An Integrated Model to Evaluate the Performance of Solar PV Firms

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Abstract: The use of renewable energy resources is being stressed in the 21st century due to the depletion of fossil fuels and the increasing consciousness about environmental degradation. Renewable energies, such as wind energy, fire energy, hydropower energy, geothermal energy, solar energy, biomass energy, ocean power and natural gas, are treated as alternative means of meeting global energy demands. After Japan's nuclear plant disaster in March 2011, people are aware that a good renewable energy resource not only needs to produce zero or little air pollutants and greenhouse gases, it also needs to have a high safety standard to prevent the chances of hazards from happening. Solar energy is one of the most promising renewable energy sources with an infinite sunlight resource and environmental sustainability. However, photovoltaic products currently still require a high production cost with low conversion efficiency. In addition, the solar industry has a rather versatile market cycle in response to economic conditions. Therefore, solar firms need to strengthen their competitiveness in order to survive and to acquire decent profits in the market. This research proposes a performance evaluation model by integrating data envelopment analysis (DEA) and analytic hierarchy process (AHP) to assess the business performance of the solar firms. From the analysis, the firms can understand their current positions in the market and to know how they can improve their business. A case study is performed on the crystalline silicon solar firms in Taiwan.

1 INTRODUCTION

As technology advances, the demand for various energy resources increases sharply. In addition to the fluctuations in commodity prices, a heavy burden on the environment is resulted, and this brings climate changes, environmental degradations, etc. The combined effects of the depletion of fossil fuels and the gradually emerging consciousness about environmental degradation have made many countries to realize the importance of making good use of natural resources and developing renewable alternative energy resources in the 21st century. In December, 2009, world leaders met at the United Nations Climate Change Conference (COP15) in Copenhagen to tackle with the issue of CO_2 reduction for stopping global warming before it causes irreversible damage (SolarCOP 15, 2009). Intense debate was centered on the challenge of reducing CO_2 emissions in each country without limiting its economic growth and ability to make life better for the citizens. One of the consensuses was that renewable energy is the key to CO_2 reduction now and in the future. The main advantages of renewable energy are the absence of harmful emissions and the conversion of infinite availability of renewable resources into electricity. Despite the global economic recession that has an impact on the demand for clean energy, many developed and developing countries have recognized that the development of renewable energies is necessary for the environment as well as the economy (Mints and Hopwood, 2009).

While there are many types of PV solar cells, they basically can be categorized into two main groups: crystalline silicon and thin film. The ultimate goal for all kinds of PV technology is to produce solar electricity at a cost comparable to currently marked dominating technologies like coal and nuclear power in order to make it the leading primary energy source (Wikipedia, 2009). PV technologies currently face a wide range of problems

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from a lack of knowledge of basic material properties, availability of production technologies, to legal concerns about patent infringements and market perspectives. The PV industry is transitioning from production in relatively small factories, with capacities of 10 to 100 MW per year, to much larger ones producing up to 1 GW or more per year (Applied Materials, 2008). Such manufacturing transition is analogous to the early years of semiconductor industry and recent flat panel display (FPD) industry, both of which depend on highly automated, high-volume manufacturing technologies. Thus, some technologies from the two industries are immediately applicable to making solar cells in volume production.

In this paper, an incorporation of fuzzy analytic hierarchy process (FAHP) and data envelopment analysis (DEA) is used in the proposed model. The rest of the paper is organized as follows. In the next section, FAHP and DEA are introduced. In section 3, FAHP model incorporated with DEA is constructed. A case study is presented next in section 4. Some conclusion remarks and future research directions are made in the last section.

2 METHODOLOGIES

2.1 Fuzzy Analytic Hierarchy Process (FAHP)

AHP is a mathematically-based multi-criteria decision-making (MCDM) tool (Saaty, 1980). Under AHP, a complex problem is decomposed into several sub-problems in terms of hierarchical levels, and the factors of the same hierarchical level are compared relative to their impact on the solution of their higher level factor. Since uncertainty may need to be considered in some or all pairwise comparison values, the incorporation of fuzzy set theory into AHP is recommended (Yu, 2002). The application of FAHP has gained popularity in the past decade, and an approach can be as follows (Lee, Kang and Wang, 2006):

1. Form a committee of experts to define the problem and to decompose the problem hierarchically.

2. Formulate a questionnaire based on the proposed structure to compare pairwise elements, or factors, in each level with respect to every element in the next higher level. Five-point scale is usually applied in fuzzy AHP rather than nine-point scale, which is often used in the traditional AHP method. Triangular membership functions can be defined to represent linguistic terms for facilitating judgment and integrating different experts' opinions (Chi and Kuo, 2001).

3. Establish fuzzy judgment matrix. With a fuzzy number, $\tilde{1},\tilde{3},\tilde{5},\tilde{7},\tilde{9}$, to represent the relative contribution of each element on the objective or the adjacent upper-level criterion, a fuzzy judgment vector can be built for each element, and the triangular fuzzy numbers $\tilde{1},\tilde{3},\tilde{5},\tilde{7},\tilde{9}$ are defined as in Table 1.

$$\tilde{\mathbf{x}}_{ij} = [\tilde{x}_{i1} \quad \tilde{x}_{i2} \quad \tilde{x}_{i3} \quad \cdots \quad \tilde{x}_{ij}] \tag{1}$$

where $\tilde{\mathbf{x}}_{ij}$ is the relative contribution of element *j* on element *i*.

A fuzzy judgment matrix can next be built to compose all fuzzy judgment vectors:

$$\tilde{\mathbf{X}} = \begin{bmatrix} \tilde{x}_{11} & \tilde{x}_{12} & \cdots & \tilde{x}_{1n} \\ \tilde{x}_{21} & \tilde{x}_{22} & \cdots & \tilde{x}_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ \tilde{x}_{m1} & \tilde{x}_{m2} & \cdots & \tilde{x}_{mn} \end{bmatrix} \tag{2}$$

Table 1: Characteristic function of the fuzzy numbers.

Fuzzy number	Characteristic (Membership) function
$\tilde{1}$	(1, 1, 3)
$\tilde{x}$	(x –2, x, x+2) for x =3,5,7
$\tilde{9}$	(7, 9, 9)

4. Establish fuzzy weight vector. The weights of criteria, which are supplied by experts' opinion, can be represented by a fuzzy weight vector, $\tilde{\mathbf{w}}$: $\tilde{\mathbf{w}}^{\mathrm{T}} = [\tilde{w}_1 \quad \tilde{w}_2 \quad \cdot \quad \cdot \quad \tilde{w}_n]$, where $\tilde{w}_p = \tilde{1},\tilde{3},\tilde{5},\tilde{7},\tilde{9}$.

5. Establish and rank aggregate fuzzy numbers. The aggregate fuzzy numbers, $\tilde{R}$, are obtained by multiplying the fuzzy judgment matrix $\tilde{\mathbf{X}}$ with the corresponding fuzzy weight vector, $\tilde{\mathbf{w}}$ (Lee et al., 2006):

$$\tilde{R} = \tilde{\mathbf{X}} \otimes \tilde{\mathbf{w}}$$

$$= \begin{bmatrix} \tilde{x}_{11} & \tilde{x}_{12} & \cdots & \tilde{x}_{1n} \\ \tilde{x}_{21} & \tilde{x}_{22} & \cdots & \tilde{x}_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ \tilde{x}_{m1} & \tilde{x}_{m2} & \cdots & \tilde{x}_{mn} \end{bmatrix} \otimes \begin{bmatrix} \tilde{w}_1 \\ \tilde{w}_2 \\ \cdot \\ \cdot \\ \tilde{w}_n \end{bmatrix}$$

$$= \begin{bmatrix} \tilde{x}_{11} \otimes \tilde{w}_1 \oplus \tilde{x}_{12} \otimes \tilde{w}_2 \oplus \cdots \oplus \tilde{x}_{1n} \otimes \tilde{w}_n \\ \tilde{x}_{21} \otimes \tilde{w}_1 \oplus \tilde{x}_{22} \otimes \tilde{w}_2 \oplus \cdots \oplus \tilde{x}_{2n} \otimes \tilde{w}_n \\ \vdots \\ \tilde{x}_{m1} \otimes \tilde{w}_1 \oplus \tilde{x}_{m2} \otimes \tilde{w}_2 \oplus \cdots \oplus \tilde{x}_{mn} \otimes \tilde{w}_n \end{bmatrix} = \begin{bmatrix} \tilde{\gamma}_1 \\ \tilde{\gamma}_2 \\ \cdot \\ \cdot \\ \tilde{\gamma}_m \end{bmatrix} \quad (3)$$

6. Fuzzy numbers can then be ranked by one of the many different methods, and each method has its own advantages and disadvantages (Klir and Yuan, 1995). A popular method is the α -cut method. Let $\tilde{\gamma}_i$ be (p_i, q_i, s_i). By defining the interval of confidence at level α , the triangular fuzzy number can be characterized as

$$\tilde{\gamma}_i^{\alpha} = \left[p^{\alpha}, s^{\alpha}\right] = \left[(q-p)\alpha + p, -(s-q)\alpha + s\right], \quad \forall \alpha \in [0,1] \quad (4)$$

2.2 Date Envelopment Analysis (DEA)

DEA, introduced by Charnes, Cooper and Rhodes in 1978, was first applied to investigate not-for-profit organizations whose success cannot be measured by a single measure, such as profit (Charnes et al., 1978). A relative efficiency score of decision making unit (DMU) is obtained under multiple inputs and outputs, and the DMUs that locate on the frontier, the envelopment, are considered to be the most efficient.

The most popular two models of DEA are CCR and BCC. CCR, introduced by Charnes, Cooper and Rhodes, generates efficiency in ratio form by obtaining directly from the data without requiring a priori specification of weights nor assuming functional forms of relations between inputs and outputs. Because nonlinear programming of fractional form cannot be solved easily, the problem is transformed into a linear programming problem. The input-oriented CCR model, CCRd-I, is introduced briefly here (Charnes et al., 1978; Chung, Lee, Kang and Lai, 2008). Assume that there are n DMUs, and each is represented by DMU*j* where $j = 1,...k...,n$. For each DMU, there are m inputs (X_{ij} ; $i = 1,...,m$) and *r* outputs (Y_{rj} ; $r = 1, \ldots, s$). The input of factor *i* for DMU *j* is X_{ij} , and the output of factor *i* for DMU *j* is Y_{rj} . The efficiency of DMU$_k$ can be obtained as follows:

$$\text{Min } h_k = \theta_k - \varepsilon\left(\sum_{i=1}^{m} s_i^- + \sum_{r=1}^{s} s_r^+\right) \quad (5)$$

$$\text{s.t } \sum_{j=1}^{n} \lambda_j X_{ij} - \theta_k X_{ik} + s_i^- = 0, \; i = 1,..., m \quad (6)$$

$$\sum_{j=1}^{n} \lambda_j Y_{rj} - s_r^+ = Y_{rk}, \; r = 1, \ldots, s \quad (7)$$

$$\lambda_j, s_i^-, s_r^+ \geq 0, \; j = 1,...,n, \; i = 1,...,m, \; r = 1, \ldots, s \quad (8)$$

where s_i^-, s_r^+ are the slack variables of inputs and outputs respectively, λ_j is the weight for DMU$_j$, and θ_k is the relative efficiency indicator of the *k*th DMU.

3 AN INTEGRATED MODEL FOR PERFORMANCE OF SOLAR PV FIRMS

In this research, an integrated FAHP/DEA model for evaluating the business performance of PV firms is proposed. In the conventional DEA, quantitative factors can be evaluated objectively, and productivity (output/input) can be measured effectively. However, the weighting of each factor cannot be subjectively determined by experts. On top of these, a good decision-making model should be able to tolerate vagueness or ambiguity, and fuzzy set theory, thus, is recommended to solve the problem. As a result, this research integrates the concepts of fuzzy set theory, AHP and DEA, and proposes a FAHP/DEA methodology. The steps of the proposed model are summarized as follows:

Step 1: Define the performance evaluation problem in the PV industry.

Step 2: Determine the competitive factors for evaluating PV firms.

Step 3: Collect the data of each factor from the PV firms under study.

Step 4: Calculate the assurance ranges (AR) of the factors by the FAHP.

Step 5: Determine the efficiencies of the PV firms by the DEA.

The DEA/AR model (Shang and Sueyoshi, 1995; Zhu, 1996; Liu, 2008) is used to calculate the efficiencies of the PV firms. The outcomes from Step 3 and 4 are used in the model, and the overall performance of the firms can be generated. The DEA/AR model for measuring the AR efficiency of a selected *DMUr* is as follows:

$$E_r = \max \sum_{k=1}^{t} u_k Y_{rk} \tag{9}$$

$$\text{s.t.} \quad \sum_{j=1}^{s} v_j X_{rj} = 1 \tag{10}$$

$$\sum_{k=1}^{t} u_k Y_{ik} - \sum_{j=1}^{s} v_j X_{ij} \le 0 \qquad , i = 1,2,3......n \tag{11}$$

$$u_k \ge \varepsilon > 0 \, , v_k \ge \varepsilon > 0 \, . \tag{12}$$

where the E_r is the relative efficiency of the *r*th DMU taking into account the minimum and maximum influence that each factor can have on E_r, X_{ij} is the amount of *j*th input (*j*=1,…,*s*) of the *i*th DMU, Y_{ik} is the amount of the *k*th output (*k*=1,…,*t*) of the *i*th DMU, v_j and u_k are the weights of the *j*th input and the *k*th output respectively, and ε is a small non-Archimedean number. Set the relative importance elicited from the experts range from L_{Op} to U_{Op} for output *p* and from L_{Oq} to U_{Oq} for output *q*, and from L_{Ip} to U_{Ip} for input *p* and from L_{Iq} to U_{Iq} for input *q*. The associated constraints are as following:

$$L_{O_p} / U_{O_q} \le u_p / u_q \le U_{O_p} / L_{O_q}, p < q = 2,....t \tag{13}$$

$$L_{I_p} / U_{I_q} \le v_p / v_q \le U_{I_p} / L_{I_q}, p < q = 2,....s \tag{14}$$

With the above model, the efficiencies of the PV firms can be calculated.

4 CASE STUDY

The proposed model is applied to evaluate the current position of firms in a specific sector in the PV supply chain in Taiwan. Five inputs and three outputs are selected in the case study. The five inputs are fixed assets (I1), cost of goods sold (I2), general and administrative expenses (I3), research and development expenses (I4), and selling expenses (I5). The three outputs are sales revenue (O1), income before income taxes (O2) and earnings per share (O3). A questionnaire based on the hierarchy is filled out by the experts, and pairwise comparison matrices for each expert are prepared. The pairwise comparison matrix of the inputs for the first expert is shown as follows:

$$\tilde{\mathbf{W}}^{Expert1}_{Input} = \begin{array}{c} \\ I_1 \\ I_2 \\ I_3 \\ I_4 \\ I_5 \end{array} \begin{array}{c} \begin{array}{ccccc} I_1 & I_2 & I_3 & I_4 & I_5 \end{array} \\ \begin{bmatrix} (1,1,1) & (1,2,3) & (1,2,3) & (1/6,1/5,1/4) & (1,1,1) \\ (1/3,1/2,1) & (1,1,1) & (1,1,1) & (1/5,1/4,1/3) & (1/5,1/4,1/3) \\ (1/3,1/2,1) & (1,1,1) & (1,1,1) & (1/5,1/4,1/3) & (1/5,1/4,1/3) \\ & & & (1,1,1) & (1,1,1) \\ & & & & (1,1,1) \end{bmatrix} \end{array}$$

Using the geometric average method to synthesize the experts' opinions, the aggregated pairwise comparison matrix of the inputs is:

$$\tilde{\mathbf{W}}_{Inputs} = \begin{array}{c} \\ I_1 \\ I_2 \\ I_3 \\ I_4 \\ I_5 \end{array} \begin{array}{c} \begin{array}{ccccc} I_1 & I_2 & I_3 & I_4 & I_5 \end{array} \\ \begin{bmatrix} (1.0000,1.0000,1.0000) & (0.6988,1.0000,1.4310) & (0.8027,1.1914,1.7188) & (0.2205,0.2841,0.4014) & (0.4353,0.5173,0.6598) \\ & (1.0000,1.0000,1.0000) & (0.4152,0.5743,1.000) & (0.2422,0.3222,0.4884) & (0.2565,0.3494,0.5610) \\ & & (1.0000,1.0000,1.0000) & (0.3155,0.4503,0.6598) & (0.2782,0.3342,0.4251) \\ & & & (1,1,1) & (0.5173,0.6598,1,0000) \\ & & & & (1,1,1) \end{bmatrix} \end{array}$$

The priorities of the inputs are:

$$\tilde{w}_{\text{Inputs}} = \begin{array}{c} \text{I1} \\ \text{I2} \\ \text{I3} \\ \text{I4} \\ \text{I5} \end{array} \begin{bmatrix} (0.12, 0.12, 0.13) \\ (0.10, 0.10, 0.12) \\ (0.12, 0.12, 0.13) \\ (0.29, 0.30, 0.31) \\ (0.32, 0.33, 0.33) \end{bmatrix}$$

By applying the α -cut method and setting α to be 0.5, the priorities of the inputs are:

$$\tilde{w}^{\alpha}_{\text{Inputs}} = \begin{array}{c} \text{I1} \\ \text{I2} \\ \text{I3} \\ \text{I4} \\ \text{I5} \end{array} \begin{bmatrix} [0.13, 0.13] \\ [0.10, 0.11] \\ [0.12, 0.13] \\ [0.30, 0.31] \\ [0.32, 0.33] \end{bmatrix}$$

The same procedure is carried out to calculate the priorities of the outputs, and they are:

$$\tilde{w}^{\alpha}_{\text{Outputs}} = \begin{array}{c} \text{O1} \\ \text{O2} \\ \text{O3} \end{array} \begin{bmatrix} [0.21, 0.22] \\ [0.39, 0.39] \\ [0.38, 0.38] \end{bmatrix}$$

Let the weight for input I1 to input I5 be $v_{I1}, \ldots, v_{I5}$ respectively, the ratio v_{I1}/v_{I2} has the lower bound of 1.18 (0.13/0.11) and upper bound of 1.3 (0.13/0.10). The AR for each pair of inputs and each pair of outputs can be calculated, as shown in Table 2.

5 CONCLUSIONS

A good evaluation of the firms in the PV industry and an understanding of a firm's position in the market are important for the firm to improve its competitiveness in the market. In this study, a FAHP/DEA model is proposed to evaluate the efficiencies of the firms in a market. The assurance ranges for inputs and outputs are calculated. A case study of crystalline silicon solar firms in Taiwan will be carried out using the proposed model.

Taiwan has a strong background and foundation for developing the PV industry because of the successes of the semiconductor and TFT-LCD manufacturing industries in Taiwan. After the analysis is performed using the proposed model, the findings shall help the firms determine their strengths and weaknesses and provide directions for future improvements in business operations.

Table 2: Assurance range for inputs and outputs.

Ratio	Lower bound	Upper bound
v_{I1}/v_{I2}	0.13/0.11	0.13/0.10
v_{I1}/v_{I3}	0.13/0.13	0.13/0.12
v_{I1}/v_{I4}	0.13/0.31	0.13/0.30
v_{I1}/v_{I5}	0.13/0.33	0.13/0.32
v_{I2}/v_{I3}	0.10/0.13	0.11/0.12
v_{I2}/v_{I4}	0.10/0.31	0.11/0.30
v_{I2}/v_{I5}	0.10/0.33	0.11/0.32
v_{I3}/v_{I4}	0.12/0.31	0.13/0.30
v_{I3}/v_{I5}	0.12/0.33	0.13/0.32
v_{I4}/v_{I5}	0.30/0.33	0.31/0.32
u_{I1}/u_{I2}	0.21/0.39	0.22/0.39
u_{I1}/u_{I3}	0.21/0.38	0.22/0.38
u_{I2}/u_{I3}	0.39/0.38	0.39/0.38

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