Efficiency Evaluation Of A Few Organic Solar Cells By Data Envelopment Analysis

Gitalee Sharma and Mithun J Sharma

Abstract: The measurement of Power Conversion Efficiency (PCE) of Organic Solar Cells (OSC) noted in literature till date is absolute and not relative. As in absolute measure, comparative ranking cannot be made by referring to a benchmark, scope for improvement is on lack. However, relative measurement compares the absolute values, thereby providing scope for benchmarking, referencing and improvement projections. This paper proposes the application of Data Envelopment Analysis (DEA), a non parametric operation research approach for relative efficiency measurement of OSCs (DMUs). The DEA model used reveal that out of the 25 OSCs studied here, one OSC (i.e. DMU Y[28]), is found to be efficient and all other DMUs are inefficient relatively taking Y[28] as benchmark. The result of input/output oriented DEA method used to measure the relative efficiency of OSCs prescribes to hold input/output constant and to determine how much of an improvement in the output/input dimensions of inefficient OSCs is necessary in order to reach the frontier.

Index Terms: Organic solar cells, Power conversion efficiency, Data envelopment analysis, Band gap

1. INTRODUCTION

THE growing demand for electricity has gained attention in photovoltaics as it is readily and freely available, environment friendly and has low maintenance property [1]. However, the photovoltaics dominated by inorganic materials because of their high conversion efficiency (highest PCE of 44.7% in lab), has its limitations of high energy consumption at fabrication and cost intensiveness [2]. In this view, organic solar cells (OSC) have attracted much attention because of their low-cost fabrication techniques, light weight, flexibility, solution processability and environment friendliness [3]. A review of the literature on organic solar cells reveal that a wide range of organic solar cell devices has been fabricated with a variety of PCE till date (highest PCE of 8.4% in lab)[4]. These variety of PCE have their absolute measure which is not relative. Relativity is required to see which input works better, easier to use or has improvement scope. Since, determination of PCE of OSC in isolation provide an absolute value, scope for improvement is limited. Therefore, the concept of relativity is vital for benchmarking, referencing and methodological improvement. However, not any technique has been incorporated to compare the relative efficiency of the organicsolar cell devices known in literature based on their input and output parameters. Thus, in this paper we propose to apply data envelopment analysis (DEA), a non-parametric operation research (OR) approach for efficiency measurement of organic solar cells. DEA is the optimization method of mathematical programming to generalize the single-input/ single-output technical efficiency measure to the multiple-input/ multiple-output case by constructing a relative efficiency score as the ratio of a single virtual output to a single virtual input [5].

- *Gitalee Sharma is currently an Assistant Professor in the Department of Engineering Chemistry, DUIET, ,Dibrugarh University, Assam, India, E-mail: gitaleesharma@dibru.ac.in*
- *Mithun J Sharma is currently an Assistant Director (Academics), DODL, Dibrugarh University, Assam, India, E-mail: mithunjsharma@dibru.ac.in*

In this paper, we have compared the relative efficiency of nine organic solar cell devices fabricated with different π-conjugated molecules (as active layer) with a few samples collected from literature. The active layers of the OSC devices were synthesized by a novel procedure [6]. The photovoltaic devices were fabricated and their current–voltage (I-V) characteristics studied [6]. The data was collected from the published record and analyzed by subsuming a linear programming mathematical technique, DEA.

2 METHODOLOGY

2.1 Device Fabrication

Nine OSC devices were fabricated with different highly conjugated imidazolinone molecules as active layers (Fig. 1).

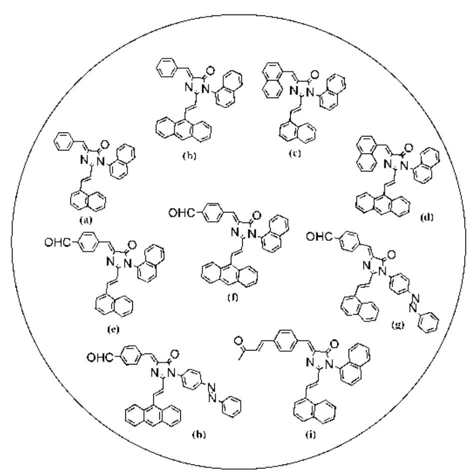

***Fig. 1** The molecules used as active layers in the fabricated OSC devices*

The organic molecules used for the devices were synthesized by a novel procedure which we have already published [6].
The photovoltaic devices were fabricated using the formula: ITO (130nm) || WPTA (90nm) || PEDOT:PSS (60nm) || Organic layer (100nm) || Al (100nm). The current–voltage (I–V)

characteristics of the photovoltaic solar cell were measured using a Keithley model 2420 source meter under day sunlight of 100mW/cm2 illumination. The solar illumination was measured by using a lux meter. In this study, the film thickness of the W-PTA and PEDOT:PSS layer was controlled by varying the weight percent of their solutions during the spin-coating process while all other experimental conditions, such as rpm (3000rpm) for 30s and annealing temperature (115 ^{0}C), were fixed. The spin coating rpm of the organic layer was maintained at 1000 rpm for 60s [6].
The Current-voltage (I-V) characteristics of the OSC devices fabricated with the synthesized molecules as active layers were studied and published [6].

2.2 Model for DEA (CRS Model)

DEA is a multi-factor productivity analysis model for measuring the relative efficiencies of a homogenous set of decision making units (DMUs) [7]. DEA models are classified with respect to the type of envelopment surface, the efficiency measurement and the orientation (input or output). There are two basic types of envelopment surfaces in DEA known as constant returns-to-scale (CRS) and variable returns-to-scale (VRS) surfaces [8]. Each model makes implicit assumptions concerning returns-to-scale associated with each type of surface. Charnes, Cooper and Rhodes introduced the CCR or CRS model that assumes that the increase of outputs is proportional to the increase of inputs at any scale of operation [9]. DEA models are also classified as radial input oriented, radial output oriented or additive (both inputs and outputs are optimized) based on the direction of projection of the inefficient unit into the frontier [10]. We here utilize only the radial output oriented models in our study of organic solar cells. Charles, Cooper and Rhodes (CCR) model allows representing multiple inputs and outputs of each DMU and can be represented as a ratio of the abstract input to abstract output, and the resulting efficiency value can then be used for comparison with other DMU in the set [9]. Mathematically, in all variations of the DEA models [11] the DMUs with the best inherent efficiency in converting inputs X_1, X_2,…..$X_n$into outputs Y_1, Y_2,…..$Y_m$is identified, and then all other DMUs are ranked relatively to the most efficient DMU.
Consider a set of n observations on the DMUs. Each observation, $DMU_j \ (j = 1,....,n)$, uses m inputs $x_{ij} \ (i = 1,2,....,m)$ to produce s outputs $y_{rj} \ (\mathrm{r} = 1,2,....,\mathrm{s})$. The (empirical) efficient frontier or best practice frontier is determined by these n observations [12]. Table 1 and Table 2 summarizes the envelopment models with respect to the orientations and frontier types [12].

Table 1. *Envelopment model (input oriented) [12]*

Frontier type	Input –Oriented
CRS	$\min \theta - \in (\sum_{i=1}^{m} s_i^- + \sum_{r=1}^{s} s_r^+)$ *subject to* $\sum_{j=1}^{n} \lambda_j x_y + s_i^- = \theta x_{io} \quad i = 1,2,......,m;$ $\sum_{j=1}^{n} \lambda_j y_{rj} - s_r^+ = y_{ro} \quad r = 1,2,.......,\mathrm{s};$ $\lambda_j \geq 0 \quad j = 1,2,........,\mathrm{n}.$
Efficient Target	$\left\{ \begin{array}{ll} \hat{x}_{io} = \theta^* x_{io} - s_i^{-*} & i = 1,2,....,\mathrm{m} \\ \hat{y}_{ro} = y_{ro} + s_r^{+*} & r = 1,2,....,\mathrm{s} \end{array} \right\}$

Table 2*. Envelopment model (output oriented) [12]*

Frontier type	Output- Oriented
CRS	$\max \phi + \in (\sum_{i=1}^{m} s_i^- + \sum_{r=1}^{s} s_r^+)$ *subject to* $\sum_{j=1}^{n} \lambda_j x_{ij} + s_i^- = x_{io} \quad i = 1,2,......,m;$ $\sum_{j=1}^{n} \lambda_j y_{rj} - s_r^+ = \phi y_{ro} \quad r = 1,2,.......,\mathrm{s};$ $\lambda_j \geq 0 \quad j = 1,2,........,\mathrm{n}.$
Efficient Target	$\left\{ \begin{array}{ll} \hat{x}_{io} = x_{io} - s_i^{-*} & i = 1,2,....,\mathrm{m} \\ \hat{y}_{ro} = \phi^* y_{ro} + s_r^{+*} & r = 1,2,....,\mathrm{s} \end{array} \right\}$

The interpretation of the envelopment model results can be summarized as

i) If $\theta^* = 1 \ or \ \phi^* = 1,$ then the DMU under evaluation is a frontier point. i.e., there is no other DMUs that are operating more efficiently than this DMU. Otherwise, if $\theta^* < 1 \ or \ \phi^* > 1$, then the DMU under evaluation is inefficient. i.e., this DMU can either increase its output levels or decrease its input levels.

ii) The left-hand-side of the envelopment models is usually called the "Reference Set", and the right-hand-side represents a specific DMU under evaluation. The non-zero optimal λ_j^* represents the benchmarks for a specific DMU under evaluation. The Reference Set provides coefficients (λ_j^*) to define the hypothetical efficient DMU. The Reference Set or the efficient target shows how inputs can be decreased and outputs increased to make the DMU under evaluation efficient.

iii) The last row presents the efficient target (DEA projection) of a specific DMU under evaluation [12].

In this paper, the Data envelopment analysis (DEA) is used to compare a number of solar cell devices based on their inputs (composition of the organic molecules for active layer) and output (maximum electrical power and power conversion efficiency). The model solution result indicates if a particular solar cell is efficient or inefficient relatively. Based on a comprehensive literature review, the input and output data of the organic molecules synthesized for fabricating solar cells were collected. These input and output data were processed using the DEA linear programming.

3. RESULTS AND DISCUSSION

The DEA analysis was performed with the nine devices fabricated with the synthesized imidazolinone molecules[6] and eleven other samples reported in literature[13-28]. The analysis was executed in the DEA software using both CCR-I and CCR-O models (where I and O stands for input and output respectively). The single input and single output case is used for the DEA analysis of the samples. The band gap of the active layer is considered as the input and the power conversion efficiency of the OSC device is the accounted output parameter. This criteria is detailed in the Table 3. In Table 3, 25 different OSC devices were considered as DMUs (Decision Making Units), as these are the units whose relative comparison is to be made using the CCR DEA model. The DMUs from Da to Di were those fabricated and published by us and the DMUs from J[13] to Y[28] are the few selected from literature [13-28]. The results of the analysis using the CCR-I model and CCR-O model revealed that DMU Y[28] is the most efficient OSC, having an efficiency rate of 1. The other DMUs are found to be inefficient relatively. The performance target for inefficient DMUs can be enabled to reach 100% relative efficiency in comparison with DMU Y[28], the most efficient. DMU Y[28] has operated in an environment similar to the others and hence using its performance as a benchmark is realistic. The DMU efficiency rate using the CCR-I model and CCR-O model are briefed in Table 4 and Table 5 respectively. Input Output parameters for the DEA comparative analysis are shown in Table 3 below. The DEA analysis on the DMUs outlined in Table 3 can be explained by taking a sample DMU, say X[27]. The same logic is applicable to the other inefficient DMUs. X[27] is ranked 5th in the input as well as output oriented CCR model with an efficiency rate of 0.62329, which is considered inefficient relatively with respect to the most efficient DMU Y[28], the reference set.

Table 3. List of DMUs with Inputs and Outputs

DMU	Input (Band Gap of the Active layer of the device)[6,13-28]	Output (PCE of the device)
Da	3.50	0.007
Db	2.96	0.05
Dc	2.83	0.10
Dd	3.07	0.01
De	3.76	0.004
Df	4.47	0.003
Dg	3.73	0.002
Dh	3.61	0.008
Di	4.45	0.003
J[13]	1.28	1.46
K[14]	1.96	2.20
L[15]	2.05	3.85
M[16]	2.53	2.00
N[17]	1.95	1.70
O[18]	1.75	2.02
P[19]	2.11	1.14
Q[20]	1.16	1.94
R[21]	2.17	7.99
S[22]	1.82	6.56
T[23]	1.90	2.50
U[24]	2.33	2.99
V[25]	1.86	3.07
W[26]	2.02	5.71
X[27]	1.66	4.00
Y[28]	1.94	7.50

A fundamental assumption behind the computation of relative efficiency in CCR-I model is that if the most efficient DMU is capable of producing a particular set of outputs using a particular set of inputs, then other DMUs should also be able to do the same if they were to operate efficiently. We can set the performance target for the inefficient DMU X[27] to enable it to reach 100% relative efficiency in comparison with DMU Y[28], the most efficient. The input target for DMU X[27] is the band gap (input) required that will enable the DMU X[27] to have same ratio of value added to the band gap used by DMU Y[28]. The input target for DMU X[27] was calculated and found to be 1.03467 (Table 4). This means that if the band gap of DMU X[27] (1.66), which is the input, is reduced to 1.03467, keeping the output constant as per the CCR-I model, then X[27] will be considered as efficient as Y[28]. For inefficient DMUs, input target will be less than the actual input. The difference between actual input and input target is the input slack. The input slack for X[27] is calculated and found to be 0.62533. In terms of % the input slack is found to be 37.67%. This implies if X[27] has to be as efficient as Y[28], it should produce the same output using 37.67% less input.

TABLE 4. *DMU Efficiency Rate: Input oriented CCR Model*

DMU	Input	Efficiency rate	Rank	Input Target	Input Slack	Input Slack %
Da	3.50	0.00052	21	0.00181	3.49819	99.95
Db	2.96	0.00437	18	0.01293	2.94707	99.56
Dc	2.83	0.00914	17	0.02587	2.80413	99.09
Dd	3.07	0.00084	19	0.00259	3.07	99.92
De	3.76	0.00028	22	0.00103	3.75897	99.97
Df	4.47	0.00017	24	0.00078	4.46922	99.98
Dg	3.73	0.00014	25	0.00052	3.72948	99.99
Dh	3.61	0.00057	20	0.00207	3.60793	99.94
Di	4.45	0.00017	23	0.00078	4.44922	99.98
J[13]	1.28	0.29504	12	0.05743	1.22257	95.51
K[14]	1.96	0.29034	13	0.56907	1.39093	70.97
L[15]	2.05	0.48579	6	0.99587	1.05413	51.42
M[16]	2.53	0.20448	15	0.51733	2.01267	79.55
N[17]	1.95	0.22550	14	0.43973	1.51027	77.45
O[18]	1.75	0.29858	11	0.52251	1.22749	70.14
P[19]	2.11	0.13975	16	0.29488	1.81512	86.02
Q[20]	1.16	0.43260	7	0.50181	0.65819	56.74
R[21]	2.17	0.95242	2	2.06675	0.10325	4.76
S[22]	1.82	0.93234	3	1.69685	0.12315	6.77
T[23]	1.90	0.34035	9	0.64667	1.25333	65.96
U[24]	2.33	0.33194	10	0.77341	1.55659	66.81
V[25]	1.86	0.42694	8	0.79411	1.06589	57.31
W[26]	2.02	0.73118	4	1.47699	0.54301	26.88
X[27]	1.66	0.62329	5	1.03467	0.62533	37.67
Y[28]	1.94	1.00000	1	1.00000	-	-

Similarly, in case of CCR-O model, if a particular inefficient DMU is to reach the efficient frontier, it should increase its output to a certain extent, at par with the reference set, keeping the input constant. Taking the same sample i.e. DMU

TABLE 5*. DMU Efficiency Rate: Output oriented CCR Model*

DMU	Output	Efficiency rate	Rank	Output Target	Output Slack	Output Slack %
Da	0.007	0.00052	21	13.5309	13.5239	193198.97
Db	0.05	0.00437	18	11.4433	11.3933	22786.60
Dc	0.1	0.00914	17	10.9407	10.8407	10840.72
Dd	0.01	0.00084	19	11.8685	11.8586	118585.57
De	0.004	0.00028	22	14.5360	14.5321	363302.06
Df	0.003	0.00017	24	17.2809	17.2779	575930.93
Dg	0.002	0.00014	25	14.4201	14.4181	720905.15
Dh	0.008	0.00057	20	13.9561	13.9482	174352.32
Di	0.003	0.00017	23	17.2036	17.2006	573353.61
J[13]	1.46	0.29504	12	4.9484	3.4885	238.94
K[14]	2.2	0.29034	13	7.5773	5.3773	244.42
L[15]	3.85	0.48579	6	7.9252	4.0753	105.85
M[16]	2	0.20448	15	9.7809	7.7809	389.05
N[17]	1.7	0.22550	14	7.5386	5.8387	343.45
O[18]	2.02	0.29858	11	6.7654	4.7455	234.92
P[19]	1.14	0.13975	16	8.1572	7.0173	615.55
Q[20]	1.94	0.43260	7	4.4845	2.5445	131.16
R[21]	7.99	0.95242	2	8.3892	0.3992	5.00
S[22]	6.56	0.93234	3	7.0361	0.4761	7.26
T[23]	2.5	0.34035	9	7.3454	4.8454	193.81
U[24]	2.99	0.33194	10	9.0077	6.0177	201.26
V[25]	3.07	0.42694	8	7.1907	4.1207	134.23
W[26]	5.71	0.73118	4	7.8093	2.0993	36.76
X[27]	4	0.62329	5	6.4175	2.4175	60.44
Y[28]	7.5	1.00000	1	1.0000	-	-

X[27], the output oriented DEA analysis can be explained. In this model, the output target, output slack and output slack percentage are computed. For inefficient DMUs, output target will be greater than the actual output. The difference between actual output and output target is the output slack. The output target for X[27] is 6.41753, output slack is 2.41753 and output slack percentage is 60.44% (Table 5). This implies that for X[27] to reach the same efficient frontier as Y[28], it should increase its power conversion efficiency (output) by 2.41753 or 60.44% for the same level of input. The DEA model determines how a particular DMU should change its behaviour to become efficient and rise to the efficiency curve. This is depicted graphically in fig. 2 for input-oriented and output-oriented CCR model. The CCR-I model suggests that for an inefficient DMU to become efficient, it must lower its inputs, keeping the output constant. In our case, DMU X[27] will be efficient if it lower the level of its band gap (input) by 0.62533 to point $X27_I$ on the efficiency curve (Fig 2).

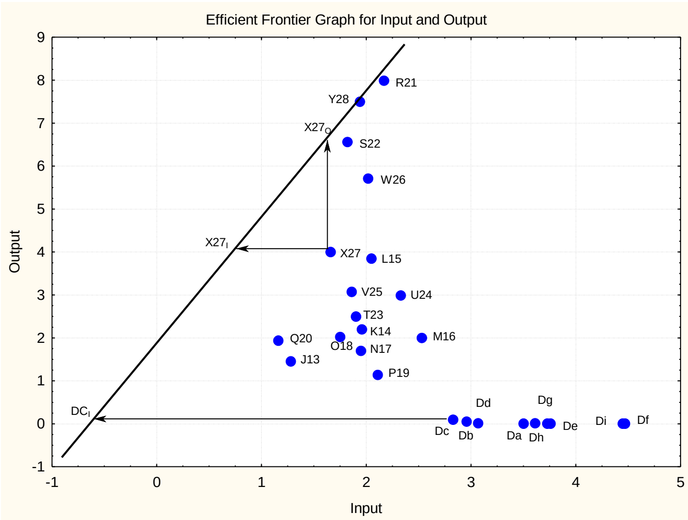

Fig. 2 *The Efficient Frontier Graph for Input and Output.*

Again, taking a sample from our fabricated devices, DMU Dc, is found to have better performance relatively. Its input target is 0.02587, input slack 2.80413 and input slack percentage is 99.09%. Thus, referring to fig 2, it can be inferred that DMU Dc will be efficient if it lower the level of its band gap (input) by 2.80413 to point DC_I on the efficiency curve. The CCR-O model suggests that in order to attain efficiency, the inefficient DMUs must increase their outputs keeping the inputs constant. In case of DMU X[27], it would therefore be necessary for it to raise the level of its power conversion efficiency (output) by 2.41753, to reach point $X27_O$ on the efficiency curve (Fig 2).

4. CONCLUSION

Although there has been a substantial body of efficiency measurement of organic solar cells research, the idea of using relative measurement instead of absolute measure in particular using DEA has not gained any attention till date. As absolute measurement cannot provide any benchmarks or improvement projections, there is a need for relative measurement to compare the absolute values for benchmarking, referencing and making improvements. This paper has applied DEA, a non-parametric operation research approach for relative efficiency measurement of OSCs. The CCR-I and CCR-O model was used for the measurement and the single input and single out case was considered. The analysis revealed that out of the 25 OSCs, one OSC i.e. DMU Y[28] was found to be efficient. From the result of the DEA analysis it was found that all other DMUs were inefficient and their improvement scope was determined relative to the DMU OSC-Y[28]. In order to explain how to achieve the performance target for the inefficient DMUs, a prototype of all inefficient DMUs, X[27] was considered. The DEA analysis shows that the efficiency of X[27] projects into observable portion of the efficient frontier of Y[28], only when it produces the same output using a less percentage of input. Furthermore, it should also increase its power conversion efficiency (output) by the same level of input. Thus, it can be concluded that efficiency up gradation is possible only if the value of the actual input is lowered by the input slack in the CCR-I model and the value of the actual output is increased by the output slack in the CCR-O model. This paper contributes to the projection of a noble approach towards scientific research in chemical field using operational research methodology, thereby providing a new viewpoint to interdisciplinary research. As a perspective, the multi-input-output DEA methodology can be used to give new standpoint to the relative measurement of efficiencies of organic solar cells.

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