Optimum Cluster of Distributed Generation Systems for Energy Management within a Virtual Utility

Khaled M. Abo-Al-Ez

Abstract— Many remote communities in developing countries suffer from lack or weak grid connection. A reliable electric energy system is essential for the residential and small industrial applications. In modern smart grids, the concept of virtual utility is used to describe a cluster of hybrid Distributed Generation (DG) and storage systems. The optimum cluster of DG and storage systems within a virtual utility is essential for a reliable energy management system, to effectively supply the load demands. This requires the minimization of the Net Present Cost (NPC) of the cluster's investment. Among various economic evaluation software tools, very effective software according to recent research and projects is the Hybrid Optimization Model for Electric Renewables (HOMER). In this paper, a remote load is used as a case study for economic evaluation of a cluster of DG resources. The available resources for the case study include PV arrays, small wind turbines, and a Hydrogen Fuel cell system along with storage battery banks. Optimization and sensitivity analysis results are thoroughly presented and discussed.

***Index Terms*— Optimum cluster, Distributed Generation, Virtual utility, Optimization, Sensitivity analysis, HOMER.**

1 INTRODUCTION

In modern smart grids, the Distributed Generation (DG) and storage systems are smartly monitored and maintained over the internet using a network of sensors and actuators. Such a small hybrid DG energy sources are seen by the internet cloud as a unified power generation utility which is called a "virtual utility" [1]. This virtual utility is working within a microgrid to serve local loads. Usually for reasons of obtaining the maximum economic benefits for energy management, the virtual utility systems are empowered by the available natural energy sources. The major benefit for the main grid is a transmission constraint reduction and postponed centralized generation investments [2], [3]. If the virtual utility has to operate reliably in a given region, the selection of the optimum cluster of the DG systems for economic feasibility is essential [2]. This selection is a defying mission because of the large number of possible choices and the uncertainties related to the operation of different renewable generation systems. In addition, demand variations and fossil fuel costs are extra factors that can affect the optimum selection. Therefore, it is important to apply an effective Decision Support System (DSS) [4], [5]. Among various DSS tools developed for economic evaluation hybrid DG power systems, a very efficient tool called Hybrid Optimization Model for Electric Renewables (HOMER) is applied for hybrid DG power systems [5], [6]. In [2] a comparative analysis between different generation systems and possible arrangements to satisfy the demand of a typical islanded load through HOMER software simulations was presented. That paper outlined some plans to encourage the utilisation of renewable energy systems in remote microgrids. In [7] HOMER is used to verify the results obtained by models built using MATLAB/Simulink for the economic analysis of a diesel power systems integrating with a photovoltaic (PV) system for devious sites. In [8] the importance of DGs for generation expansion planning for developing nations is revealed. That paper stated several options generated by various operation scenarios. The cost of energy and the net present cost (NPC) of various planning scenarios, such as a single DG operation mode, or microgrid formation with or without grid connection, are calculated. In [9] HOMER was applied for case studies of a parallel hybrid power system, which simulates a mini-grid cluster of DG power systems with reverse osmosis water desalination plant. In addition to its user-friendliness, flexibility to model a cluster of DG systems, the main advantages of HOMER can be summarized as [10]:

1. It performs an optimization process that finds the cluster of the generating systems for a specific demand at the lowest operating cost.
2. It performs sensitivity analysis to determine how the optimization outcomes change with the variations in input parameters.

The three main required steps to find the optimum cluster of DG systems for a virtual utility are:

1. Systems simulation,
2. Optimization,
3. Sensitivity analysis.

In the simulation step, the performance of a specific cluster of DG systems is assessed each hour of the year to evaluate the cluster's technical feasibility and cost. Thereafter, in the optimization step, it is required to simulate different choices of the cluster to find the optimum cluster that fulfils the system's constraints at the lowest operating cost. Finally, in the sensitivity analysis step, it is required to determine how the optimization outcomes change with the variations in input parameters. This is done by performing numerous optimizations under different input scenarios.

In this paper, a remote load is taken as a case study for economic evaluation of a cluster of DG systems forming a virtual utility. The optimum cluster of DG and storage systems within a virtual utility is essential for a reliable energy management system, to effectively supply the load needs. The available resources for the case study include PV arrays, small wind turbines, and a hydrogen fuel cell system along with storage battery banks. Optimization and sensitivity analysis results are thoroughly presented and discussed.

The following sections of this paper are structured as follows: Section 2 provides the configuration of a cluster of

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DG power systems; Section 3 sets the optimization problem definition for economic evaluation; Section 4 describes the design procedures and simulation results; lastly, in Section 5 the conclusions are presented.

2 CONFIGURATION OF A CLUSTER OF DG SYSTEMS

With the increase of the distance from the centralized electric grid to some rural areas in many developing countries, the costs of the energy increases drastically to the degree that most of the remote users are weakly connected or totally disconnected from the main grid. In remote areas, the end users usually use fossil-fuel based generation units such as diesel. However, the polluting effect as well as the high cost of transportation of the fuel is creating more negative impacts [11]. A cure to these problems could be in a form of a cluster of DG systems forming a virtual utility that uses the available natural resources in the specified area. They can operate in a hybrid configuration with conventional diesel generators to reduce the amount and the cost of the fossil fuel used. For many technical benefits, the series DC based cluster of DG systems is widely used. This configuration is built by connecting all of the DG systems to a unified DC bus.

For systems having grid access; the grid would be treated as a virtual inertia back up to the cluster of DG systems [12]. Whether the DG cluster that forms the virtual utility operates in grid connected mode or in a standalone mode, the techno-economic evaluation of the cluster energy resources for its feasibility is essential if the system has to operate properly. The next section provides the description of the optimization problem definition used for techno-economic evaluation.

3 OPTIMIZATION PROBLEM DEFINITION

The optimization objective function usually utilized is the minimization of the Net Present Cost (NPC) of the investment of a cluster of DG systems [6]-[11]. The total NPC sums all the costs and profits within the project operating time into one monetary lump sum, with future cash flows to the present using the discount rate specified by the project manager [1]. The NPC includes the initial costs such as the installation and fuel costs, the cost of the consumed power from the main grid, and other costs such as emissions' fines. Profits include income from selling excess energy to the main utility, plus any saving value that occurs at the end of the project operating time [4].

For each component of the cluster of DG systems, the project manager is required to designate the following costs [13], [14]:

- The primary investment cost (at the starting year of the virtual utility project).
- The component's replacement cost.
- The operation & maintenance cost (for each year of the project running period).

The saving's amount of each component of the cluster of DG systems by the end of the running period of the project is calculated as [5]:

$$S_a = C_{rep} \frac{R_{rem}}{R_{comp}} \qquad (1)$$

Where:

S_a is the saving's amount (Money unit),
C_{rep} is component's replacement cost (Money unit),
R_{rem} is the remaining life of the component (years),
R_{comp} is the lifetime of the component (years).

By the end of each year of the project running period, the mentioned costs and the saving's amount would produce a net present cost (NPC) equal to all the costs and incomes related to each cluster's component over the project running period. The following equation is used to calculate the total NPC [4]:

$$C_{NPC} = \frac{C_{ann,tot}}{CRF(i, R_{proj})} \qquad (2)$$

Where:

$C_{ann,tot}$ is the total annualized cost (Money unit),
i the annual the discount rate (%),
R_{proj} the project running period (years),

The capital recovery factor (CRF), given by the equation [4]:

$$CRF(i, Ny) = \frac{i\,(1+i)^N}{(1+i)^N - 1} \qquad (3)$$

Where:

N_y is the number of years.

4 MODELING AND SIMULATION USING HOMER

In this section HOMER is applied for the economical evaluation of a cluster of DG systems forming the virtual utility supplying a remote load.

4.1 METHOD

The procedures of modeling and simulation using HOMER are shown in the flowchart Fig. 1. This paper proposes a cluster of DG systems with available resources of PV systems, small wind turbines, and hydrogen fuel cell system. The PV and wind systems are intermittent, while the fuel cell system depends on the availability and price of the hydrogen fuel. The cluster of DG systems could be composed of all or some of these sources based on economic feasibility studies. The DG cluster model is built in HOMER is shown in Fig. 2.

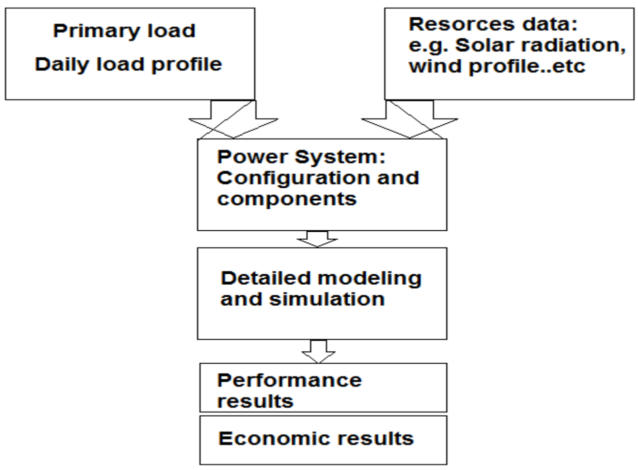

Fig. 1. Modeling and simulation using HOMER

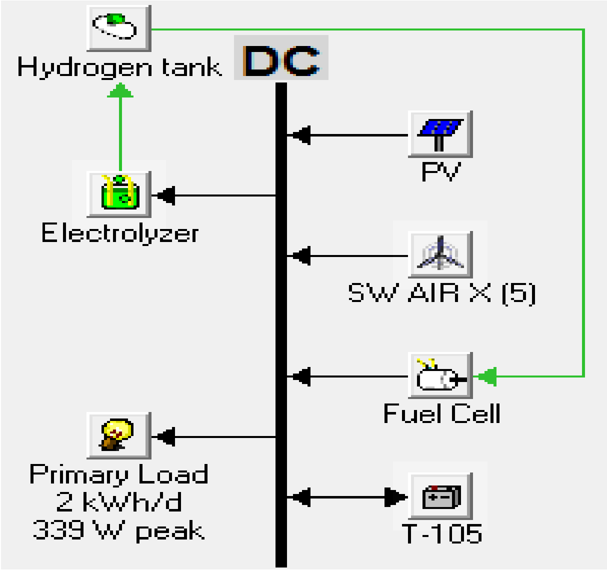

Fig. 2. The DG cluster model built in HOMER

4.2 SYSTEM DATA

The load is modeled by a primary load block in HOMER with the daily load profile presented in Fig. 3. The two peak periods in this load profile occur in the hours from 5:00 to 7:00 and from 17:00 to 19:00.

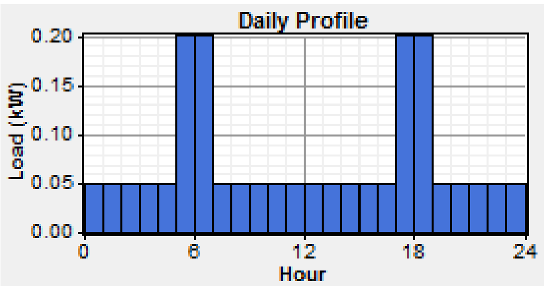

Fig. 3. Daily load profile of the load

The load scaled data are power and energy data are provided in Table 1. To create scaled data, each of the 8760 baseline values of the load profile are multiplied by a common factor that results in an annual average value equal to the value that is specified in scaled annual average [15].

Table 1 load scaled data

Scaled load data	
Average (kWh/day)	2
Average (kW)	0.0833
Peak(kW)	0.399
Load factor	0.246

The data of the available DG and storage technology options (including Hydrogen generator and tank) are as shown in Table 2. The cost curves of the cluster of the DG systems are shown in Fig. 4. The sizes and quantities to consider for each DG and storage option are as shown in Table 3.

Table 2 Possible DG and storage options

DG and Storage available options	Costs			Lifetime
	Capital ($)	Replacement ($)	O&M ($/yr)	
PV (for 1 kW size)	6000	5000	0	20 years
Wind (for one wind energy generator of 0.55 kW DC rated power)	1500	1300	25	15 years
Fuel cell (for 1 kW size)	3000	2700	0.02	40000 hours
Hydrogen generation Electrolyzer (for 1 kW)	2000	1800	30	25 years
Hydrogen tank (for 1 kg)	1300	1200	10	25 years
Battery storage (for one battery of 6V, 225 Ah, 1.35 kW)	120	120	1.5	Throughput of 845 kWh

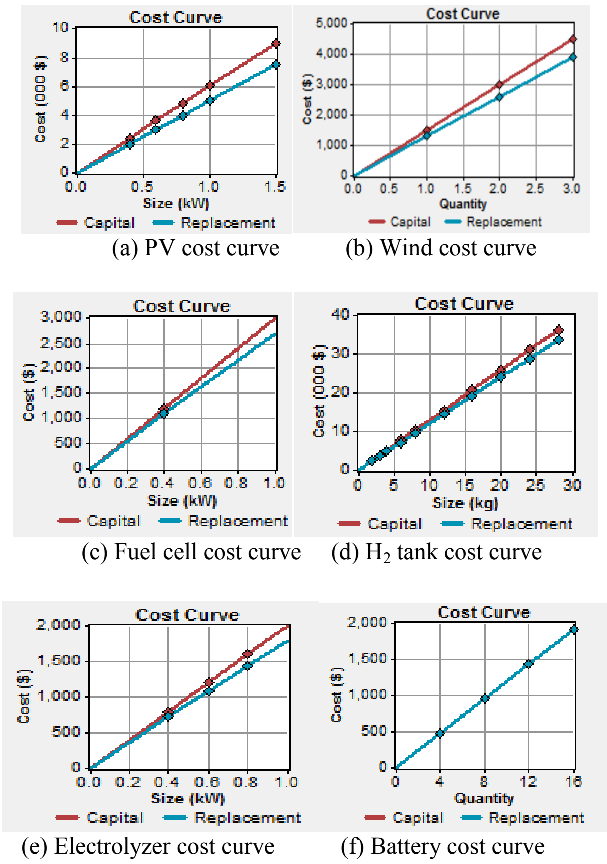

Fig. 4. Cost curves of the possible DG and storage options

Table 3 Possible sizes and quantities of DG and storage options for the telecom load case

PV (size kW)	Wind (units)	Fuel cell (size kW)	Hydrogen generation Electrolyzer (size kW)	Hydrogen tank (size kg)	Battery (units)
0	0	0	0	0	0
0.4	1	0.4	0.4	2	4
0.6	2		0.6	3	8
0.8	3		0.8	4	12
1				6	16
1.5				8	
				12	
				16	
				20	
				24	
				28	
Total number of options = 6	Total number of options = 4	Total number of options = 2	Total number of options = 4	Total number of options = 11	Total number of options = 5

A sensitivity analysis is a "*technique used to determine how different values of an independent variable impact a particular dependent variable under a given set of assumptions*" [16]. Sensitivity analysis is performed on the following independent variables (see Table 4):

- The wind speed (m/s).
- The cost multipliers of:
    1. Fuel cell capital & replacement costs.
    2. Electrolyzer capital & replacement costs.
    3. Hydrogen storage tank capital and replacement costs.

Table 4 Sensitivity analysis values for the specified independent variables shown in HOMER

	Wind (m/s)	FC Cap. (Mult.)	FC Rep. (Mult.)	Elec. Cap. (Mult.)	Elec. Rep. (Mult.)	H2 Tank. Cap. (Mult.)	H2 Tank. Rep. (Mult.)
1	3	1	1	1	1	1	1
2	4	0.75	0.75	0.75	0.75	0.75	0.75
3	5	0.5	0.5	0.5	0.5	0.5	0.5
4	6	0.25	0.25	0.25	0.25	0.25	0.25
5	7	0	0	0	0	0	0
6	8						

As mentioned earlier, the solar and wind energy resources are intermittent; therefore their variation has to be provided for accurate calculation of the optimum cluster. The average wind speed (m/s) for each month and the average daily solar radiation (kWh/m^2/day) for each month, for a specified location is as in Fig.5 and Fig.6 respectively.

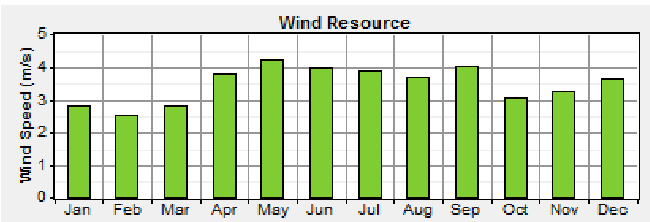

Fig. 5. Average wind speed (m/s) profile

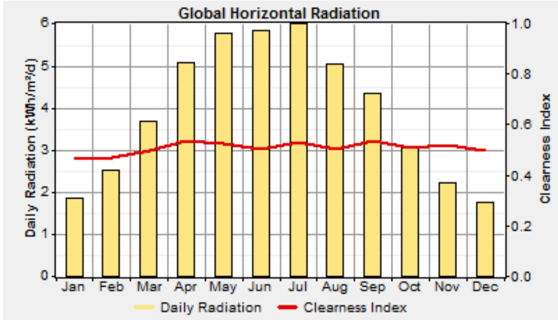

Fig. 6. Average daily solar radiation (kWh/m^2/day) profile

4.3 Simulations and Results

For each hour, comparison is performed between the load needs, and the energy that the cluster of DG systems can supply. The simulations are performed for all possible arrangements with the cluster's DG and storage systems. The simulation decides the following:

1. The feasibility of the chosen cluster.
2. The total cost of the installation and operation of the chosen cluster over the required running period.

When one or more of the intermittent DG systems are assisted with an hour-to-hour energy storage and a backup power source (in this case study a fuel cell is used), some unique dispatch options are required. As used here, the term "dispatch" refers to the control strategy that manages the energy flows among the major components of the cluster [17]. In HOMER, two dispatch strategies can be implemented, namely [15]:

1. Load following.
2. Cycle charging.

While the simulation process models a particular system arrangement, the optimization process decides the optimum system cluster, which is the one that fulfills the required constraints at the lowest total NPC. Decision variables that could be considered are:

- The PV size
- The fuel cell size
- The number of wind turbines
- The number of batteries

From Table 4, if the independent variables chosen are a wind speed of 3 m/s, and a cost multiplier of one for the fuel cell costs, the optimization results from HOMER are shown in Table 5. The arrow points to the optimum cluster with the lowest total NPC. The cluster is composed 0.8 kW PV system, and 12 T-105 batteries.

Table 5 optimization results (wind speed = 3 m/s)

PV (kW)	AIR	FC (kW)	T-105	Elec. (kW)	H2 Tank (kg)	Disp. Strgy	Initial Capital	Operating Cost ($/yr)	Total NPC	Ren. Frac.	Capacity Shortage	FC (hrs)
0.8			12			CC	$ 10,210	396	$ 15,269	1.00	0.00	
0.8	1		8			CC	$ 11,230	421	$ 16,612	1.00	0.00	
0.8		0.4	12	0.4		CC	$ 12,210	389	$ 17,178	1.00	0.00	0
0.8	1	0.4	8	0.4		CC	$ 13,230	414	$ 18,520	1.00	0.00	0
1.5		0.4		0.6	2	LF	$ 17,970	507	$ 24,446	0.83	0.00	5,225
1.0	1	0.4		0.6	3	LF	$ 17,770	550	$ 24,796	0.79	0.00	5,232
	3	0.4	4	0.6	20	LF	$ 37,350	789	$ 47,431	0.57	0.01	4,352
	3	0.4		0.4	28	LF	$ 46,870	949	$ 59,006	0.48	0.00	7,789

Under new assumptions for the wind speed to be 5 m/s, the optimization results are shown in Table. 6. The arrow points to the optimum cluster with the lowest total NPC. The cluster is composed on 0.4 kW PV system, one wind turbine and 12 batteries.

Table 6 optimization results (wind speed = 5 m/s)

PV (kW)	AIR	FC (kW)	T-105	Elec. (kW)	H2 Tank (kg)	Disp. Strgy	Initial Capital	Operating Cost ($/yr)	Total NPC	Ren. Frac.	Capacity Shortage	FC (hrs)
0.4	1		12			CC	$ 9,310	434	$ 14,856	1.00	0.01	
0.8			12			CC	$ 10,210	396	$ 15,269	1.00	0.00	
0.4	1	0.4	12	0.4		CC	$ 11,310	427	$ 16,764	1.00	0.01	0
0.8		0.4	12	0.4		CC	$ 12,210	389	$ 17,178	1.00	0.00	0
	3		16			CC	$ 10,390	566	$ 17,623	1.00	0.00	
	2	0.4	12	0.4	2	LF	$ 13,010	495	$ 19,335	0.93	0.01	517
0.4	2	0.4		0.6	2	LF	$ 14,370	550	$ 21,399	0.85	0.01	4,768
	3	0.4		0.4	4	LF	$ 15,670	643	$ 23,891	0.84	0.01	5,911
1.5		0.4		0.6	2	LF	$ 17,970	507	$ 24,446	0.83	0.00	5,225

The comparison between the optimization results at two different wind speeds shows the effect of this sensitive value on the optimum cluster cost and configuration.

4.4 Sensitivity Analysis for Different Wind Speeds and Fuel Cost Multipliers

The sensitivity analysis on hourly data sets is performed considering different wind speeds in the range between 3 and 8 m/s, and fuel cell cost multiplier from 0 up to 1, as shown in Fig. 7.

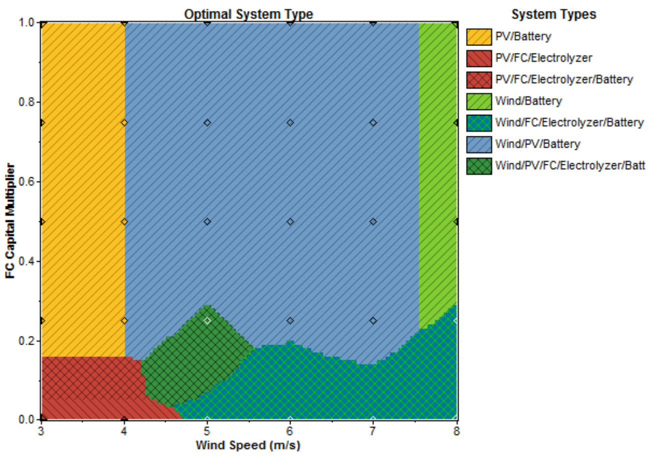

Fig. 7. the optimal system graph with sensitivity variables

The diamonds in the graph indicate the sensitivity cases, and the color of each diamond indicates the optimal system type for that sensitivity case. To specify the optimum system components between the diamond points, a two dimensional linear interpolation is used. For example, at a FC cost multiplier of 0.13 and an average wind speed of 4 m/s, the optimal system type is PV–FC-Electrolyzer–battery. For low wind speed less than 5 m/s, and a low cost of hydrogen with cost multiplier less than 0.5, the battery storage system is not used. Otherwise, for other cases the battery storage is recommended.

1 Conclusions

This paper explained the concept of virtual utility in modern smart grids. The energy management with in a virtual utility requires the calculation of the optimum cluster of distributed generation and storage systems. The optimum solution is achieved through an optimization process of the Net Present Cost (NPC) objective function. The sensitivity analysis is also performed to determine how the optimization results vary with changes of inputs to different DG units. For the studied example, optimization and sensitivity analysis are produced using the HOMER software.

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