# CHAPTER-IV

# Selection of renewable distributed generation technology

## 4.1. Introduction

Limitation of the conventional energy sources and their adverse environmental effect causes the increased demand for renewable energy sources in electricity generation. With small-scale generating capacity of renewable energy sources, uses of distributed generation technologies with smart grid have exponentially increased worldwide in the recent past. The uncertainty of power generation from the renewable distributed generation along with smart microgrid needs effective tools and techniques to get optimal utilization (Sola and Vitetta, 2016). Renewable distributed generation planning efforts involve finding a set of sources and conversion devices in the power sector, to meet the electricity requirement or load demand in an optimal manner. Renewable distributed generation planning decision also involves balancing multiple aspects like technical, economical, environmental, and social aspects over a period. For maintaining the ecology and sustainable development, balancing of these factors is critically very important.

The critical task of selecting renewable distributed generation technology becomes a strenuous procedure because the decision maker would have to choose between an abundance of alternatives (Hafez et al., 2012; and Zangeneh et al., 2009). Maintaining harmony between renewable energy sources and grid supply is also a big challenge (Desai et al., 2016). Decision makers' or investors' interest in the selection of the suitable renewable distributed generation technology or selection of the renewable energy projects has been continuously growing. Optimal utilization of small-scale generation units of renewable distributed generation helps us in multiple ways like reducing per unit generation cost, avoid carbon emissions and harness abundant available renewable energy sources. Based on past literature in this area, multiple authors agreed on a large number of criteria considered for making the selection of appropriate renewable distributed generation technology are more complex (Barry et al., 2011; and Sengu¨l et al., 2015). For this, the research community is researching to develop an appropriate technique to grab preferences and to define evaluation models and algorithms for this kind of problems (Opricovic and Tzeng, 2007; and Polatidis et al., 2006).

Planning of renewable energy projects by using multi-criteria analysis is being attracted by the decision makers for the past many years. With increased utilization of renewable distributed generation technologies in recent time, it also increased the importance of decision-making process in the selection of best-fitted renewable distributed generation technology.

Earlier, dealing with the problems of renewable distributed generation by single criterion approaches was aimed to identify the most efficient power generation options with minimum cost. Now a day, growing environmental awareness modified the above decision-making framework. The need for the integration of social and environmental considerations in renewable distributed generation planning resulted in the increased usage of renewable distributed generation technologies with multi-criteria approaches (Kaya and Kahraman, 2010).

Identification of an appropriate alternative with the increased complexity of the decision-making process is a very tedious task. At the operational level, renewable energy projects assessment dealing with the attribute is difficult to define. An assessment may cover technical or economical areas whose boundaries may not be easily identifiable, or it may cover regions of the socio-economic, which could be an effect on various interest groups or stakeholders with their socio-economic needs or their demands (Beccali et al., 2003). Because of these difficulties, VIKOR method could be quite useful in undertaking difficult judgment procedures. The VIKOR method has been introduced in the work of Opricovic and Tzeng (2004), to express the conflicting and incommensurable attributes or criteria and assuming that compromise is acceptable for conflict resolution, where the decision maker wants a solution that will be closest to the ideal solution and all the alternatives would be evaluated according to all the recognized criteria. VIKOR method ranks the alternatives and finds out the solution with compromise and closeness to the ideal solution. This shows that the VIKOR method is a multi-criteria decision-making technique which has a simple computational procedure and that allows simultaneous consideration of the closeness to the ideal and anti-ideal alternatives. As per the previous literature, there are many authors who have used VIKOR method in their work in a comparative manner (Opricovic and Tzeng, 2004; and Opricovic and Tzeng, 2007).

This methodology is used in the present research work for the decision support to solve the renewable distributed generation technology selection problem. The usefulness of this methodology has been established through a case of BHU campus. For which, decision-makers want to find and select the appropriate renewable distributed generation technology at BHU campus and will provide decision support services on this basis.

## 4.2. Methodology

### 4.2.1. Performance evaluation using AHP method

With the help of AHP method, we can assign weights to the relative importance of the attributes (Saaty, 1990). Based on our objective function we can find out the relative importance of the attributes. For that, we should have to construct a pair-wise comparison matrix with a scale of the relative importance. Values entered in the pair-wise comparison matrix should be based on Saaty’s nine-point scale. Saaty’s nine-point scale for the AHP is; comparison of an attribute with itself will always assign the value of 1, it means the main diagonal entries of the matrix will have same values 1. For the other cells the numbers 3, 5, 7, and 9 based on experts verbal judgments “moderate importance”, “strong importance”, “very strong importance” and “absolute importance” along with 2, 4, 6, and 8 for compromise between the previous values.

Suppose we have n number of attributes, the pair-wise comparison matrix will develop between the $i_{th}$ attributes and $j_{th}$ attributes which will be a square matrix $A_{nxn}$ and $a_{ij}$ will denote the comparative importance of $i_{th}$ attribute with $j_{th}$ the attribute. In this pair-wise comparison matrix, $a_{ij} = 1$ when $i = j$ and $a_{ji} = 1/a_{ij}$. The eigenvector or priority weights vector w will be calculated by the summation of each column of the matrix and then divide each element of the matrix with the summation of its column. Then, averaging across the rows will give us the normalized Eigen vector.

$$A=\begin{bmatrix} a_{11} & \cdots & a_{1n} \\ \vdots & \ddots & \vdots \\ a_{n1} & \cdots & a_{nn} \end{bmatrix} \tag{3.1}$$

We have to know the vector $w = [w_1,w_2,...,w_n]$ which represents the weight of each criterion which is given in pair-wise comparison matrix A. To recover the vector w from the pair-wise comparison matrix A, it will go for a method of two-step procedure:

For each of the A’s column divide each entry in column i of A by the sum of the entries in column i. This yields a new matrix, called Anorm (for normalized) in which the sum of the entries in each column is 1.

Estimate $w_i$ as the average of the entries in row i of $A_{norm}$.

$$w_i = \frac{\sqrt[n]{\prod_{i=1}^{n} a_{ij}}}{\prod_{j=1}^{n} \sqrt[n]{\prod_{i=1}^{n} a_{ij}}} \tag{3.2}$$

Where n = number of criteria

$$\lambda_{max} = \frac{(Aw)_i}{nw_i} \tag{3.3}$$

$$\text{CI} = (\lambda_{max} - n)/(n-1) \tag{3.4}$$

$$\text{CR} = \text{CI} / \text{RI} \tag{3.5}$$

For getting the value of CI, we must have the $\lambda_{max}$ by multiplying each element of the matrix with the eigenvector. The smaller the CI represents the, smaller the deviation from the consistency. If CI is sufficiently small, it means the decision-makers' comparisons are probably consistent enough and give useful estimates of the weights for their objective. Perfectly consistent decision-maker will give the $i_{th}$ entry in $Aw^T = n$ ($i_{th}$ entry of $w^T$ ). It shows that a perfectly consistent decision-maker has CI = 0. Then, find out the consistency ratio (CR) with dividing the consistency index (CI) from the random index (RI). Finally, if the CR<0.01, then the degree of consistency is satisfactory. Otherwise, judgment matrix needs to be readjusted until satisfactory.

### 4.2.2. VIKOR method

Opricovic (1998), Opricovic and Tzeng (2002) developed VIKOR, the Serbian name: VlseKriterijumska Optimizacija I KompromisnoResenje, means multi-criteria optimization and compromise solution (Chu et al., 2007). The VIKOR method was developed for multi-criteria optimization of complex systems (Opricovic and Tzeng, 2004). This method focuses on ranking and selecting from a set of alternatives, and determines compromise solutions for a problem with conflicting criteria, which can help the decision makers to reach a final decision. Here, the compromise solution is a feasible solution which is the closest to the ideal, and a compromise means an agreement established by mutual concessions (Opricovic and Tzeng, 2007). It introduces the multi-criteria ranking index based on the particular measure of ‘‘closeness” to the ‘‘ideal” solution (Opricovic, 1998).

The main steps of multi-criteria decision making are the following (Opricovic and Tzeng, 2004):

(a) Establishing system evaluation criteria that relate system capabilities to goals;

(b) Developing alternative systems for attaining the goals (generating alternatives);

(c) Evaluating alternatives in terms of criteria (the values of the criterion functions);

(d) Applying a normative multi-criteria analysis method;

(e) Accepting one alternative as ‘‘optimal’’ (preferred);

(g) If the final solution is not accepted, gather new information and go into the next iteration of multi-criteria optimization.

When the decision maker is unable to take a decision or doesn't know to express their preferences at the beginning stage of the system design, the VIKOR method would be an effective tool for the multi-criteria decision-making process. For the value of a maximum group utility of the ‘‘majority” (min S, given by Eq. (3.7)), and a minimum individual regret of the ‘‘opponent” (min R, given by Eq. (3.8)), obtained compromise solution would be accepted by the decision makers. Based on the involvement of the decision-makers' preferences by weights of criteria, the compromise solutions would be the base for negotiation. The result of the VIKOR ranking depends on the ideal solution Q with values of $v$, which will be only for a given set of alternatives. Any changes to a given set of alternatives will lead to the result of modified VIKOR ranking for the new set of alternatives. The fixed ideal solution would be defined by the decision maker based on the best $f_i$ and the worst $f_i$ values, but it could be avoided.

Here each alternative would be evaluated with each criterion function and, the compromise ranking would be performed with the comparison of the measure of closeness to ideal solution F*. Compromise solution $F^C$ will be a feasible solution that will be the closest to the ideal solution and will have a compromise established by mutual concessions (Polatidis et al., 2006). With multi-criteria measure for the compromise ranking of alternatives is developed from the Lp-metric by using an aggregating function from the compromise programming method (Yu, 1973; and Zeleny, (1982) :

$$L_{pj} = \left[ \sum_{i=1}^{n} \left\{ w_i\left(f_i^* - f_{ij}\right) \Big/ \left(f_i^* - f_i^-\right) \right\}^{p} \right]^{1/p} \tag{3.6}$$

$1 \leq p \leq \infty$, j=1, 2,....., J

where $L_{1,j}$ denoted as $S_j$ in Eq. (3.7) and $L_{\infty,j}$ denoted as $R_j$ in Eq. (3.8), are used to formulate the ranking measure.

For the VIKOR method, the number of j alternatives is denoted as $a_1, a_2, \ldots, a_j$. For any alternative $a_j$ the rating of the $i_{th}$ facet is denoted by $f_{ij}$, and this is the value of the $i_{th}$ criterion for the alternative $a_j$; where j=1,2,....,m and i=1,2,.....,n. The compromise ranking algorithm of the VIKOR method is divided into the following four steps which are given below (Opricovic and Tzeng, 2004):

*Step I:* For all the criterion functions, find out the best $f_i^*$ and the worst $f_i^-$ values, i = 1,2,...,n. If the $i_{th}$ function represents a benefit then $f_i^* = \max_j f_{ij}$ and $f_i^- = \min_j f_{ij}$, whereas if the $i_{th}$ function represents a cost $f_i^* = \min_j f_{ij}$ and $f_i^- = \max_j f_{ij}$.

*Step II:* Compute the values of $S_j$ and $R_j$, j = 1,2,...,m from the relations of

$$S_j = \sum_{i=1}^{n} {w_i\left(f_i^* - f_{ij}\right)} \Big/ {(f_i^* - f_i^-)} \tag{3.7}$$

$$R_j = \max_i \left[ {w_i\left(f_i^* - f_{ij}\right)} \Big/ {(f_i^* - f_i^-)} \right] \tag{3.8}$$

Where $w_i$ denotes the weights of criteria, which expresses the decision maker's preference for the relative importance of the criteria.

*Step III:* compute the values of $Q_j$, from the given relation

$$Q_j = {v\left(S_j - S^*\right)} \Big/ {(S^- - S^*)} + {(1 - v)\left(R_j - R^*\right)} \Big/ {(R^- - R^*)} \tag{3.9}$$

Where $S^* = \min_j S_j$; $S^- = \max_j S_j$; $R^* = \min_j R_j$; $R^- = \max_j R_j$ and as a weight v has been introduced for the strategy of maximum group utility, while (1 - $v$) is for the weight of the individual regret. The solution will be obtained by $\min_j S_j$ with a maximum group utility based on "majority" rule, where the solution will be obtained by $\min_j R_j$ with a minimum individual regret of the "opponent". In general, the value of the $v$ is taken as 0.5, but we can take any value of $v$ in the range of 0 to 1.

*Step IV:* Now rank the alternatives with the sorting of the results of S, R, and Q in decreasing order. From this we will have three ranking lists for S, R, and Q. Suppose we have a compromise solution of the alternative $A^1$ best ranked by the minimum value of the measure Q, then it should satisfy the given conditions. Propose as a compromise solution the alternative $A^1$, which is the best ranked by the measure Q (minimum), if t he following two conditions are satisfied:

a. First one is the acceptable advantage. $Q(A^2) - Q(A^1) \geq DQ$, where DQ=1/(J-1) and $A^2$ is the alternative with the second position on the ranking list by Q;

b. The second one is the acceptable stability in decision-making. The alternative $A^1$ should also be the best ranked by S or/and R. This compromise solution should be stable for a decision-making process, that could be the strategy of maximum group utility (when $v > 0.5$ is needed), or by consensus ($v \approx 0.5$), or with veto ($v < 0.5$).

If one of the above conditions is not satisfied, then we will have to propose a set of compromise solutions, which will consist of:

c. Alternative $A^1$ and $A^2$ when the condition b is not satisfied, or

d. Alternatives $A^1$, $A^2$,..., $A^M$ when the condition a is not satisfied and, $A^M$ is determined by the relation $Q(A^M) - Q(A^1) < DQ$ for maximum value n means the positions of these alternatives are "in closeness".

### 4.3. A case of BHU campus

One of the characteristics of the BHU power consumption system is its high degree of dependence on the fossil fuel based central power generation system. With limitations of conventional energy sources and their economic impact with environmental concern motivating towards the adoption of renewable energy sources. With small-scale generating capacity and flexibility of onsite power generation increased the demand for renewable distributed generation technology and helps to reduce the load of grid supply. In our case, we are proposing a set of alternatives which could be feasible for onsite power generation at BHU campus.

With the overall aim of making it possible and having a budget constraint, we have to select the best alternative for renewable distributed generation. To do so, we have set more ambitious goals in renewable energy area that is developing rapidly and has established new measures to support energy sector that has not yet managed to take off. From the different areas covered by the overall renewable energy project, we have selected as an example for multi-criteria decision-making, only the feasible alternatives for the electric generation at BHU campus. These are shown in Table-4.1, which are photovoltaic (PV), concentrated solar power (CSP), wind turbine (WT), biomass (BM) and geothermal (GT).

**Table 4.1:**List of feasible renewable distributed generation alternatives at BHU campus

| **Alternatives** | |
|---|---|
| A1 | Photovoltaic (PV) |
| A2 | Concentrated Solar Power (CSP) |
| A3 | Wind Turbine (WT) |
| A4 | Biomass (BM) |
| A5 | Geothermal (GT) |

**Table 4.2:**Criteria used in selection of best renewable distributed generation technology at BHU campus

| **Criteria** | |
|---|---|
| C1 | Power (P) |
| C2 | CO2 emission (gCO2eq/kWh) |
| C3 | Implementation Period (IP) |
| C4 | Investment Ratio (IR) |
| C5 | Operation & Maintenance Costs (O&M) |
| C6 | Operating Hour (OH) |
| C7 | Useful Life (UL) |
| C8 | Installation Area (IA) |

We have to prioritize alternatives based on selected criteria, which affect in decision making. We considered region specific criteria for BHU campus to have better simulation and managerial decision. The designed model evaluated with these criteria is shown in Table-4.2. Consultation with experts and department of Electric and Water Supply Service (EWSS) BHU, we considered the criteria specific for case of BHU: Investment Cost (Crores), Operation and Maintenance Cost (INR/kWh), Implementation Period (Year), Power Generation (MW), Annual Operating Hours, Environmental Loss (gCO2eq/kWh), Useful Life (Year), Area Acquisition (square meter). Consideration of the regional factors of BHU region is helpful in selection of the best alternative. Values of each criterion for different alternatives have been given in Table-4.3. Investment Cost criterion shows individual investment cost of different alternatives in BHU campus. Expected future Operation and Maintenance Cost, and Implementation Period data for different technologies are given by the EWSS, BHU. A Power Generation criterion is derived from geographical data like hourly wind speed and solar irradiation of BHU region. Hourly wind speed and solar irradiation data have been taken from the National Renewable Energy Laboratory website for BHU region with 25.16$^o$ N to 25.26$^o$ N and 82.89$^o$ E to 82.99$^o$ E (India Solar Resource Data: Hourly Data and TMYs). Annual Operating Hours criterion is showing some hours for power generation in a year.

**Table 4.3:**Criterion values for each alternative

| **Criteria** | **PV** | **CSP** | **WT** | **BM** | **GT** |
|---|---|---|---|---|---|
| P (max) | 10 | 2.50 | 11.11 | 10 | 3.85 |
| gCO2eq/kWh (min) | 41 | 27 | 11 | 230 | 38 |
| IP(min) | 1 | 1.5 | 1 | 1.5 | 2 |
| IR(min) | 5 | 20 | 4.5 | 5 | 13 |
| O&M(min) | 0.05 | 2 | 0.67 | 4 | 1.33 |
| OH(max) | 3800 | 3800 | 3850 | 7000 | 7500 |
| UL(max) | 25 | 30 | 20 | 20 | 30 |
| IA(min) | 36.9 | 15.3 | 72.1 | 543.4 | 7.5 |

Environmental Loss is considered as gram equivalent of carbon emitted from different technologies per kWh of power generation. The life span of the different alternatives is considered as Useful Life criterion. Area required for installation of different technologies is considered as Area Acquisition.

$$A=\begin{bmatrix} 1 & 2 & 9 & 8 & 9 & 5 & 7 & 3 \\ 1/2 & 1 & 5 & 4 & 7 & 1 & 5 & 3 \\ 1/9 & 1/5 & 1 & 2 & 2 & 1/4 & 1/2 & 1/3 \\ 1/8 & 1/4 & 1/2 & 1 & 3 & 1/5 & 1/3 & 1/5 \\ 1/9 & 1/7 & 1/2 & 1/3 & 1 & 1/7 & 1 & 1/5 \\ 1/5 & 1 & 4 & 5 & 7 & 1 & 3 & 5 \\ 1/7 & 1/5 & 2 & 3 & 1 & 1/3 & 1 & 1/2 \\ 1/3 & 1/3 & 3 & 5 & 5 & 1/5 & 2 & 1 \end{bmatrix}$$

W1=0.36, W2=0.19, W3=0.04, W4=0.04, W5=0.03, W6=0.18, W7=0.05, W8=0.10

$\lambda_{max} = 8.88$

CI = 0.1258

CR = 0.089

CR<0.1

**Table 4.4:**Benefit and cost values

| **Criteria** | $f_i^*$ | $f_i^-$ |
|---|---|---|
| P (max) | 11.11 | 2.50 |
| gCO2eq/kWh (min) | 11 | 230 |
| IP(min) | 1 | 2 |
| IR(min) | 4.5 | 20 |
| O&M(min) | 0.05 | 4 |
| OH(max) | 7500 | 3800 |
| UL(max) | 30 | 20 |
| IA(min) | 7.5 | 543.4 |

Table-4.4 is having the benefit and cost values of each criterion. It represents the maximum values for the benefit and minimum values for cost criteria. Table-4.5 represents the ranking of given alternatives with their S and R values. Values of Q from the value of S and R for each alternative with different values of v in between 0 and 1 have been shown in Table-4.6.

**Table 4.5:**Ranking of given alternatives with their S and R values

| | PV | CSP | WT | BM | GT |
|---|---|---|---|---|---|
| $S_j$ | 0.284 | 0.630 | 0.244 | 0.462 | 0.398 |
| $R_j$ | 0.180 | 0.360 | 0.177 | 0.19 | 0.303 |

**Table 4.6:** Values of ideal solution "Q" for different values of *v*

| *v* | PV | CSP | WT | BM | GT |
|---|---|---|---|---|---|
| 0 | 0.016 | 1 | 0 | 0.071 | 0.689 |
| 0.1 | 0.025 | 1 | 0 | 0.120 | 0.660 |
| 0.2 | 0.034 | 1 | 0 | 0.170 | 0.631 |
| 0.3 | 0.043 | 1 | 0 | 0.219 | 0.602 |
| 0.4 | 0.051 | 1 | 0 | 0.269 | 0.573 |
| 0.5 | 0.060 | 1 | 0 | 0.318 | 0.544 |
| 0.6 | 0.069 | 1 | 0 | 0.367 | 0.515 |
| 0.7 | 0.077 | 1 | 0 | 0.417 | 0.486 |
| 0.8 | 0.086 | 1 | 0 | 0.466 | 0.457 |
| 0.9 | 0.095 | 1 | 0 | 0.515 | 0.428 |
| 1.0 | 0.104 | 1 | 0 | 0.565 | 0.399 |

Ranking the proposed alternatives by the VIKOR method that we have proposed as a compromise solution and for all the considered values of *v*, the alternative wind turbine is the best one. The alternative of a wind turbine with the capacity of ten megawatts is the best ranked from the values of Q. As this alternative is also the best ranked by S and R, conditions IV-a and IV-b are satisfied.

### 4.4. Conclusion

Selecting the best renewable distributed generation technology from a set of renewable energy investment projects requires different groups of decision-makers involvement in the decision-making process. It is well known that the number of factors considered in the decision-making process makes this more complex. In this work, we have taken eight factors for ranking of the five alternatives in the decision-making process for the selection of suitable renewable distributed generation technology at BHU campus. For this kind of problem, traditional single-criterion decision-making process is unable to handle anymore. The policy formulation for the use of renewable distributed generation technology under rapidly growing renewable energy markets should be addressed in a multi-criteria context. For getting the solution, we have used the VIKOR method in this work, which gives the multi-criteria ranking index with the particular measure of closeness to the ideal solution. Weighing the importance of the different criteria for ranking of the given alternatives, we used AHP technique with VIKOR method that allows the decision-maker for assigning the values of relative importance to the attributes of their preferences. The results have shown that the wind power plant alternative is the best choice, followed by the photovoltaic alternatives with capacities of 11.11 MW and 10 MW respectively. In this case, greater weight has been given by the decision-makers to the criteria of Power (P) and CO2 emission (gCO2eq/kWh) followed by operating hour (OH).