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Optimal Sizing of Distributed Generators in MicroGrid

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***Abstract*— Hybrid Optimization Model for Electric Renewables (HOMER), developed by National Renewable Energy Laboratory (NREL), enables economic analysis for single source and hybrid Distributed Energy Resources (DERs). However, current version of HOMER does not support MicroGrid analysis. In this paper, Economic Analyzer for Distributed Energy Resources (EADER) is developed. It finds minimum Cost of Energy (COE) and optimal mix of DERs with multiple sources and sinks. In addition to single source Distributed Generator (DG) and hybrid DG, EADER is also capable to analyze MicroGrid. EADER results are validated for single source DG and hybrid DG with results obtained from HOMER for the same systems. Further, a sample practical system from Western Maharashtra, India, is analyzed using EADER. The results which consider all practical constraints are presented and discussed.**

***Index Terms*— Combined Heat and Power (CHP), Distributed Generation, Economic analysis, MicroGrid.**

NOMENCLATURE

η_i	Efficiency of i^{th} generator
ρ_{air}	Density of air at site in kg/m^3
ρ_{std}	Standard density, i.e., 1.225 kg/m^3
A_i	Availability of i^{th} generator
C_g	Cost of selling power to grid in \$/kWh
C_{ann}^{cap}	Annualized capital cost in \$/year
C_{ann}^{f}	Annualized fuel cost in \$/year
C_{ann}^{grid}	Cost recovered by selling power to grid in \$/year
C_{ann}^{in}	Annualized cost recovery from consumers in \$/year
C_{ann}^{mis}	Annualized miscellaneous cost in \$/year
C_{ann}^{onm}	Annualized operation and maintenance (O&M) cost in \$/year
C_{ann}^{rep}	Annualized replacement cost in \$/year
C_{ann}^{xtl}	Annualized cost of transformer and transmission lines in \$/year
C_i^{cap}	Capital cost of i^{th} DG in \$/kW
C_i^{f}	Fuel cost of i^{th} DG in \$/unit fuel
C_i^{onm1}	O&M cost of i^{th} DG in \$/hr
C_i^{onm2}	O&M cost of i^{th} DG in \$/kWh
C_i^{rep}	Replacement cost of i^{th} DG in \$/kW
C_{tl}	Cost of T&D network in \$/km
C_{xmr}	Total cost of transformers in a MicroGrid in \$
CF	Factor relating wind speed and power output of Wind Turbine Generator (WTG)
e_g	Energy sell to grid in kWh/year
E_{ann}^{out}	Annual electrical energy output in kWh/year
e_g^{max}	Maximum power exchange between DERs and grid
E_i^{out}	Electrical output of i^{th} DG in kWh/year
En_i	Net Calorific Value (NCV) of fuel used by i^{th} DG in kWh/unit fuel
F_i^{rep}	Replacement factor for i^{th} DG
FU_i^f	Fuel utilized by i^{th} DG in unit fuel/year
hr_i	Heat recovery ratio for i^{th} DG
i	DG index
L_i^{DG}	Life of i^{th} DG in years
L_i^{rep}	Replacement life of i^{th} DG in years
L_{proj}	Life of project in years
l_{tl}	T&D network's length of MicroGrid in km
m	Total number of DG types
P	Payback period in years
$P2h_i$	Power to heat ratio of i^{th} DG
P_D	Total connected load of in kW
P_G	Total power generated in kW
Pg_i	Power generation of i^{th} DG
Pg_i^{max}	Maximum generation limit of i^{th} DG
r	Interest rate
R_i	Rating of i^{th} generator in kW
S_i	Salvage value of i^{th} DG in \$
Th_{ann}^{out}	Thermal energy output in kWh/year
ws	Wind speed in m/s

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I. INTRODUCTION

IN India currently, the average peak demand and energy shortages for all regions taken together are of the order of 12.39% and 10.32% respectively. Still, more than 80000 villages are not electrified [1]. Hence, the Government of India has emphasized on development of infrastructure with top priority given to the power sector. To electrify remote and rural areas, it may be difficult as well as uneconomical to transmit power over long distances through transmission lines. On the contrary, single source DG, hybrid DG or MicroGrid are more favorable to electrify such areas. Single source DG is an individual Distributed Energy Resource (DER) connected to load. The load it serves can be electrical, thermal or combination of both. Since most of the DERs can directly

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supply load without involving T&D network; they reduce losses and overall initial investment on T&D network during power transmission. Hybrid DG technology includes integration of two or more DGs and energy storage devices, supplying the same load. Some of the common hybrid configurations are, viz., Wind Turbine Generator (WTG)-diesel, WTG-Photo Voltaic (PV) cell, Micro Turbine (MT)-Fuel Cell (FC), WTG-MT, etc.

Concept of MicroGrid supersedes all the advantages of single source DG and hybrid DG. Moreover, it also includes all the advantages of *networking*, at mini scale. From reliability point of view it may not be always possible to operate few types of DGs like WTG and PV cell, in stand-alone mode. The MicroGrid concept, as it involves small T&D network, efficiently makes use of all location specific DGs.

A simulink based model similar to Hybrid Optimization Model for Electric Renewables (HOMER) is reported in [2]. The model is used for economic analysis and it finds impacts of PV with diesel-battery system for Lime village, Alaska. A numerical algorithm developed in [3] is used for and unit sizing and cost analysis of wind, PV and hybrid wind-PV systems. The feasibility of MicroGrid is justified in [4]. Various attributes taken into consideration are Energy Not Served (ENS) per annum, capital cost, and profit by selling energy to grid in peak time.

Economic feasibility study includes calculation of Cost of Energy (COE), Net Present Cost (NPC), Life Cycle Cost (LCC), etc. For minimum COE, investment on each type of DG technology has to be optimized. In this paper, development of Economic Analyzer for Distributed Energy Resources (EADER) software is discussed. The software finds minimum COE for variety of available schemes, and selects an optimal mix of available resources to supply load. EADER facilitates analysis of single source DG, hybrid DG as well as MicroGrid. A case study of practical system in the State of Maharashtra, India, has been done using EADER. Where, it finds best possible combination of wind, bagasse, biomass and natural gas based DERs to supply energy demands of MicroGrid.

Organization of the paper is as follows. Section II introduces basic routines implemented in EADER for analysis of single source DG and hybrid DG. Section III gives algorithm for analysis and elaborates constraints on the objective function. Section IV compares single source DG and hybrid DG results, obtained from EADER and HOMER. Section V suggests modifications in basic EADER routines to make it capable of analyzing MicroGrid. Section VI briefs features and limitations of EADER. The details of site in the Western Maharashtra for the execution of MicroGrid project is listed in Section VII. Results of the analysis are discussed in section VIII, and section IX concludes the paper.

II. EADER Development

EADER has been developed in *C programming language* to find optimal mix of available resources, which results into minimum COE to consumer. This section explains development of EADER which can analyze single source DG and hybrid DG. Evolution and modification of EADER routines to analyze MicroGrid is explained in a later section. The EADER evaluates COE by calculating various costs as follows:

A. Annualized capital cost
B. Annualized replacement cost
C. Annual energy output
D. Annualized O&M cost
E. Annualized fuel cost
F. Annual earning by selling power to grid

A. Annualized capital cost

Annualized capital cost (C_{cap}^{ann}), is the cost that needs to be recovered yearly for payback period of P years and interest rate r. The main components of C_{cap}^{ann} are, C_i^{cap} and Capital Recovery Factor (CRF).

The CRF is a ratio used to calculate the present value of an annuity (a series of equal annual cash flows). The equation for the CRF is expressed as,

$$CRF(r,P) = \frac{r(r+1)^P}{(r+1)^P - 1} \tag{1}$$

Then, annualized capital cost of DG can be written as,

$$C_{ann}^{cap} = CRF(r,P)\sum_{i=1}^{m} C_i^{cap} R_i \tag{2}$$

B. Annualized replacement cost

Replacement cost of a DG depends upon the salvage value of DG after life years. The salvage value of a DG can be expressed as a function of Sinking Fund Factor (SFF).

SFF is a ratio used to calculate the future value of a series of equal annual cash flows. It given by,

$$SFF(r,P) = \frac{r}{(r+1)^P - 1} \tag{3}$$

Life of replacement is given by,

$$L_i^{rep} = L_i^{DG} Floor(\frac{L_{proj}}{L_i^{DG}}) \tag{4}$$

where, *Floor* returns integer part of a real value.

Replacement factor F_i^{rep} arises because the component lifetime can be different from the project lifetime. F_i^{rep} is given by,

$$F_i^{rep} = \frac{CRF(r, L_{proj})}{CRF(r, L_i^{rep})} \tag{5}$$

The salvage value of the component at the end of the project lifetime is assumed to proportional to its remaining life. Therefore the salvage value S is given by,

$$S_i = R_i C_i^{rep}[1 - \frac{L_{proj} - L_i^{rep}}{L_i^{DG}}] \tag{6}$$

Annualized replacement cost is given by,

$$C_{ann}^{rep} = \sum_{i=1}^{m} R_i C_i^{rep} F_i^{rep} SFF(r, L_i^{DG}) - \sum_{i=1}^{m} S_i SFF(r, L_{proj}) \quad (7)$$

C. Annual energy output

Electrical energy output from IC engine, fuel cell, PV cell, wind etc., will be different. Hence, each type of DG has to be modeled separately.

Electrical energy output from i^{th} fuel powered generator (e.g., bagasse, biomass, natural gas) is given by,

$$E_i^{out} = A_i R_i 8760 \quad (8)$$

whereas, electrical output of a i^{th} WTG is given by,

$$E_i^{out} = (ws)^3 CF \frac{\rho_{air}}{\rho_{std}} \quad (9)$$

Now, the annual energy produced by a combination of DGs can be calculated by summing up energy produced by individual DG. It is given by,

$$E_{ann}^{out} = \sum_{i=1}^{m} E_i^{out} \quad (10)$$

Maximum thermal energy produced by a DG depends upon the Power to Heat ratio (*P2h*). Then, total thermal energy produced by hybrid combination can be found out by summing energy produced by all individual DGs. This is expressed as,

$$Th_{ann}^{out} = \sum_{i=1}^{m} \frac{E_i^{out}}{P2h_i} hr_i \quad (11)$$

D. Annualized O&M cost

The O&M cost of DGs may be specified in \$/hr. Hence, O&M cost for a DG for a time period can be calculated by multiplying O&M cost of DG with operating hours. The total cost of DG combination is expressed as,

$$C_{ann}^{onm} = \sum_{i=1}^{m} C_i^{onm1} A_i 8760 \quad (12)$$

E. Annualized fuel cost

Fuel cost for WTGs can be taken as zero. For fuel powered generators annual fuel used is given by,

$$FU_i^f = E_i^{ann} Slope_i \quad (13)$$

where $Slope_i$ is fuel used per unit power generated for i^{th} generator, and it is expressed as,

$$Slope_i = \frac{1 + \frac{hr_i}{P2h_i}}{\eta_i En_i} \quad (14)$$

Annualized fuel cost now can be calculated as,

$$C_{ann}^f = \sum_{i=1}^{m} FU_i^f C_i^f \quad (15)$$

F. Annual earning by selling power to grid

Power selling to the grid depends upon the available surplus power with DGs. Charges recovered by selling power the to grid over a period of one year is expressed as,

$$C_{ann}^{grid} = e_g c_g \quad (16)$$

With all the annualized costs obtained, amount of money recovered from the consumers over a period of one year is expressed as:

$$C_{ann}^{in} = C_{ann}^{cap} + C_{ann}^{rep} + C_{ann}^{onm} + C_{ann}^f - C_{ann}^{grid} \quad (17)$$

COE to the consumers is the objective function which needs to be minimized. The COE is expressed as,

$$COE = \frac{C_{ann}^{in}}{E_{ann}^{out}} \quad (18)$$

III. Algorithm and Constraints

A. Algorithm steps:

1) Select different types of generators depending upon the availability of resources. Prior survey of site for available resources, load and existing generation is required for this purpose.
2) Decide maximum generation capacity for each type of generation. The attributes to be taken into account for this purpose can be reliability of MicroGrid and operating reserve. Power exchange with grid can be additional attribute for energy deficit country.
3) Select incremental step size for each generator which is available commercially and generally installed. For example, biomass gasifier systems are commercially available in the range of 500 kW to few MW. Hence, incremental step size can be set to 500 kW for biomass fuelled generators.
4) Give priority to the DGs, i.e., from where the power should come first. For example, natural resources will be on higher priority as compared to fossil fuel based DGs.
5) Generate all possible combinations for selected generators, ranging from zero to maximum possible installation of each DG.
6) Check the generated combinations for validity. Each valid combination has to satisfy system's electrical as well as thermal load requirement.
7) Calculate COE for each valid combination.
8) Find minimum of all COE values and index corresponding to the minimum COE.
9) The combination corresponding to minimum COE is the optimal mix of the DGs.

B. Constraints on the objective function:

1) The output of each generator must be always positive, i.e., $Pg_i \geq 0$. It is assumed, that in abnormal conditions as soon as a DG tries to draw power from other sources, it is isolated from the network.
2) Maximum generation limit of renewable energy resources is limited by expected power selling, amount of reserve capacity, and availability of natural resources. Maximum rating of fuelled generator should be such that, total load of MicroGrid can be supplied irrespective of other types of DGs. This maximum limit is defined as $P_g \leq Pg_i^{max}$.
3) The amount power exchanged between DG and utility is restricted by a mutual contract and Government regulations. According to [5], the import of electricity from the grid in any quarter during the financial year should not exceed 10% of the total generation of electricity by such system, except in case of unforeseen breakdown in the generation system for temporary periods. This is expressed as $e_g \leq e_g^{max}$.
4) A self-sufficient system must not draw power from the utility grid.
5) Constraint based on availability of fuel can be simulated by setting availability of generators to 1 or 0 depending upon whether unit is generating or not. Alternatively, fuel price can be modified if the unit is run with another fuel.
6) Power generation and load balance is expressed by $P_G = P_D$.
7) The existing generation can be set as an equality constraint to the objective function.

IV. Validating EADER Results

The EADER results are validated with HOMER results in two different cases. Firstly, results of single source DG obtained from both the softwares are compered. Thereafter, optimal combination of two DGs to supply a load is determined by using both the softwares.

A. Single source DG analysis

A single source, bagasse based generator is selected for the analysis. To see the effect of availability of generator and load change, analysis is done in two cases. Case 1 is with 100 kW load and availability equals to unity. In case 2, load considered is 70 kW, while the DG is assumed to be OFF in the month of March and December. Thermal load considered in both the cases is 500 kW. Payback period of the project is a variable in EADER. For the analysis, P is assumed to be the same as project life, i.e., 25 years. Interest rate of 0.07 is assumed for the analysis. Other analysis related data is shown in appendix I.

The results of the analysis for case 1 and case 2 are shown in the table I. It can be noticed that, various annualized costs as well as annual energy output calculated from both the softwares are the same. In this analysis, comparison of COE obtained from both the softwares is not important. Because, at the time when DG is not available, the load has to be supplied from the grid or nearby DG. Hence, overall COE will also depend upon tariff rates of importing power from another sources. Our main objective of single source DG analysis is to check performance of EADER routines.

TABLE I
Single source DG analysis results

Particular	Case 1		Case 2	
	EADER	HOMER	EADER	HOMER
C_{ann}^{cap}	6864.84	6865	6864.84	6865
C_{ann}^{rep}	825.37	825	825.37	825
C_{ann}^{onm}	10512	10512	8726.40	8726
C_{ann}^{fuel}	12614.45	12619	7330.21	7333
E_{out}	876000	876000	509040	509040
Th_{out}	4380000	4382090	2545200	2546421

B. Hybrid DG analysis

In hybrid DG analysis, optimal combination of two DGs is found to supply a load, which gives minimum COE to consumer. Analysis includes two cases (case 3 and case 4), with different availability and load in each case.

In case 3 maximum generation from DG1 and DG2 are restricted to 700 kW and 1500 kW respectively, with incremental step size of 100 kW for each DG. The total electrical and thermal loads in this case are 1200 kW and 1000 kW respectively. Also it is assumed that, each DG is available throughout the year.

In case 4, the maximum generation from DG1 and DG2 are restricted to 1000 kW and 1500 kW respectively, with incremental step size of 100 kW for each DG. The total electrical and thermal loads in second case are 950 kW and 1000 kW respectively. It is assumed that, in this case DG1 is switched OFF between the months of July to November while, DG2 is switched OFF in the month of March.

Here, DG1 and DG2 indicates bagasse and natural gas powered generators respectively. Project life of 25 years and interest rate of 0.07 is assumed for the analysis. The payback period is assumed to be same as project life. Other analysis related details of each DG are given in appendix II.

The results of the analysis for case 3 show that, the optimal combination found by EADER and HOMER is the same, i.e., DG1 size should be 700 kW and DG2 installation should be 500 kW. The COEs calculated by EADER and HOMER are 0.1088 $/kWh and 0.109 $/kWh respectively. The annualized costs and energy output of both DGs in EADER and HOMER are shown table II.

For the case 4, the results of the analysis indicate that, optimal combination found by EADER and HOMER is 1000 kW installation of DG1 and 1000 kW installation of DG2. The minimum COEs are 0.1864 $/kWh and 0.186 $/kWh in EADER and HOMER respectively. The annualized costs

TABLE II
HYBRID DG ANALYSIS RESULTS: CASE 3

Particular	DG1		DG2	
	EADER	HOMER	EADER	HOMER
C_{ann}^{cap}	48053.89	48054	38614.73	38615
C_{ann}^{rep}	5777.62	5778	11624.18	11624
C_{ann}^{onm}	73584.14	73584	525600	525600
C_{ann}^{fuel}	88301.14	88340	352634.09	350400
E_{out}	6132000	6132000	4380000	4380000
Th_{out}	30660000	30676602	4325652.5	4270501

involved and energy output of both the DGs calculated by EADER and HOMER are shown table III.

TABLE III
HYBRID DG ANALYSIS RESULTS: CASE 4

Particular	DG1		DG2	
	EADER	HOMER	EADER	HOMER
C_{ann}^{cap}	68648.42	68648	77229.47	77229
C_{ann}^{rep}	8253.74	8254	23248.36	23248
C_{ann}^{onm}	61056	61056	961920	961920
C_{ann}^{fuel}	69604.12	69630	280851	279072
E_{out}	4833600	4833600	3488400	3488400
Th_{out}	24178850	24178850	3445116	3401190

In both the analysis, maximum installation size of each DG can consist of multiple DG units of the same type.

V. MODIFICATION OF EADER TO ANALYZE MICROGRID

The EADER described in section II is able to analyze maximum up to hybrid DG, i.e., its capability is limited to the extent same as HOMER. In order to analyze MicroGrid economics, the code has to be modified.

Small T&D network is a part of MicroGrid. MicroGrid also includes transformers at the load ends. Hence, costs of T&D network and transformers have to be modelled. Moreover, the overall operation of MicroGrid is controlled by three controllers [6]:

1) MicroGrid Central Controller (MGCC)
2) Micro source Controller (MC)
3) Load Controller (LC)

Hence, MicroGrid analysis must include investment upon these controllers. In addition to above mentioned additional costs, overhead charges, contingency amount, taxes and insurance charges for the MicroGrid should be taken into account. These costs are calculated as follows:

A. Annualized transformer and transmission line costs

Transmission line and transformer investment is also calculated as per equation below.

$$C_{ann}^{xtl} = (C_{xmr} + C_{tl}l_{tl})CRF(r, P) \tag{19}$$

B. Annualized miscellaneous cost

The miscellaneous charges of MicroGrid include cost of controllers, overhead charges, contingency amount, taxes and insurances. The charges can be taken as 20%, 10%, 3%, 5% of annualized capital cost of DGs respectively. This is given by,

$$C_{ann}^{mis} = \sum_{i=1}^{m} 0.38 C_i^{cap} CRF(r, P) R_i \tag{20}$$

Moreover, O&M cost for a DG is generally available in the form of $/kWh of electrical energy generated. Hence, the equation (12) to calculate total O&M cost of MicroGrid in a year can be expressed as,

$$C_{ann}^{onm} = \sum_{i=1}^{m} C_i^{onm2} E_i^{out} \tag{21}$$

With additional annual costs taken into consideration, the equation (17) is modified as follows:

$$\begin{aligned} C_{ann}^{in} = C_{ann}^{cap} + C_{ann}^{rep} + C_{ann}^{onm} + C_{ann}^{f} \\ + C_{ann}^{xtl} + C_{ann}^{mis} - C_{ann}^{grid} \end{aligned} \tag{22}$$

VI. FEATURES AND LIMITATIONS OF EADER

A. Features of EADER

- In EADER, fuel used in a year is more accurately calculated by taking into account Power to Heat ratio, Heat recovery ratio, and efficiency of the DG.
- Any number of WTGs and fuel powered generators can be simulated using the developed algorithm.
- O&M cost is modelled in $/kWh. By making O&M cost to be a function of generated electrical energy, O&M cost is more accurately calculated.
- Transmission line and transformers can be modelled in EADER.
- Controller costs, overhead charges, contingency amount, taxes and insurances are taken explicitly into account. Hence, MicroGrid can be analyzed using EADER.

B. Limitations and assumptions of EADER

The limitations and assumptions listed below are applicable to the current version of EADER.

- Only prime mover based generators are modelled, i.e., PV cell, Fuel cell and battery are not modelled.
- The emissions from different DERs and total emissions of MicroGrid can't be calculated in the current model.
- It is assumed that thermal loads can always be supplied by the predefined $P2h$, i.e., maximum electrical and thermal loads are always in proportions to $P2h$ of the DG.
- The grid break-even distance analysis is not included.

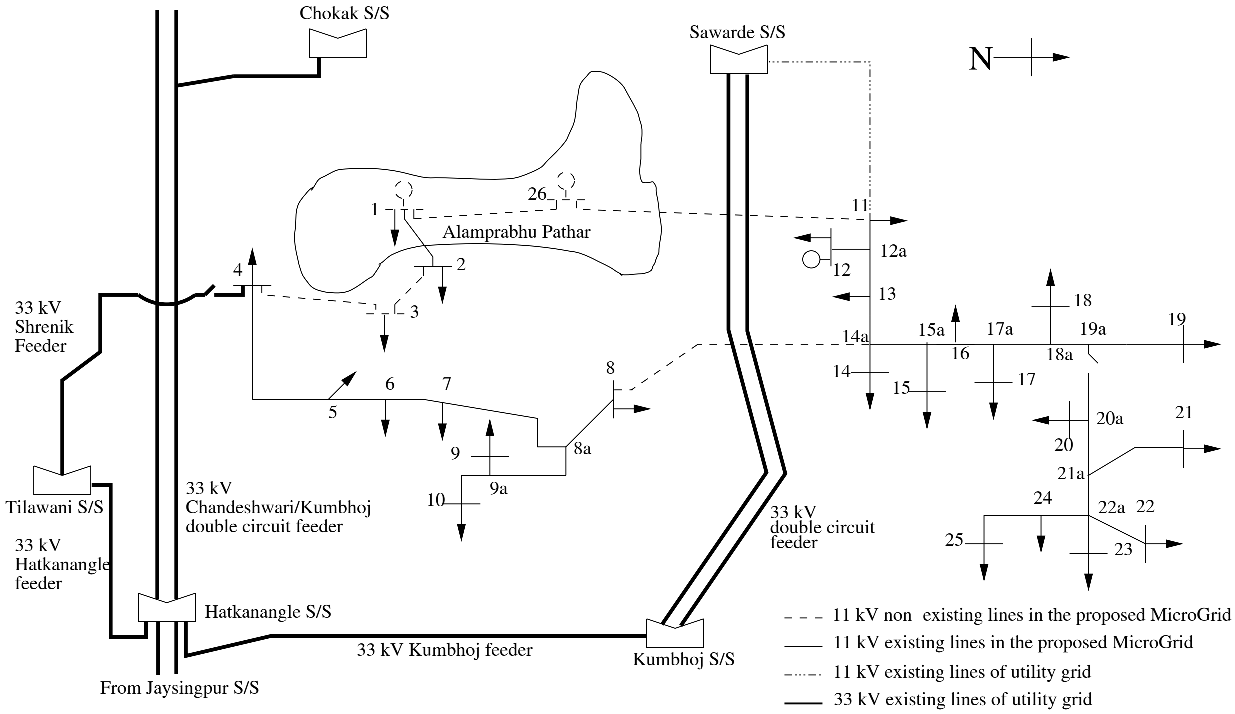

Fig. 1. Alamprabhu Pathar MicroGrid network.

VII. MicroGrid in Maharashtra

Different non-conventional energy potentials available in the State of Maharashtra are shown in table IV. Since the cumulative tapped potential is about 10% of the total available potential, there exist opportunities to use the remaining potential for local power generations. As wind, bagasse and biomass are the renewable energy sources with highest potential in the State, the MicroGrid likely to consist of DGs based on these resources. Since wind energy can't be predicted accurately, and bagasse is seasonal, natural gas based MT, IC engine and mini gas turbine can play an important role in reliability improvement of the MicroGrid. Based on identified resources, Alamprabhu Pathar in the state of Maharashtra has been selected for the execution of the MicroGrid project.

TABLE IV

Non-conventional energy potential in Maharashtra as on 31^{st} March 2003 [5]

Source	Potential in MW	Achievement in MW
Wind	3650	399.35
Small Hydro	600	226.57
Bagasse Co-generation	1000	23.50
Biomass	781	7.50
Municipal Solid Waste	100	0.00
Industrial Waste	210	6.12
Total	6341	663.05

Alamprabhu Pathar is a hilly area in Kolhapur district in the State of Maharashtra, India. The site is rich of identified energy resources, and is characterized by adequate load growth. Maharashtra Energy Development Agency (MEDA) has declared Alamprabhu Pathar as one of the wind sites, where good amount of wind power can be tapped off. Presence of sugar industries in close vicinity of Alamprabhu Pathar has made it possible to include bagasse based generators as one the constituents of the MicroGrid. The Alamprabhu Pathar area is well connected to the rest of the Maharashtra by roads. Hence, biomass and natural gas can be easily transported up to the generation point. Around the Alamprabhu Pathar area, there exist good amount of residential, agricultural, commercial and industrial consumers. The 11 kV T&D network of MicroGrid is shown in Fig. 1. The 33 kV distribution network around Alamprabhu Pathar is not a part of MicroGrid. But, MicroGrid can be connected to grid to 33 kV network at a single Point of Common Coupling (PCC, not shown in the Figure) to exchange power between the two. In Fig. 1, numbers 1 to 26 refer to load/generation points. Nodes 1 and 26 indicate WTGs. Node 12 is a sugar cane industry (Sharad Sahkari Sakhar Karkhana Ltd.). Majority of industrial load is concentrated on nodes 5 to 10 while, nodes 13 to 25 mainly consist of residential, agricultural and commercial loads. The category-wise consumers as well as other details of MicroGrid are listed in table V.

VIII. MicroGrid Analysis and Results

As mentioned in the previous section, for Alamprabhu Pathar MicroGrid, it is preferable to have DGs based upon available resources, viz., bagasse, wind, biomass and natural gas. To form a MicroGrid of available dispersed resources,

TABLE V

MICROGRID DATA

Total installed capacity	12000 kW
Total electrical load	8907 kW
Residential consumers (approx.)	1000
Commercial consumers (approx.)	20
Industrial consumers (approx.)	20
Agricultural consumers (approx.)	320
Length of 11 kV network	48.16 km
Average wind speed at Alamprabhu Pathar	6.58 m/s
Grid selling	10% of total load
C_g	0.067* $/kWh
Reserve capacity	15.775% of installed capacity
Existing generation	Bagasse 6000 kW

* 1 $ = INR 45.

TABLE VI

RESULT OF MICROGRID OPTIMIZATION

Particular	Bagasse	Natural gas	Biomass	Wind
DG (kW)	6000	2400	500	14250
C_{ann}^{cap}	278026	143338	23169	733680
C_{ann}^{rep}	33428	17234	2786	88212
C_{ann}^{onm}	1515888	209207	17716*	138541
C_{ann}^{f}	1085714	603815	—	0
C_{ann}^{mis}	105650	54468	8804	278798
E_{out}	17424000	16092872	393683	27708194
Th_{out}	92928000	19215370	629893	0
e_g	7017430			

* The charges include O&M cost and fuel cost.

one needs to evaluate the amount of investment to be done on each particular type of DG resource, so as to have minimum COE at consumer level.

As shown in table V, maximum connected electrical load of MicroGrid is 8907 kW. For planning purpose, maximum possible load has to be considered with best possible reliability. The power exchange with the utility grid under normal conditions is limited to 10% of the capacity of MicroGrid. The reserve capacity is assumed to be 15.775% of the MicroGrid size. As a consequence, MicroGrid size becomes 12000 kW.

It is assumed that subsidy of 40% on capital cost of each DG, is given by the Government . The internal load of the sugar factory is 4000 kW, and its generation capacity of 6000 kW. When the sugar cane is not available, the sugar factory remains OFF. As a consequence, the MicroGrid's total electrical load reduces to 4907 kW, and generating capacity reduces by 6000 kW during that period. MicroGrid's month-wise connected loads are shown in appendix III. It is assumed that, natural gas based generator remains OFF in the month of March, and biomass based generator remains OFF in the month of May and June.

Investment on transformers is 282708 $. Length of transmission line network for the MicroGrid is 48.16 km. Erecting 11 kV, pin type ACSR Weasel (0.03) and RSJ pole transmission line of 1 km costs 9619 $. Project life of 25 years and interest rate of 0.07 is assumed for the analysis. The payback period is assumed to be same as project life.

A. *Deciding maximum limits and incremental step size of each generation for EADER*

It is important to give maximum limit as well as correct step size of each type of DG. More precise step size and accurate maximum limit would save considerable amount of execution time and memory size required. As mentioned previously, MicroGrid already consists of 6000 kW (2 $\times$ 3000 kW) bagasse based generation at Sharad Sahkari Sakhar Karkhana Ltd. With that equality constraint, rest of the generation has to be optimized. Alamprabhu Pathar hill is approximately $6000 \times 1000\ m^2$ area. It has a total wind generation potential of about 45 MW. But, for the MicroGrid purpose, only few of the WTGs can be part of the MicroGrid considered in this analysis. Others may be connected to utility grid or other MicroGrid in a nearby area. On the reliability point of view, stand-alone WTGs are inferior than natural gas based and biomass based generators. Hence, WTG size will be limited up to supply to utility grid and reserve capacity. For a typical 950 kW WTG, upper limit of wind generation is installed capacity of 14250 kW with 15 generators. Biomass and natural gas based generators should be able to supply rest of the load even with (N-1) contingency. Hence, maximum installation of each type of generators has to be at least 8907 kW. Since 500 kW biomass based generators are successfully installed and operated at many places, it is preferable to increase the biomass generation in the step of 500 kW. Natural gas fuelled IC engine based DG can be installed with single unit of 300 kW. Accordingly the total installed capacity of each kind of generation is limited up to 9000 kW. Other generator details are listed in appendix III.

B. *Results of proposed MicroGrid*

Analysis shows that, we should install 2400 kW of natural gas based generators, 500 kW of biomass based generators and 14250 kW of WTGs. The minimum COE comes out to be 0.080046 $/kWh. That means total 8 units of natural gas based generators, each of 300 kW capacity can be installed at various locations in the MicroGrid. Only one biomass based generator is required which is of 500 kW capacity. Similarly total 15 WTGs should be installed. Table VI shows breakup costs of different DGs in the MicroGrid. To decide location of the selected DGs will require further studies.

IX. CONCLUSION

This paper develops economic analyzer EADER, which is tested for sample systems. The EADER is validated for single and hybrid DER, and yields very close results compared to HOMER. More modifications are made to improve performance of EADER as compared to HOMER. HOMER in its present version is unable to analyze MicroGrid. The results of practical MicroGrid using EADER are presented which minimize COE and find the optimal mix of proposed DERs with one DER existing. The slight increase in COE for MicroGrid as compared to single source DG and hybrid DG can be justified by increased reliability and self-sufficiency. Though results seem to promising, EADER can be extended further to include all possible types of DG technologies.

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APPENDIX I
SINGLE SOURCE DG DATA

Description	Value	Description	Value
DG rating	100 kW	C^f	0.02
E_n	30 MJ/kg	L^{DG}	20
C^{cap}	800	*hr*	1
C^{rep}	800	*P2h*	0.2
C^{onm}	1.2	η	1

APPENDIX II
HYBRID DG DATA

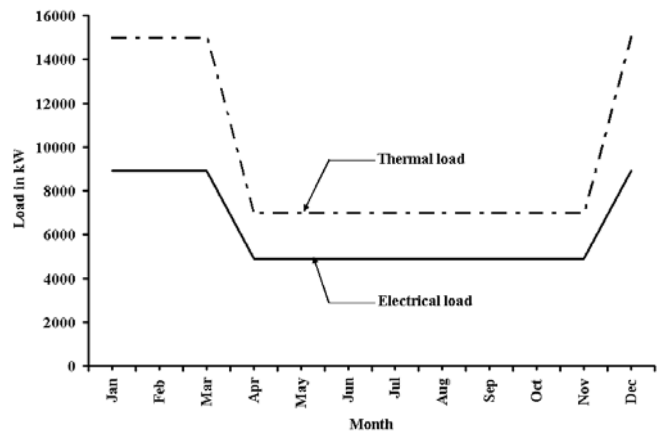
Fuel type	Bagasse	Natural gas
E_n	30 (MJ/kg)	45 (MJ/m^3)
C^{cap}	800	900
C^{rep}	800	900
C^{onm}	1.2 $\$/hr$	12 $\$/hr$
C^f	0.02 $\$/kg$	0.4 $\$/m^3$
L^{DG}	20	15
hr	1	1
P2h	0.2	1.012564
η	1	1

APPENDIX III
MICROGRID DG DATA

Particular	Bagasse	Natural Gas	Biomass	Wind
C^{cap}	900	1160	900	1000
C^{rep}	900	1160	900	1000
C^{onm}	0.087	0.013	0.045*	0.005
C^f	0.02**	0.1274***	—	—
E_n	2.64^{+}	9.675^{++}	3.29	—
L_{DG}	20	20	20	20
hr	0.8	0.8	0.8	—
P2h	0.15	0.67	0.5	—
η	0.77	0.77	0.7	—

* The charges include O&M cost and fuel cost, ** Expressed in \$/kg, *** Expressed in \$/m^3, + Expressed in kWh/kg, ++ Expressed in kWh/m^3.

Figure shows the MicroGrid's monthly connected electrical and thermal load.



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