Microgrid: Planning of Solar PV Incorporation to the Optimal CHP-System–An Evolutionary Algorithmic Approach

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Abstract

The author has planned to introduce the solar PV priority sources to the existing 14-bus optimal self-sufficient CHP-microgrid to reduce the use of scarce fuel resources and their emission of pollutants like hazardous NO_x. The Priority PV output is analyzed as negative demand and modifies, directly, the profile demand of the microgrid. The hourly change of kW output of PV modules at the site is obtained from the website of Surface Meteorology and Solar Energy, sponsored by NASA, using HOMER software. It is observed that at any solar insolation power output from the solar module is directly proportional to the module capacity. To plan the best economic solar PV capacity incorporation in the system, PV output is varied over a suitable range and in discrete steps, depending on hour of profile electric demand and availability of solar insolation at the site. At each modified tracking of hourly electrical demand, Pareto-bi-objective EELD optimization is performed, simultaneous with compromised reduction between the cost of fuel and NO_x emission of the DERs. The sets of results of best optimal output of sharing of strategically deployed DER-mix could be obtained and these results are kept within their respective capacity limits. For optimization both differential evolution (DE) and PSO algorithms is used for comparison of results. Hourly heat demand requires to be met by waste heat recovery from DERs and, if required, by stand-by boiler. An array is formed of these best solutions per annum for each solar PV capacity change. These results, in comparison with the No-PV base case results, are used for economic analyses based on benefit-to-cost ratio (BCR). It is found that best BCR value of 1.416 occurs at PV capacity of 130 kW and so, the best PV capacity size is decided as 130 kW.

Keywords Differential evolution · Microgrid · Solar PV · HOMER · Benefit-to-cost ratio

Nomenclature

HOMER	Hybrid optimization model for electric renewable	P_{SPV}	Output of non-dispatchable Solar PV modules in kW at the said hour of P_D
DG	Distributed generator/generation	PV	(solar) photo Voltaic
DE	Differential evolution	N	Total nos. of dispatchable CHP-DERs
P_L	System electric losses in kWh	C	Total cost of emission plus fuel in \$/hr
$PG_i, PG_{imax}, PG_{imin}$	Active power generation of i^{th} bus DER, its upper and lower limits in kW respectively	a_i, b_i, c_i	Fuel cost coefficients of i^{th} bus DER
f_1 and f_{1max}	Fuel cost functions in \$/hr. and its value at PG_{imax} respectively	$\alpha_i, \beta_i, \gamma_i$	Emission coefficients of i^{th} bus DER
f_2 and f_{2max}	NO _x emission functions in g/kWh and its value at PG_{imax} respectively	η_{liht}	Thermal efficiency of i^{th} bus DER
P_D	Total Profile-electric demand in kW at the proposed hour	η_{hex}	Efficiency of heat exchanger
		H_D	profile-Heat demand in kWh
		W	Weighting factor
		P_{fn}	Penalty factor for NO _x emission
		BCR	Benefit to cost ratio
		EELD	Economic emission load dispatch

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Introduction

Fossil fuels such as coal, oil and natural gas are, still, the major resources of the world's electricity generation and these

conventional energy resources come across a number of obstacles, namely, price hike, dependence on imports from a limited number of fossil-fuel-enriched countries and the climate change risks. The Paris agreement at COP21, 2015 is an indication of global concern over the climate change issue and it is the first time to achieve a global agreement on reduction of climate change. Recent COP 23 in Bonn, Germany in November 2017 has indicated one step forward to the intention of the participating countries towards reduction of green house gas emission. Also, in to-day's deregulated and rapidly developing market, the concept of a microgrid, forming with mix of both CHP (Combined heat and power) DERs (Distributed Energy Resources) and solar PV, is gaining greater importance in technical, environmental and economic fields throughout the world. Governments (both local as well as central), business houses and customers are increasingly supporting the utilization of non-conventional energy resources for electricity generation. Solar PV has emerged as potentially alternative to play a significant role taking into account the current environmental commitment of several countries. The objective of the National Solar Mission in India is to reduce the cost of solar power generation to be competitive with fossil-based energy options and to grow solar installations manifolds. CHP-based DERs are responsible for creating environmental pollution with the emission of NO_x , SO_x , CO_2 etc. NO_x emissions have direct health effects. It affects, indirectly, to ozone level. Mixing of optimal size of solar PV with CHP DERs has the advantages like reduced dependence on fossil fuels and less environmental pollution [1–5].

Like main grid, optimization of a microgrid needs special attentions on objective functions, constraints, algorithmic techniques etc. Due to uncertain nature of solar insolation, the incorporation of this generation to the microgrid, is a matter of great concern. The authors of [6, 7] have taken PV modules as a priority source and these generations have been dealt with as negative loads. Modern soft computing techniques, like DSM (Direct Search Method) [8], dynamic programming [9, 10], mixed-integer linear program [11], DER-CAM [12], linear programming [13], Bayesian particle filtering [14], genetic algorithms (GA) [15], Controlled elitist NSGA-II [16], stochastic mixed integer program [17] etc. have successfully been applied by many previous researchers to obtain optimal solution on ELD, EELD and related topics in their works. Varieties of objective functions have been used by different authors. The authors of [9] have used minimization of the cost, which comprised of cost-

of-deployment, cost-of-heat-compensation and cost-of-fuel. The authors of [12] have taken minimization of cost of combination of CHP equipments and renewable sources for commercial building, whereas the authors of [13] have suggested minimization of equivalent yearly cost of taking care of a given energy demand profiles, both electricity and heat. Multi-objective EELD cases have also found applications in previous works [10, 14, 16]. Some authors [16] used Pareto optimality for best compromised solution, others [10] used dynamic programming based algorithm to achieve bargain between fuel cost and CO_2 emission. The authors of [11] developed an optimal model of DG-mix with NO_x emission as one of the constraints. The authors of [12] have reported carbon reduction in their results. The electricity market models were found in some researchers' similar types of works – the authors of [18] focused the unit commitment issue on the assumption of linear, continuous and convex bid functions for both DG and loads in addition to market price. In the grid-connected mode, the model of both pool and hybrid electricity market [15] were studied in the context of optimal design of microgrid, constituting of PV array, fuel cell and battery bank, to maximize the total net present worth of the microgrid, DGs and DISCO. The author of [19] has designed optimally the microgrid with REs, such as solar PV, wind generator and storage system based on availability and the reduction of network cost and in this context the author [19] used multi-objective PSO and GA for comparative study. The authors of [20] have used a risk-based stochastic method to address the uncertainty of loads and renewable DERs, such as solar and wind. The Cuckoo optimization algorithm (COA) has been used in the context of optimal location and size of these DER units and the authors claimed that integrated COA & ICA (imperialist competitive algorithm) has convergence speed and implementation time lesser than other conventional algorithms, such as GA, PSO, etc. The approach to address the uncertainty of Wind energy by information gap decision theory (IGDT) based on voltage stability constrained-wind energy planning (VSC-WEP) model has shown important to be noted for long term wind energy planning [21].

Contribution of the Present Paper

The 14-bus radial self-sufficient microgrid is located at the Siliguri in Darjeeling district, West Bengal, India,

possessing latitude and longitude of the site respectively of 26°72'N and 88°41'E [22]. The motivation behind the work arises as there are threats of environment pollution and fossil fuel shortage in the operation of the microgrid and so, the microgrid is intended to run with the support of solar PV generation without storage, treating as the priority source i.e. utilization at the time of availability, reducing the operating hour of existing 4-CHP-DER mix. CHP-DERs consume fuel and emit pollutants. But at the same time they cater both electricity and heat to the customers. Therefore, optimum size of the solar generation (i.e. module size) is to be incorporated into the microgrid, which is economically viable. In this context complete analysis, at each module size, comprises of two folds— firstly, EELD analysis of the system, on hourly-basis, using solar data at the site, profile data of both heat and electricity demands along with relevant constraints as mentioned in section 3. Lastly, economic feasibility study using benefit-to-cost ratio (BCR) over the life cycle of the project is performed on the EELD results of each annual hours (i.e. each of 8760 h) of each of suitable range of module capacities, with comparison to NO-PV base cases, to decide the best solar PV size.

The hourly annual data of incident solar radiation and corresponding kW output of a particular-sized PV module at the site are obtained from the Surface Meteorology of NASA and the website of Solar Energy using HOMER software. It is noted from these data that the hourly kW output of the module is directly proportional to the incident radiation. In the present analyses the hourly kW output of the module has been taken as the negative demand [6, 7] i.e. it is subtracted from hourly profile electric demand. As the present microgrid spreads over smaller region at the site, the solar radiation is assumed same for all the 14-buses at any instant (hour). With the change of hourly incident solar radiation on the modules during the day there is a change of hourly PV kW output as well as corresponding modified hourly profile demand. Starting from a suitable size, the solar PV capacity is varied in discrete steps over a wide range depending on the profile electric demand. At each such step, the EELD technique has uniquely been addressed to the microgrid where simultaneous electric and heat demands are catered to the customers with best Pareto optimality compromising between fuel cost and NO_x emission [23, 24]. BCR values are estimated on annual EELD results and are stored in an array with ascending order of module capacity. From this array it is identified that best

BCR value of 1.416 occurs at 130 kW PV capacity. Assuming incorporation of standard 5 kW or its multiplier sizes of modules at each of 13 load buses in the microgrid, 130 kW PV capacity means 10 kW sized-module at each of 13 Load Buses. It is, also, found from the array that BCR value is increased from 1.3411 at 65 kW PV capacity incorporation to 1.416 at 130 kW PV capacity but falls to 1.3511 at 195 kW PV- so, a turnaround at higher size incorporation. For investment decision on PV capacity size, 130 kW is taken as the best.

The optimizations are performed using differential evolution (DE) algorithm and the results are compared with Particle swarm optimization (PSO) algorithm. It is found tallying of results in both the cases and justifies the robustness of the methodology. DE [25–27] uses its different crossover strategies and is found to yield better and faster convergence, satisfying all the constraints. DE is faster than PSO. The algorithm is coded and run in MATLAB 7.1 using Intel Core i3 CPU with 2.0 GB of RAM.

Though the study case is a particular 14-bus microgrid, the formulation section 3 has been generalized in eye to address systems of any scale—larger number of buses, buses under different solar insulations, load profiles of any variation etc. to name a few. The work emanates the originality of the research.

Starting with abstract, keywords and nomenclature, this paper is organized into seven sections: - section 1 on introduction, section 2 on contribution of the present paper, section 3 on detailed modeling of the problem, section 4 on the DE algorithms in the context of the present EELD problem, section 5 on the case study, conclusion on section 6 and acknowledgement in the section 7. References are appended last.

Mathematical Modeling of the Problem

The present paper addresses the EELD based scheduling of committed dispatchable CHP-DER-mix, comprising of Mts and Dgs, at a particular hour of the day when a non-dispatchable solar PV generation is incorporated in the system as the priority sources. To plan for the best capacity-size of the solar PV source, the benefit-to-cost ratio (BCR) tool is applied on EELD results. Therefore, the present work requires to be modeled on both EELD and BCR. The formulations are furnished below with reference to the author's previous works [23, 24].

EELD Modeling [23, 24]

The objective function of EELD is given by the Eq. (1).

$$\text{Minimize}(C = W \times f_1 + (1-W) \times (P_{fn}) \times f_2) \quad (1)$$

Here, C : the total cost of combined emission and fuel, P_{fn} : blending NO_x emission costs (f_2) with the normal fuel costs (f_1). NO_x has been considered for the analysis because of most hazardous pollutant. W : the weighting factor – having uniform variation between $[0, 1]$.

Constraints to be satisfied at each of the EELD results are:

Constraints - Power Balance

$$\sum_{i=1}^N PG(t, i) = \sum_{j=1}^{N_B} (P_D(t, j) - P_{SPV}(t, j)) + P_L; \text{ where } t = 1, 2, \dots, 8760 \quad (2)$$

Where $P_{SPV}(t, j)$ = hourly output power of non-dispatchable solar PV sources – converter losses are neglected, here. $P_D(t, j)$ is the hourly electric demand; both P_{SPV} and P_D are varies with hour (t) of the day and number of buses (N_B) due to their sites. $(P_D(t, j) - P_{SPV}(t, j))$ is modified profile demand at any hour (t) and location of bus (j), $\sum_{j=1}^{N_B} (P_D(t, j) - P_{SPV}(t, j))$ = modified electric demand to be met by CHP-DERs at any hour (t). At every hour (t) there must be power balance among CHP-DER generation (PG), modified profile electric demand and network power loss (P_L), as per Eq. (2). In EELD problem, these PV sources are considered as priority sources and are dealt with as negative loads. Hourly statistical solar PV output data (P_{SPV}) are obtained from the website of Surface Meteorology and Solar Energy, NASA, using HOMER software. HOMER uses a more generic model for the PV array in the simulations. That is, HOMER estimates PV power production based on the rated capacity of the PV module. Hourly variation of this output could, easily, be accommodated in the existing microgrid as both Dgs and Mts are very fast-start-stop (i.e. plug-and-play) dispatchable generators. Therefore, the microgrid does not require any spinning reserve and, also, self-sufficiency of the system does not hamper. Absence of spinning reserve reduces consumption of fuel as well as emission of NO_x .

The Kron's loss formula for the network loss (P_L) using B-coefficients, and the dependent virtual utility (slack bus) generator capacity (PG_1) is formulated as per reference [23, 24].

Constraints - Limits of DER Capacity

There are two limits of respective DER capacity- PG_{imin} : lower operation limit and PG_{imax} : upper operation limit, Eq. (3). For each of the i^{th} bus DER.

$$PG_{imin} \leq PG_i \leq PG_{imax} \quad (3)$$

Constraints -Inequality of Heat Balance

As referred to [23, 24], inequality of Heat balance constraint is as follows Eq. (4):

$$\sum_{i=1}^N \theta_i PG(t, i) \geq \left[H_D(t, i) - \sum_{i=1}^N \theta_i P_{SPV}(t, i) \right] \quad (4)$$

θ_i : heat-to-power ratio of i^{th} DER; As electric demand is tracked in Eq. (2), there is inequality relation between heat recovery from CHP-DER and heat demand (H_D) at every ' t '. With more solar PV generation, CHP-DER generation becomes lesser and so is the heat recovery. Therefore, to satisfy Eq. (4) H_D needs to be adjusted proportionally to $\theta_i P_{SPV}$. Deficit demand is met by stand-by boiler.

Constraints - Power Flow

B-coefficients have been determined, in the present paper, using Newton-Raphson power flow method where all constraints of load flow, like bus voltage limit, reactive power flow limit (5) are checked. For each of the i^{th} bus:

$$|V_i|_{\max} \geq V_{imin} \geq |V_i|_{\min}; \quad Q_{imin} \leq Q_i \leq Q_{imax} \quad (5)$$

Constraint- Spinning Reserve for Non-Dispatchable Solar PV Generation

If solar generation is introduced into the system without storage then its uncertainties could be tackled keeping stand-by CHP-generator in spinning mode. In the spinning mode both emission and fuel consumption take place – emission level is very high. Loading of these units are required when solar generations are downed. Each of the generators has its own ramp rate constraint – Up rate (increase of generation) and Down rate (decrease of generation). Total spinning reserve generation (ΣPG_{10}) is kept less than that of solar generation (ΣP_{SPV}). PG_{10} is generation at spinning condition of i^{th} DER;

$$\sum_l PG_{l0} (\leq \sum P_{SPV}) = \sum_l (a_l + \alpha_l) \quad (6)$$

Where a_l and α_l are respectively fuel cost and NO_x emission coefficients of l^{th} DER at spinning condition i.e. at no-load; From spinning DERs ramp up to load condition or vice versa for ramp-down to spinning – both happen for availability of solar generation.

$$\text{For Ramp rate-Up : } PG_l - PG_{l0} \leq UR_l \text{ and Ramp rate-Down : } PG_{l0} - PG_l \leq DR_l \quad (7)$$

Due to ramping of DERs, respective inequality constraint of generation dispatch is modified as in Eq. (8)

$$\text{And } \max(PG_{lmin}, PG_{l0} - DR_l) \leq PG_l \leq \min(PG_{lmax}, PG_{l0} + UR_l) \quad (8)$$

DR_l is down ramp rate of l^{th} DER; UR_l : Up ramp rate of l^{th} DER; PG_l is generation of l^{th} DER at certain value to back-up the non-availability of solar generation. It is important to note that the small DERs at microgrid level like, diesel generators, micro-turbines etc. are plug and play devices and they could be kept stand-by, without spinning, in the microgrid.

Steps to Find out Pfn for NO_x: [28]

The price penalty factors for NO_x emissions (Pfn) are the most important part of EELD. Its determination is given in the reference [23]. The formulations for fuel cost, NO_x emission and $pfn[i]$ of i^{th} DER at its maximum capacity are referred to [23]. In the present paper, available solar PV power at any hour reduces the profile demand of that hour and Eq. (9) indicates the change with respect to [23]:

$$\sum PG_{imax} \geq \sum (P_D - P_{SPV}) \quad (9)$$

After arranging the $pfn[i]$ in ascending order, PG_{imax} (maximum capacity of each DER) is summed up one at a time – starting DER is smallest capacity. Equation (9) indicates the check value to stop the capacity summing. And the last unit in the process is the pfn for the particular demand.

Once the value of Pfn is determined, Eq. (1) can be optimized subject to the constraints of Eq. (2) to Eq. (8).

Economic Modeling for Decision of PV Capacity

It is obvious that with the more introduction of solar generation there will be more reduction of emission

and fuel consumption, provided CHP-DERs are strategically deployed. For a particular system there is a limit up to which these advantages could be harvested. For the economic analysis life cycle of the microgrid is considered and clearly, indicates whether this limit is economically feasible. The economic analysis requires investment costs, (O&M) costs, revenues and savings. The discounted cash flow analysis has been performed in the present paper to determine the benefit-to-cost ratio (BCR) of the microgrid. Its formulation is as per reference of the author's previous work [24] – here, only the changes in the formulation due to solar PV incorporation to the system are shown below:

$$I_0 = C_{DG} + C_{Boiler} + C_{HEX} + C_{TS} + C_{mg} + (C_{SPV} + C_{CV} + C_{MCB}) \quad (10)$$

The initial investment (I_0), Eq. (10) includes the additional capital cost due to Solar PV sources/modules (C_{SPV}), solar PV converter (C_{CV}), and solar PV system switches (C_{MCB}). The capital cost of the rest of the equipments like DGs (C_{DG}), heat exchangers (C_{HEX}), thermal storage (C_{TS}), boiler (C_{Boiler}), and microgrid construction cost (C_{mg}) will remain same.

In the benefit formulation [24], there is a loss reduction term (ΔE_{loss}) – due to solar PV incorporation this reduction will increase when compared to “No PV base case”. Again, emission reduction (ΔB_{NOX}) is increased with solar PV incorporation in comparison to “No PV base case”. Solar PV has no O&M cost. Cost of heat energy, mitigation fee of C_{NOX} , charges for electric tariff will remain same in the formulation of [24].

DE Based Algorithms for EELD

Overview of DE technique, which addresses the steps of initialization, mutation, crossover and selection of populations, was skipped, here, as it was discussed in the previous works of the author [23, 24]. Differential evolution has been used as a software tool for solving EELD problem. Particle i^{th} of the population are the DERs generation i.e. $p_i = [PG_{i1}, PG_{i2}, \dots, PG_{iN}]$ and is the trial vector $i = 1, 2, 3, \dots, NP$, where NP is the population size. ‘ N ’ indicates the number of DER units. The DE algorithm for EELD is described in Flow chart below:

Case Study

The present study is to plan the incorporation of a best capacity-size of solar PV resources in the existing 14-bus CHP-microgrid. This radial hypothetical microgrid is similar to one the author developed in [23, 24]. With the solar PV incorporation, the microgrid improves its operation environmentally, maintaining its optimal self-sufficiency and economy. In this context, Benefit-to-cost ratio (BCR) analysis is performed on the results of EELD at various PV capacities incorporation and the best capacity could be decided. Before going into details of the present study cases, a glimpse of the existing system, which is the ‘No PV Base Case’ for the present study, is highlighted again.

Previously Optimized Microgrid System [23, 24, 29] –no PV Base Case

The author had developed in his earlier works a 4-CHP-DERs 14-bus radial self-sufficient optimal microgrid, with all commercial customers in a small commercial hub like a shopping mall. Line data and bus data of the 14-bus system are as per Ref [23, 24]. The major contributions in the earlier work were (i) Optimal siting of DERs, (ii) Optimal sizing of these DERs and (iii) lastly, Economic Emission Load Dispatching (EELD). Optimal siting of the DERs was determined on the basis of Loss Sensitive Index (LSI) with consideration of reliability of supply to the customers. Accordingly, four DERs were located, suitably, at buses 2, 6, 11 and 12. Optimal sizes of these DERs were evaluated under the condition of minimum system loss and results of simulation were obtained, at self-sufficiency constraint of microgrid, as - 200 kW diesel generator (Dg) at bus 2, 80 kW microturbine (Mt) at bus 6, 100 kW Dg at bus 11 and 30 kW Mt. at bus 12.

The demands profiles of both heat and electricity were chosen as shown in Fig. 1. For EELD analysis, all emission and fuel consumption data of the DERs were obtained by second-order polynomial curve fitting between 20% and 100% of rated power of respective DER. The Fuel Consumption Coefficients & Operational Limits of DERs are as per Ref [23, 24]. The results (Table 1) of sharing of demand, solely, by four dispatchable DERs without grid participation (i.e. case of self-sufficiency) are shown, here again, as the base case for the present study.

Present Study Case with Incorporation of Solar PV in the System – Bi-Objective Optimization

Due to strategic deployment of DERs, the number of DERs in operation is varied with the availability of the solar generation. B-coefficients for three cases of 4-DERs, 3-DERs and 2-DERs in operation are presented below.

1) B-coefficients with 4-DERs in operation:

$$B_{ij} = \begin{bmatrix} 0.4355 & -0.1694 & 0.1482 & -0.2684 & -0.0925 \\ -0.1694 & 0.2366 & -0.0247 & -0.0061 & -0.0689 \\ 0.1482 & -0.0247 & 0.1636 & -0.2391 & -0.1046 \\ -0.2684 & -0.0061 & -0.2391 & 0.6517 & 0.1987 \\ -0.0925 & -0.0689 & -0.1046 & 0.1987 & 0.1864 \end{bmatrix}$$

$$B_{0i} = [-0.0326 \quad -0.0314 \quad 0.0057 \quad -0.0018 \quad 0.0050]; \quad B_{00} = [0.0014];$$

2) B-coefficients with 3-DERs in operation:

$$B_{ij} = \begin{bmatrix} 0.425 & -0.0259 & 0.0353 & -0.1211 \\ -0.0259 & 0.0326 & 0.0119 & -0.0146 \\ 0.0353 & 0.0119 & 0.0842 & -0.0989 \\ -0.1211 & -0.0145 & -0.0989 & 0.3892 \end{bmatrix}$$

$$B_{0i} = [0.0229 \quad -0.0051 \quad -0.0002 \quad -0.0058]; \quad B_{00} = [7.3010e-004];$$

Fig. 1 Load profiles –both Heat and Electric

Table 1 Best compromised solution by Pareto: At No- PV Generation (Base Case)

Demand, kW	Committed DERs Output at Buses (KW)					Fuel cost (\$/yr)	NOx (kg/yr)	Heat (kWh/yr)	Loss, kWh/yr
	1	2	6	11	12				
169	0.0	Stand-by	79.999	67.106	22.603	32,672	9466.7	293,900	1078.9
248	0.0	153.003	75.9603	Stand-by	20.046	73,049	22,112	677,480	2832.6
338	0.0	150.54	80.0	90.92	20.55	105,330	44,433	997,829.7	11,709
400	0.0	194.366	75.921	99.857	25.808	75,086	31,980.13	720,490	8562.9

3) B-coefficients with 2-DERs in operation:

$$B_{ij} = \begin{bmatrix} 0.0380 & 0.0115 & -0.0333 \\ 0.0115 & 0.0575 & -0.0692 \\ -0.0333 & -0.0692 & 0.2606 \end{bmatrix}; B_{0i} = [0.0017 \ -0.0019 \ -0.0021]; B_{00} = [6.7142e-004];$$

Other data for the analysis, including DE and PSO algorithms data, are shown below: [23, 24].

- 4) Price of utility electricity (C_e): \$0.12/kWh – at this price the owner of the microgrid earns incentive from utility. Incentive is due to reduction of system loss. The Prices of diesel fuel (\$ 1.10/U.S. gallon), price of natural gas (\$ 6.0/MMBtu) and Price of heat (\$0.05/kWh) are as per ref. [24].
- 5) Boiler Data, Economic Analysis data (i.e. Interest rate, inflation rate and economic life cycle (EL)), Microgrid construction cost data, Data for Electricity Tariff, Cost data of thermal storage, Data of heat exchanger are as per ref. [24].

- 6) Data of solar PV modules & MCB: Capital cost is \$2000/kW and replacement cost is \$1800/kW. O&M cost is nil [22]. Cost of MCB (C_{MCB}) is \$2835.00 (Same as C_{CB} LV breaker of microgrid). The MCB is required to connect module to the grid.
- 7) Data of converter for Solar PV: Capital cost of inverter is \$850/kW. Replacement cost is \$25/kW/yr. O&M cost is nil [22].
- 8) DE and PSO algorithmic data: same as ref. [23, 24].

The proposed site of the microgrid is at Siliguri, West Bengal, India. The latitude and longitude of the site are 26°72'N and 88°41'E respectively. The solar radiation data of the site are obtained from the NASA Surface Meteorology and solar Energy website [30, 31, 32] using HOMER software. The microgrid is extended over a small area, so it is under same solar radiation. The average solar radiation and clearness index of the study area are obtained respectively as 4.788 kW/m²/day and 0.533 [22] (Table 2). The hourly kW output of the PV source/module is dependent on the incident solar radiation. Figure 2 shows hourly incident solar radiation data (8760 in numbers) of the site over the year. It is noted from the HOMER data that annual maximum

Table 2 Solar radiation and clearness index data for Siliguri, West Bengal, India

Month	Clearness index	Daily radiation (kWh/m ² /day)
January	0.629	4.03
February	0.654	4.950
March	0.643	5.820
April	0.594	6.140
May	0.539	5.970
June	0.438	4.950
July	0.375	4.190
August	0.401	4.24
September	0.418	3.960
October	0.596	4.760
November	0.672	4.470
December	0.664	4.0
Average	0.533	4.788

Fig. 2 Hourly incident solar radiation –annual variation (using HOMER Data)

Fig. 3 Hourly solar PV output from 2 kW Module on 10th November (using HOMER Data)

hourly incident solar radiation at the site occurs on 10th November at 12–00 h and corresponding maximum kW outputs are obtained as: from each 2 kW module: 1.984 kW, from each 5 kW module: 4.959 kW, from each 10 kW module - 9.921 kW and 14.88 kW from each 15 kW module – i.e. generation is directly proportional to module capacity. HOMER uses a more generic model for the PV module/array in the simulations. That is, HOMER calculates PV power production based on the rated capacity of the array [33].

Table 3 kW output of solar PV (Reference to 2 kW module) and number of hourly occurrence

Solar PV kW output	Load 169 kW Hrs/annum	Load 338 kW Hrs/annum	Load 400 kW Hrs/annum
0.0–0.1	256	60	207
0.1–0.2	135	125	108
0.2–0.3	153	147	78
0.3–0.4	117	132	97
0.4–0.5	54	142	60
0.5–0.6	56	165	18
0.6–0.7	71	163	1
0.7–0.8	45	211	-x-
0.8–0.9	16	221	-x-
0.9–1.0	1	178	-x-
1.0–1.1	-x-	203	-x-
1.1–1.2	-x-	212	-x-
1.2–1.3	-x-	180	-x-
1.3–1.4	-x-	178	-x-
1.4–1.5	-x-	183	-x-
1.5–1.6	-x-	154	-x-
1.6–1.7	-x-	136	-x-
1.7–1.8	-x-	85	-x-
1.8–1.9	-x-	30	-x-
1.9–2.0	-x-	13	-x-

Figure 3 depicts the hourly output variations of a 2 kW module on the 10th November. Being used as the priority source the hourly generation of non-dispatchable solar PV resources is considered as the negative load on the bus and hence actual profile electric demand on the bus is decreased (2). Equal capacity of solar PV resources is assumed to distribute on each of the 13 load buses, except the bus number 1 (i.e. slack bus). Due to position of the PV sources near the load, the system loss is reduced. It is, also, observed from the annual HOMER data that solar PV generation is available during the periods of the day when loads (Fig. 1) are 169 kW (from 05:00 to 09:00 h), 338 kW (from 09:00 to 17:00 h) and 400 kW (from 17:00 to 22:00 h). In Table 3 the range of yearly output of solar PV, with reference to 2 kW module, is shown. This range is divided into steps of 0.1 kW. Annual occurrence of each such step with reference to the profile demand is, also, sorted out and shown in Table 3.

As the microgrid is formed in a shopping mall whose seasonal load variation is negligible. Daily load profile (Fig. 1) is assumed same throughout the year. In the present analyses, the incorporation of solar PV generation at a particular load hour is changed in the range from 10% to 40% of the hourly profile demand with a suitable increment of 1 kW (say) to cover the annual variation of solar PV radiation and corresponding generation. At each incremental step EELD multi-optimal Pareto-solution of the microgrid, compromising between fuel cost and NO_x emission, is obtained with the different combinations of committed dispatchable units. These results are considered at electric demand tracking and at zero slack bus injection i.e. at self-sufficiency. Thus, at each load an array of best solutions over the year is formed. Assuming placement of standard 5 kW or its multiplier module capacities at each of 13 load buses, three chosen capacities of 65 kW (i.e. 5 kW module at each of 13 load bus), 130 kW (10 kW module at each of 13 load bus) and 195 kW (15 kW each of 13 load bus) - are arbitrarily sorted out for discussion on the results.

The Mts and Dgs are plug-and-play dispatchable DERs. These DERs do not require to be kept spinning to tackle the uncertainty of solar generation. The results (Tables 1, 3, and 4) from these studies reveal the following valuable information. These results help in the energy management planning as well as in the decision of capacity size incorporation of PV module.

- 1) Like electricity heat is another demand to be catered to the customers – its higher recovery is also to be concerned. Unlike electric demand heat is not tracked, so there may exist a difference between its demand and recovery from CHP-DERs at any instant (hour). Recovery amount higher than the demand is stored and utilized later at the time of need. Higher the heat recovery at the time of need, lower will be the supply from the storage and hence the capacity of storage will be reduced – cost of investment will be lesser. The results (Table 4) show lesser heat

Table 4 Annual results - waste heat generation, fuel cost, NO_x emission and system loss

Load, kW	Heat, kWh/yr	Fuel cost, \$/yr	NO _x Emission, kg/yr	System loss, kWh/yr	Remarks
65 kW Solar PV Capacity					
169	283,600.0	31,975.0	9571.4	1052.3	200 kW Dg as stand-by
248	677,500.0	73,049.0	22,112.0	2838.9	100 kW Dg as stand-by & No-PV generation
338	883,440.0	98,135.0	41,121.08	7912.4	For higher values of PV Output, 100 kW Dg as stand-by
400	717,890.0	74,494.0	31,851.0	8656.1	All 4-DERs in operation
130 Solar PV kW Capacity					
169	272,030.0	31,289.0	9686.3	1071.8	200 kW Dg as stand-by
248	677,500.0	73,049.0	22,112.0	2838.9	100 kW Dg as stand-by & No-PV generation
338	798,920.0	89,809.0	37,064.0	5542.0	For higher values of PV Output, 100 kW Dg as stand-by
400	713,780.0	74,135.0	32,046.0	8612.9	No stand-by
195 kW Solar PV kW Capacity					
169	263,360.0	30,646.0	9627.7	10,018.8	200 kW Dg up to 68.25 kW PV generation and rest with both 200 kW & 100 kW Dgs as stand-by
248	677,500.0	73,049.0	22,112.0	2838.9	100 kW Dg as stand-by & No-PV generation
338	710,010.0	81,835.0	36,910.0	3930.5	100 kW Dg up to 126.75 kW PV generation and rest with 100 kW Dgs as stand-by
400	709,230.0	73,794.0	32,078.0	8542.7	No stand-by

generation with 195 kW capacity sizes of PV modules (i.e. 6466.0 kWh of heat daily) compared to both 130 kW capacity sizes (i.e. 6745.8kWh of heat daily) and 65 kW capacity sizes (i.e. 7020.4 kWh of heat daily). Higher the PV output and its hourly occurrence (Tables 1, 3 and 4) lesser will be both DER utilization and heat generation. All the three cases are in deficit of the daily heat generation than the requirement (i.e. 7371 kWh of heat daily required, which is recovered in No-PV case).

Alternative heat-source, like back-up boiler, is to be installed to meet the deficit.

- 2) Fuel consumption as well as emission from DERs is affected with change of PV output. Higher the PV generation, lower are the sharing of dispatchable DERs and consequence is lower fuel consumption (hence, lower fuel cost) but higher emission. The DERs, usually, operate at lower output with high emission. Mts are better choice than Dgs in the context of lower emission, lower fuel cost

Fig. 4 Pareto optimal front for fuel cost and NO_x emission at 338 kW Demand and 64.5 kW PV Output

Fig. 5 3-D plot of optimal front showing the relations among fuel cost, NO_x emission, and heat recovery at 338 kW Demand and 64.5 kW PV Output

and higher heat generation. So, whenever possible, more Mts are used and Dgs are kept as stand-by (Table 4).

- 3) Due to space constraint all results are not possible to show, besides curves at all results are similar in nature, so the Fig. 4, Fig. 5 and Fig. 6 have been chosen arbitrarily where electric demand is 338 kW, PV output as 64.5 kW and 100 kW Dg as stand. At a particular electric demand, more heat recovery is possible if load sharing is shifted from Dg to Mt. 100 kW Dg as stand-by has a good effect on both fuel cost and emission reduction, compared to 4-DER operation (Table 1).
- 4) The sensitivity of parameter change over the results is important. It is noted that at constant heat demand (say, at 285 kWh), optimal emission and optimal fuel cost are, respectively, 0.06% (low) and 0.89% (high) sensitive to per kW increase in load at 338 kW. Similar results are obtained at other cases.

Fig. 6 NO_x Emission versus Heat Recovery at 338 kW Demand and 64.5 kW PV Output

Economic Analysis and Comparison

The microgrid is formed with commercial customers in a small commercial hub like a shopping mall. The average temperature of summer at the microgrid site, Siliguri, is around 35 °C. The winter of Siliguri continues during December to February and temperature is around 15 °C. Load profiles of the mall is hardly varied with seasons and is considered almost same. With this assumption, calculations of annual costs and benefits would be simple. The mall opens at 09:00 and runs upto 22:00. Due to utilization of the daylight inside, the load in the day time (from 05:00 to 09:00 and from 09:00 to 17:00) is less. The load is at peak during 17:00 to 22:00 when there is no daylight. The profiles, both heat and electric demands, (Fig. 1) are considered stable and constant during unit hour.

With the introduction of solar generation in the microgrid, the electric profile demand is modified. The CHP-based DERs supply hourly both heat and modified electric demand. Simultaneous tracking of both electric and heat demands are not possible as these demands are independent variables, whereas generation of electric and heat by DERs are dependent. Thus the modified electric demand profile is tracked. The strategic deployment of these CHP-DERs helps operate these DERs near their respective rated capacities and the EELD results are shown in Table 1 and Table 4. Balance between daily thermal demand and daily thermal supply are to be met and to achieve the balance, accumulation of waste heat from supply sources, presently, like CHP-based DERs, from back-up boiler and from stored heat in thermal storage are important. Necessity of boiler arises when DERs and storage, jointly, cannot meet the demand. The modified electric demand along with the profile-heat demand at the same hour is to be catered to the customers of the microgrid.

Evaluations of BCR are performed on the EELD results obtained over the year of 8760 h and in comparison with

Table 5 Economic data of DERs

Bus no	DER Type	Investment cost, \$/kW	O&M Cost, \$/kW/Yr.	
			Fixed	Variable fuel cost
1	500 kW Dg	386	27	From Fuel cost curve (f_i)
2	200 kW Dg	514	27	do
6	80 kW Mt	753	27	do
11	100 kW Dg	690	27	do
12	30 kW Mt	1333	27	do

No-PV base case results. An array of results of BCR values in ascending order of PV sizes is formed. It is observed from the array that Best BCR value is reached at 1.416 of BCR value when PV size is 130 kW in the microgrid. To show the trend of BCR value change around 130 kW PV capacity, one lower value (65 kW) and another higher value (195 kW) module sizes have been considered as the study cases (Table 1 and Table 4). This study helps decide

the owner of the microgrid in investment planning on solar PV resources as well as its capacity selection. This discounted cash flow analysis requires investment costs for all equipments in the microgrid, (O&M) costs of DERs, revenues from selling of heat and electricity and savings from reduction of loss and emission. These vital inputs are obtained at best optimal EELD results. The economic data of DERs are obtained from Table 5.

Table 6 Economic analysis at best Pareto optimality

Description	Units	No-PV Case	65 kW PV Case	130 kW PV Case	195 kW PV Case
Installation Cost					
Gen-Set (Mts and Dgs)	US\$	272,030.0	272,030.0	272,030.0	272,030.0
Solar PV modules plus Converter plus MCBs	US\$	-x-	222,104.0	407,354.0	592,605.0
Boiler	US\$	-x-	3000.0	6000.0	6000.0
Heat Storage	US\$	276,320.0	270,140.0	273,320.0	267,770.0
Heat Exchanger	US\$	77,900.0	77,900.0	77,900.0	77,900.0
Microgrid	US\$	68,046.48	68,046.48	68,046.48	68,046.48
Total installation cost	US\$	694,300.0	913,220.0	1,104,650.0	1,284,400.0
Parameters					
Interest Rate	%	10	10	10	10
Inflation Rate	%	3	3	3	3
Operating Cost					
Gen-Set (Mts and Dgs)	US\$/Yr.	286,245.0	277,761.0	268,390.0	259,324.0
Solar PV modules plus Converter	US\$/Yr.	-x-	7475.0	14,950.0	22,425.0
Boiler	US\$/Yr.	-x-	7678.1	13,692.0	19,820.0
Heat Storage	US\$/Yr.	-x-	-x-	-x-	-x-
Heat Exchanger	US\$/Yr.	-x-	-x-	-x-	-x-
Microgrid	US\$/Yr.	-x-	-x-	-x-	-x-
Total Operating cost	US\$/Yr.	286,245.0	292,910.0	297,032.0	301,569.0
Revenues /Benefits					
Selling of Electricity	US\$/Yr.	319,558.35	319,558.35	319,558.35	319,558.35
Selling of Heat	US\$/Yr.	134,520.7	134,520.7	134,520.7	134,520.7
Benefit from Loss Reduction	US\$/Yr.	-Base value-	124.57	236.85	447.096
Benefit from Emission Reduction	US\$/Yr.	- Base value -	52,349.0	111,520.0	114,080.0
Total Revenues (B_i)	US\$/Yr.	454,080.0	506,550.0	565,840.0	568,610.0
present value cost	US\$	3,776,400.0	4,067,100.0	4,302,900.0	4,531,500.0
present value benefit	US\$	4,889,300.0	5,454,300.0	6,092,700.0	6,122,500.0
Benefit-to-cost ratio (BCR)	-x-	1.2947	1.3411	1.416	1.3511

Table 6 gives the all relevant results for estimation of BCR of the microgrid.

Following assumptions are made in the evaluation of BCR:

- Operation of CHP-based DERs and Mall: 24×7 days in a week
- All customers are Commercial like shopping Mall and tariff structure is considered as constant rate.
- As the operations of both types of DERs are plug-and-play, cost of starting is neglected.
- DERs are plug-and-play devices and not kept running as spinning reserves.
- DERs and other equipments: No spare capacity required
- No seasonal variations of commercial load profiles
- Solar PV inverter loss has been neglected
- Same tariff for both solar energy and the energy from other DERs

No-PV case has been taken as the base case. The results of the cases with PV have been compared with the base case. A mitigation fee of \$16.5/kg [34] may be suggested for NO_x emission reduction over the base case.

Following observations are obtained from the analysis (Table 6):

- 1) Boiler as a backup source is needed for all the three cases - required capacity chosen for 65 kW PV case, 130 kW PV case and 195 kW PV case are 50 kWh, 100 kWh and 100 kWh respectively. In the later two cases of same 100 kWh boilers, daily running hours are different as heat requirements are not same.
- 2) Investment in 130 kW PV case is 17.33% more with respect to 65 kW PV case, but 16.27% lower with respect to 195 kW PV case – this difference is mainly due to solar system cost. To create a competitive market, tariff for the solar energy has been taken as same as the energy from other DERs. The revenues from both electric and heat demands are same in all the cases as catering the same profiles. Revenue differs from one PV case to other PV case, majorly, due to different emission reductions with respect to base case. Annual O&M expenditures (i.e. fuel cost) with respect to base case are lower by 2.96%, 6.24% and 9.4% respectively in 65 kW PV case, 130 kW PV case and 195 kW PV case. The advantage of lower fuel cost in the last case (i.e. 195 kW PV case) is overtaken by both higher solar PV plus inverter replacement cost and boiler fuel cost.
- 3) As referred to [24], for evaluations of both present value (*pv*) cost (24) and benefit (26), equal yearly cash flow over the life cycle and straight line depreciation schedule are considered for simplification. Among the three cases highest value of BCR (1.416) is obtained at 130 kW PV case (Table 6). In other two cases, BCR values are 1.3411 (for 65 kW PV case) and 1.3511 (for 195 kW PV case). Three BCR values

indicate that from case I to case II there is increasing tendency of BCR value, whereas from case II to case III there is a downward tendency. The 130 kW PV case is best choice for investment in the present microgrid.

Conclusion

Solar energy is widely available and the most essential and pre-requisite resource of sustainable energy when the whole world is concerned with the environmental damage caused by the fossil fuel as well as its declining reserve. EELD technique is used, here, because it encompasses both pollution and fuel usage in relation to the energy generation by CHP-resources. Best Pareto optimal results of EELD (Tables 1 and 4) at each of solar module sizes are used for comparative economic analyses by BCR and higher value of BCR (1.416) indicates that 130 kW PV modules are seemed suitable choice for the microgrid as per present study. Block of 8760 simulation results annually corresponding to any discrete module capacity size can be selected for study for investment decision – three such blocks have been selected presently. It is observed from the results that with the increase of solar PV generation capacity, DER utilization is reduced and so recovery of waste heat is lessen. The effect is to introduce higher capacity boiler to meet the heat demand – further consequences are more capital investment and higher NO_x emission. For higher DERs utilization as well as lower emission, Dgs are strategically kept as stand-by. This strategy works well from 65 kW PV modules case to 130 kW PV modules case and it is found there is an increase of BCR value from 1.3411 to 1.416, but turnaround of BCR value happens from 130 kW PV modules case to 195 kW PV modules case. It is, also, to be noted that all the three cases of PV incorporation is better than the no-PV base case, as far as BCR value is concerned (Table 6).

This technique shows one of the many avenues of economic analysis. If more number of PV capacity sizes are compared then decision would be more accurate. Again, type of manufacturers and technology of DERs, on which both fuel consumption and emission depend, influence the simulation results. Moreover, the results are also sensitive to the customers' demand profiles –both heat and electric.

At the outset, the most important conclusion is that though the approach has been applied for a particular system but it could be accepted for any system –having different capacities of solar modules at different buses, having seasonal variation of demand profiles etc.

The EELD results obtained by DE algorithm have, also, been compared with the results by PSO algorithm and it is noted that results of both simulation techniques are tallying each other. Due to space limitation, PSO results are not presented. As DE algorithm is faster than PSO, DE algorithm results have been considered with foremost importance.

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References

- Basu AK, Chowdhury S, Chowdhury SP, Paul S (2011) Microgrids: energy management by strategic deployment of DERs- a comprehensive survey. *Renew Sust Energy Rev* 15: 4348–4356
- Al-Karaghoul A, Kazmerski LL (2010) Optimization and life-cycle cost of health clinic PV system for a rural area in southern Iraq using HOMER software. *Sol Energy* 84(4):710–714
- Ackermann T, Andersson G, Soder L (2001) Distributed generation: a definition. *Electr Power Syst Res* 57(3):195–204
- Miranda GJ (2003) Be prepared! An overview of process industry options in the deregulated power era. *IEEE Ind Appl Mag* 9(2):12–20
- Adefarati T, Bansal RC (2016) Integration of renewable distributed generators into the distribution system: a review. *IET Renew Power Gener* 10(7):873–884
- Jiayi H, Chuanwen J, Rong X (2008) A review on distributed energy resources and microgrid. *Renew Sustain Energy Rev* 12(9): 2472–2483
- Tsikakakis AG, Hatzigargyriou ND (2005) Financial evaluation of renewable energy source production in microgrids markets using probabilistic analysis. *Proceedings of IEEE power tech. 2005. Russia* 1–7
- Ahn, S. and Seung, I.M. (2009), “Economic scheduling of distributed generators in a microgrid considering various constraints. *PESGM 2009, PES'09 IEEE*, Calgary, AB- 26–30, 1–6
- Mitra J, Vallem MR, Patra SB (2006) A probabilistic search method for optimal resource deployment in a microgrid. In: *Proceedings of the 9th International Conference on Probabilistic Methods Applied to Power Systems*. KTH, Stockholm, Sweden, pp 1–6
- Kanchev H, Colas F, Lazarov V, Francois B (2014) Emission reduction and economical optimization of an urban microgrid operation including dispatched PV-based active generators. *IEEE Trans Sustainable Energy* 5(4):1397–1405
- Pipattanasomporn M, Willingham M, Rahman S (2005) Implications of on-site distributed generation for commercial/Industrial facilities. *IEEE Trans Power Systems* 20(1):206–212
- Marnay, C., Chard, J.S., Hamachi, K.S., Lipman, T., Moezzi, M.M., Ouaglal, B. and Siddiqui, A.S., (2001), “Modeling of customer adoption of distributed energy resources. *CERTS*
- Hawkes AD, Leach MA (2009) Modelling high level system design and unit commitment for a microgrid. *Appl Energy* 86(7–8):1253–1265
- S'aenz JP, Celik N, Xi H, Son Y, Asfour S (2013) Two-stage economic and environmental load dispatching framework using particle filtering. *Electric Power Energy Syst* 48:93–110
- Mohammadi M, Hosseini SH, Gharehpetian GB (2012) GA-based optimal sizing of microgrid and DG units under pool and hybrid electricity markets. *Electric Power Energy Syst* 35:83–92
- Abul'Wafa AR (2013) Optimization of economic/emission load dispatch for hybrid generating systems using controlled elitist NSGA-II. *Electr Power Syst Res* 105:142–151
- Hytowitz RB, Hedman KW (2015) Managing solar uncertainty in microgrid systems with stochastic unit commitment. *Electr Power Syst Res* 119:111–118
- Hatzigargyriou ND, Anastasiadis AG, Vasiljevska J, Tsikalakis AG (2009) Quantification of economic environmental and operational benefits of microgrids. In: *Proc of IEEE Bucharest Power Tech Conf*. Bucharest, Romania, pp 1–8
- Ghiasi M (2019) Detailed study, multi-objective optimization, and design of an AC-DC smart microgrid with hybrid renewable energy resources. *Energy* 169:496–507
- Gazijahani FS, Salehi J (2018) Optimal Bilevel model for stochastic risk-based planning of microgrids under uncertainty. *IEEE Transactions On Industrial Informatics* 14(7):3054–3064
- Rabiee A, Nikkiah S, Soroudi A (2018) Information gap decision theory to deal with long-term wind energy planning considering voltage stability. *Energy* 147:451–463
- Roy B, Basu AK, Paul S (2014) Analysis of a grid-connected PV household system in West Bengal using HOMER. In: *Proceedings of international conference on control, instrumentation, Energy & Communication- CIEC14*. University of Calcutta, Kolkata, India
- Basu AK, Bhattacharya A, Chowdhury S, Chowdhury SP (2012) Planned scheduling for economic power sharing in a CHP-based micro-grid. *IEEE Trans On Power Systems* 27(1):30–38
- Basu AK (2013) Microgrids: planning of fuel energy management by strategic deployment of CHP-based DERs – an evolutionary algorithm approach. *Int J Electr Power Energy Syst (ELSEVIER)* 44(1):326–336
- Storn, R. and Price, K. (2008), Home page of differential evolution. [Online]. Available: <http://www.icsi.berkeley.edu/~storn/code.html>
- Price K, Storn R, Lampinen J (2005) *Differential evolution: a practical approach to global optimization*. Springer-Verlag, Berlin
- Storn, R. and Price, K. (1995), “Differential evolution- a simple and efficient adaptive scheme for global optimisation over continuous spaces”. Technical Report TR-95-012 International Computer Science Institute Berkley, CA
- Bhattacharya A, Chattopadhyay PK (2010) Application of biogeography-based optimization for solving multi-objective economic emission load dispatch problems. *Electr Power Compon Syst* 38(3):340–365
- Basu AK, Chowdhury S, Chowdhury SP (2010) Impact of strategic deployment of CHP-based DERs on microgrid reliability. *IEEE Trans Power Delivery* 25(3):1697–1705
- Solar Irradiation in West-Bengal, India [Online]. Available: <http://emaxgreenenergy.com/incentives-bangal.html>
- Solar and Wind Energy Resource Assessment (SWERA), 2001 [Online]. Available: <http://swera.unep.net>
- Earth Observing System (EOS), NASA, 1991 [Online]. Available: <http://eosweb.larc.nasa.gov>
- Tomislav M, Pavlovi TM, Dragana D, Milosavljevi DD, Pirs DS (2013) Simulation of photovoltaic systems electricity generation using HOMER software in specific location in Serbia. *Therm Sci* 17(2):333–347
- Marnay C, Chard JS, Hamachi KS, Lipman T, Moezzi MM, Ouaglal B, Siddiqui AS. (2001), “Modeling of customer adoption of distributed energy resources. *CERTS*