.838	0.279
DMU ₅₂	0.155	0.100	0.101	0.788	0.025
DMU ₅₃	0.222	0.130	0.542	0.807	0.010
DMU ₅₄	0.151	0.257	0.170	0.810	0.018
DMU ₅₅	0.115	0.264	0.087	0.779	0.009
DMU ₅₆	0.083	0.122	0.088	0.789	0.007

DMU ₅₇	0.483	0.843	0.294	0.898	0.076
DMU ₅₈	0.120	0.168	0.321	0.804	0.011
DMU ₅₉	0.100	0.104	0.258	0.802	0.009
DMU ₆₀	0.157	0.029	0.255	0.861	0.009
DMU ₆₁	0.306	0.149	0.266	0.898	0.103
DMU ₆₂	0.191	0.055	0.267	0.863	0.041
DMU ₆₃	0.555	0.170	0.134	0.892	0.016
DMU ₆₄	0.210	0.145	0.126	0.819	0.042
DMU ₆₅	0.479	0.128	0.125	1	0.115
DMU ₆₆	0.100	0.255	0.244	0.863	0.018
DMU ₆₇	0.226	0.279	0.318	0.865	0.034
DMU ₆₈	0.016	0.055	0.411	0.799	0.001
DMU ₆₉	0.030	0.587	0.488	0.819	0.001
DMU ₇₀	0.287	0.154	0.131	0.831	0.003
DMU ₇₁	0.347	1	0.110	0.927	0.071
DMU ₇₂	0.186	0.130	0.229	0.849	0.019
DMU ₇₃	0.113	0.176	0.672	0.870	0.025
DMU ₇₄	0.063	0.625	0.233	0.824	0.003
DMU ₇₅	0.205	0.140	0.429	0.864	0.044
DMU ₇₆	0.167	0.280	0.095	0.847	0.007
DMU ₇₇	0.140	0.198	0.313	0.864	0.017
DMU ₇₈	0.087	0.190	0.328	0.804	0.003
DMU ₇₉	0.276	0.198	0.125	0.918	0.047
DMU ₈₀	0.030	0.113	0.313	0.851	0.001
DMU ₈₁	0.015	0.089	0.108	0.777	0.007

4. Results

Table IV shows DMUs from which the efficiency value is set to 1 in BCC model. The data of Table III is applied by the input-oriented CCR model and the input-oriented and the output-oriented BCC models, and the result of the sensitivity analysis is also shown in Table IV.

The point where the data of the input is small showed the more efficient value, comparing the input-oriented model result with data. On the contrary, the point where the data of the output is large showed the more efficient value, comparing the output-oriented model result with data.

In the input-oriented model, calculation becomes infeasible at two places, whereas in the output-oriented model infeasible at five places. Calculation become infeasible in seven cases in total, because this paper treats larger numbers of outputs and DMUs than those in [14]. Next, the efficiency value of the point where calculation becomes infeasible is set to 1, the efficiency values of the input-oriented and the output-oriented are integrated using the equation (7), and the values of S_I and S_O are calculated. Large S_I and small S_O imply high efficiency. The top three candidates are DMU₁₆, DMU₁₇, and DMU₂₂. If we focus attention on the value of S_I , ranking will be DMU₂₂, DMU₁₆, DMU₁₇. If we focus attention on the value of S_O , ranking will be DMU₁₇, DMU₁₆, DMU₂₂. In the feature of these three DMUs, as compared with data, DMU₁₆ is second-largest in the amount of global solar radiation and inputs have comparatively small values. Although DMU₁₇ has fourth-smallest earthquake occurrence and the loss is third-smallest, the value of the land cost is large. DMU₂₂ is the point where the land cost is the highest, while population density is the largest. In CCR model, DMU₁₆ is

Table IV. - Results

Point	CCR	Input-oriented	Output-oriented	S_I	S_O
DMU ₅	1.0008	1.093607	0.9524989	1.07174	0.93345
DMU ₈	2.22840	2.417120	infeasible	1.70856	0.70686
DMU ₉	1.37982	1.394187	infeasible	1.19709	0.85863
DMU ₁₆	0.96779	2.609837	0.8762254	1.87555	0.62970
DMU ₁₇	1.36123	1.841881	0.5842974	1.77667	0.56361
DMU ₁₈	0.82174	1.505003	0.9419112	1.28334	0.80318
DMU ₂₂	2.09198	infeasible	0.3581903	1.89591	0.67910
DMU ₂₃	0.99662	1.004207	0.9959145	1.00416	0.99586
DMU ₃₅	1.28641	1.334918	infeasible	1.16746	0.87456
DMU ₆₀	0.93173	1.168498	0.9816134	1.09362	0.91871
DMU ₆₅	0.52852	infeasible	0.9722234	1.01429	0.98611
DMU ₆₈	1.52494	1.624796	infeasible	1.31240	0.80773
DMU ₈₀	0.70984	1.771562	0.9564656	1.40854	0.76047
DMU ₈₁	2.24608	2.264061	infeasible	1.63203	0.72084

not efficient, but it is turned out to be efficient evaluating by BCC model.

5. Conclusion

In this paper, DEA is applied to the problem of the mega-solar optimal allocation for Chubu District 81 points in Japan, and the efficiency value is measured. By evaluating both models of input-oriented and output-oriented, we avoid one-sided evaluation. Moreover, it is shown that the candidate which is evaluated as not efficient by CCR model can become efficient in the case of BCC model.

In our future studies, various types of data will be treated. Furthermore, we plan to improve the feasibility of the proposed method.

References

- [1] M. Akatsuka, R. Hara, H. Kita, T. Ito, Y. Ueda, Y. Saito, "Estimation of battery for suppression of a PV power plant output fluctuation," IEEE PVSC, 2010, pp. 000540-000543
- [2] H. Konishi, T. Iwato, M. Kudou, "Development of Large-scale Power Conditioning System in Hokuto Mega-solar Project," IPEC, 2010, pp. 1975-1979
- [3] A. Charnes, W.W. Cooper, E. Rhodes, "Measuring efficiency of decision making units," European Journal of Operational Research, Vol.2, 1978, pp.429-444
- [4] H. M. Khodr, D. Feijoo, E. Perez, I. J. Zepa, P. M. De Oliveira-De Jesus, J. M. Yusta, "Efficiency Control of the Electrical Distribution Utilities Using Data Envelopment Analysis," IEEE/PES TDC, 2006, pp. 1-6
- [5] Chen-Fu Chien, Wen-Chih Chen, Feng-Yu Lo, Yi-Chieh Lin, "A Case Study to Evaluate the Productivity Changes of the Thermal Power Plants of the Taiwan Power Company," IEEE Transactions on Energy Conversion, vol. 22, 2007, pp. 680-688.
- [6] A. Azadeh, S.F. Ghaderi, M.R. Nasrollahi, "Energy Efficiency Modeling and Estimation in Petroleum Refining Industry - A Comparison Using Physical Data" (ICREPQ'8), 2008, <http://www.icrepq.com>.
- [7] A. Azadeh, S.F. Ghaderi, A. Maghsoudi, "Location optimization of solar plants by an integrated hierarchical DEA PCA approach," Energy Policy, vol.36, 2008, pp.3993-4004
- [8] A. Azadeh, S.F. Ghaderi, M.R. Nasrollahi, "Location optimization of wind plants in Iran by an integrated hierarchical

- Data Envelopment Analysis,” *Renewable Energy*, vol.36, 2011, pp.1621-1631
- [9] S. Yokota, T. Kumano, “Mega-solar Optimal Allocation using Data Envelopment Analysis” *IEEJ Trans. PE*, vol.131, No.10, 2011, pp.819-825
- [10] R. D. Banker, A. Charnes, W. W. Cooper, “Some Models for Estimating Technical and Scale Inefficiencies in Data Envelopment Analysis” *Management Science*, vol. 30, 1984, pp.1078-1092
- [11] L. M. Seiford, R. M. Thrall, “Recent developments in DEA: The mathematical programming approach to frontier analysis” *Journal of Econometrics* 46, 1990, pp.7-38
- [12] L. M. Seiford, J. Zhu, “Infeasibility of super-efficiency data envelopment analysis models” *INFOR*, Vol.37, 1999, pp.174-187.
- [13] Y. Chen, “Measuring super-efficiency in DEA in the presence of infeasibility” *European Journal of Operational Research*, Vol.161, 2005, pp.545-551.
- [14] Y. Chen, “Ranking efficient units in DEA” *Management Science*, Vol.32, 2004, pp.213-219.
- [15] The New Energy and Industrial Technology Development Organization “Investigation about photovoltaic generation system stabilization for large-scale power supplies” 2006-3 (in Japanese)
- [16] K. Aratame “The foundation of power system technical calculation” 1980 (in Japanese)