Optimal Design of Arafat Electrical Microgrid During Hajj Season Considering Renewable Energy Sources

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Abstract

Increase in energy demand is one of the major challenges that utilities are faced with, which results in increase in environmental pollution and global warming. Also, one of the main goal of Saudi Arabia vision 2030 is to achieve environmental sustainability, therefore, the Government of Saudi Arabia has chalked out a path to move toward a green energy economy, aimed towards increased penetration of renewable energy sources. In this paper the optimal design of Arafat electric demand with the goal of minimizing the lifecycle cost, while taking into account environmental emissions, is presented. Different energy sources of renewable energy technology are considered, with realistic inputs on their physical, operating and economic characteristics. In another study, the Arafat microgrid is assumed to be connected to the main electric grid as a smart energy hub. The real data of Arafat demand during Hajj season is used. Analysis is also carried out to compare the economics of a grid-connected with an isolated microgrid. The planning of microgrid, considering renewable energy sources, requires the definition of several factors, such as: the best sources of renewable energy to be used, the number and capacity of these generation sources, the total system cost, the amount of emissions that can be saved, the distance from the nearest grid connecting point. In addition, in many countries governments strongly encourage the planners of microgrids to be motivated towards investment in the renewable energy sector. In this paper, all of the above factors, as well as their effect on the proposed system, are examined.

Introduction

With the price of oil is being increased and the costs of transmission line expansion rapidly increasing, combined with the desire to reduce carbon dioxide emissions, renewable energy has become an important alternative as a power provider in rural systems [1]. The cost of energy from conventional sources is less than that from renewable energy sources, but a supply-mix of renewable energy and diesel can reduce the cost of energy.

Energy demands are increasing rapidly, requiring energy resources to meet these demands, resulting in an exponential increase in environmental pollution and global warming [2,3]. On the other hand, these days' renewable energy, which is clean and limitless sources of energy, is catching the attention of energy developers. However, the estimation of the correct type of renewable energy system needs to be done under optimizations technique. In addition, for remote, rural isolated power systems, *i.e.*

Arafat microgrid, renewable energy sources are being increasingly recognized as cost-effective generation sources. In isolated areas, the high cost of transmission lines and higher transmission losses are encouraging the use of green sources of energy [4]. Combining two or more renewable energy sources, such as solar, wind, hydro, diesel, etc., together gives a stable energy supply in comparison to non-renewable energy systems .

The main objectives of this paper can be outlined as follows:

- Optimal design and planning of a renewable energy based microgrid of Arafat considering various renewable energy technology options and with realistic inputs on their physical, operating and economic characteristics.

- Compare the overall benefits from the optimally designed renewable energy based microgrid with existing microgrid configurations of Arafat.

The Mathematical Model

The mathematical models used herein for the different system configurations are available in HOMER [5]. The model inputs are the Arafat load demand, the solar energy availability profile of the region, and the cost and size data of all system components considered. The software then considers different dispatch strategies that yield the minimum project cost for each Arafat microgrid configuration. The optimal design is determined by minimizing the total net present cost (NPC) comprising the capital cost, replacement cost, operation and maintenance (O&M) cost, fuel consumption cost, and cost of purchased power from the grid.

The objective of minimization of the total NPC is given as follows:

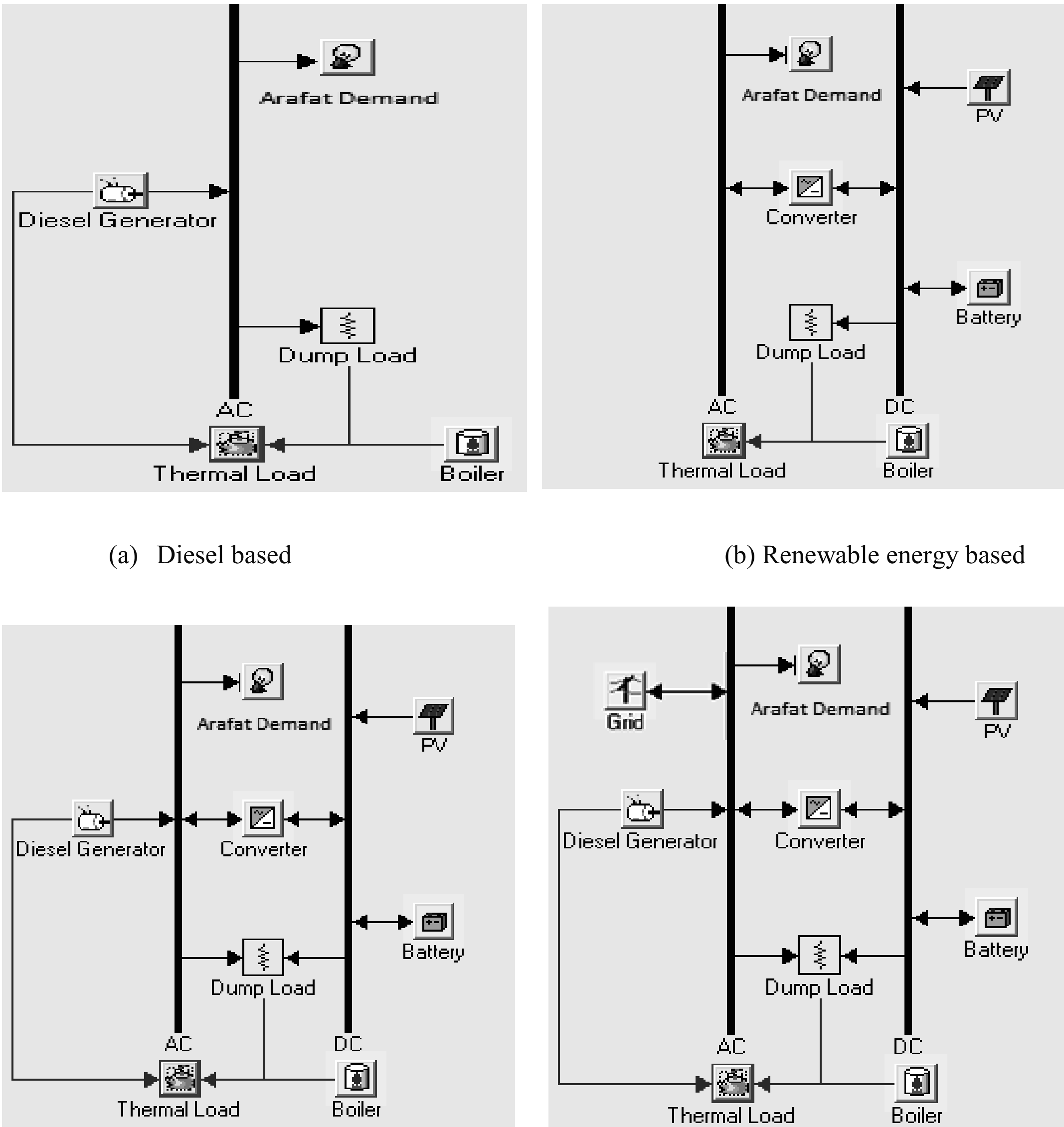
$$TNPC = \sum_{\in x} AC_x \times PWF(i, N) \qquad (1)$$

where the total NPC of the Arafat microgrid is the total present value of all the component costs, and the present worth factor (PWF) is given as follows:

$$PWF_{(i,N)} = \frac{(1+i)^N - 1}{i(1+i)^N} \qquad (2)$$

System under Consideration:

Diesel generation (Base Case), Renewable energy technology option, and the option of Arafat microgrid being connected to the grid are considered to determine the optimal design of microgrid.



(a) Diesel based

(b) Renewable energy based

c) Diesel-renewable mixed

(d) Grid-connected Arafat microgrid

Figure 1: Available portfolio of energy supply options for Arafat microgrid

Input Data (Costs, Sizing and Other Parameters)

In Table 1 the capital cost, replacement cost and O&M cost of each supply option considered, are presented, while the different sizing options and other associated parameters are presented in Table 2.

Table 1

COST DATA OF ENERGY SUPPLY RESOURCES

Options	Capital Cost	Replacement Cost	O&M Cost
Solar	$7.50/W	$7.50/W	$10/year
Battery	$75/ Battery	$75/ Battery	$2/Battery /year
Converter	$1,000/kW	$1,000/kW	$100/year
Grid Extension	$20,000/km	$20,000/km	$10/year/km
Diesel Generator (4.25 kW)	$2,550	$2,550	$0.15/h

Table 2

DATA ON SIZING AND OTHERS PARAMETERS OF ENERGY SUPPLY RESOURCES

Options	Options on Size and Unit Numbers	Life	Other Information
Solar	1, 10, 50, 100, 150, 200, 300, 500 kW	20 yrs	De-rating factor = 90%
Battery	10, 50, 100, 200, 500, 1,000, 1,500	(Lifetime throughput)845 kWh	Nominal capacity 225 Ah
Converter	0, 10, 50, 100, 200, and 500 kW	15 yrs	Can parallel with AC generator. Converter Efficiency = 90% Rectifier Efficiency = 85%
Grid Connectio n	10, 25, 50, 100, 500, 1,000 kW	-	Purchase = $0.12/kWh Sellback = $0.39/kWh [2]
Diesel Generator	0 to 500 kW	500,000 h	Minimum load ratio = 30% Heat recovery ratio = 10%
Diesel Fuel	-	-	Price = $0.70/L Density of 820 kg/m^3 Carbon Content 88% Sulfur Content 0.33%

The hybrid optimization platform (HOMER):

The Hybrid Optimization platform (HOMER) is a simulation tool developed by the (U.S.) National Renewable Energy Laboratory (NREL) to assist in the planning and design of renewable energy based microgrids. The physical behavior of an energy supply system and its lifecycle cost, which is the sum of capital and operating costs over its lifespan, is modeled using HOMER [5]. Options such as distributed generation (DG) units, stand-alone, off-grid and grid-connected supply systems for remote areas, and other design options, can also be evaluated using HOMER [5]. HOMER is designed to overcome the challenges of analysis and design of microgrids, arising from the large number of design options and the uncertainty in key parameters, such as load growth and future fuel prices. Simulation, and optimization analysis, are the two principal tasks performed in HOMER and used in this work.

Where, on the aspect of simulation, HOMER determines the technical feasibility and lifecycle costs of a microgrid for each hour of the year. In addition, the microgrid configuration and the operation strategy of the supply components are tested to examine how these components work in a given setting over a period of time. The simulation capability of HOMER captures the long-term operation of a microgrid. The optimization component of HOMER depends on this simulation capability. In the optimization section, HOMER determines the feasible systems with their configurations under the search space defined by the user, sorted by the minimum total net present cost of the microgrid. After the simulation section determines the system configuration of a microgrid, the optimization section calculates and displays the optimal microgrid configuration. HOMER defines the optimal microgrid configuration, which is that configuration with the minimum total net present cost and meeting the modeler's constraints.

Results and Discussions:

In this section the different designs of Arafat microgrid are examined from the standpoint of economics, emissions, and operational performance. Four cases are considered as mentioned earlier, the isolated Arafat microgrid which is including (Base Case) diesel only, renewable energy sources only, diesel-renewable mix, and a grid-connected Arafat microgrid as a smart energy hub. The objective is to determine the optimal design of Arafat microgrid while minimizing the lifecycle cost, taking into account environmental emissions and considering various energy supply options .

In Case-1 the Arafat microgrid is assumed to be an isolated microgrid fed by diesel generators. However, diesel generator units are very expensive because of their high cost of maintenance, fuel supply, and fuel transportation. In addition, the diesel generators are emission intensive. Therefore, supplying the Arafat microgrid with solar PV and BESS sources is also examined in Case-2; Accordingly, the Arafat microgrid is assumed to be supplied by a mixed configuration comprising both diesel and solar PV sources in Case-3. In Case-4 it is assumed that the Arafat microgrid is grid-connected and has the option of drawing/selling-back energy from/to the external grid, while also having its own resources.

Optimal Design Configurations:

The optimal Arafat microgrid design for each case is obtained from HOMER simulations, and the optimal configurations are shown in Table 3.

Table 3: COMPARISON OF COST COMPONENTS

Component	Cases			
	Case-1	Case-2	Case-3	Case-4
Net Present Cost, M$	1.617	2.724	0.945	1.020
Levelized COE energy, $/kWh	1.075	1.816	0.625	0.675
O&M Cost, M$/year	0.118	0.031	0.043	0.071

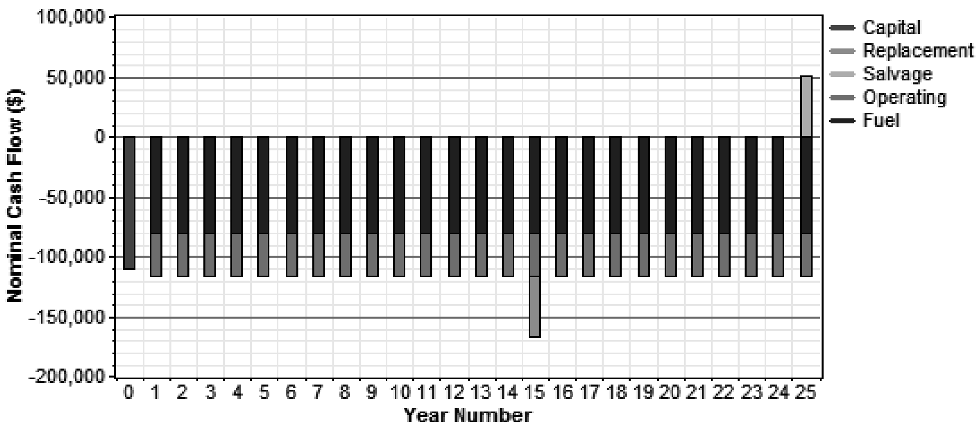
Table 3 shows the NPC, levelized COE, and the O&M costs for the different cases. It is noted that the NPC and the levelized COE are significantly low in Case-3 and Case-1 as compared with Case-2 and 4, and hence are the most favorable designs for isolated and grid-connected Arafat Microgrid. When the Arafat microgrid is based on solar and BESS only (Case-2), it is noted that the levelized

COE is significantly high because of the large capital cost component. Although in the diesel dependent microgrid the levelized COE is reduced, to 1.075 $/kWh and to 0.675 $/kWh in Case-4, and it is higher than the diesel-solar PV-BESS mix because of the significantly high cost of fuel in diesel based. It is also to be noted that in Case-4 there is a negative O&M cost, which pertains to the revenue earned by the operator of Arafat microgrid from selling power to external grid.

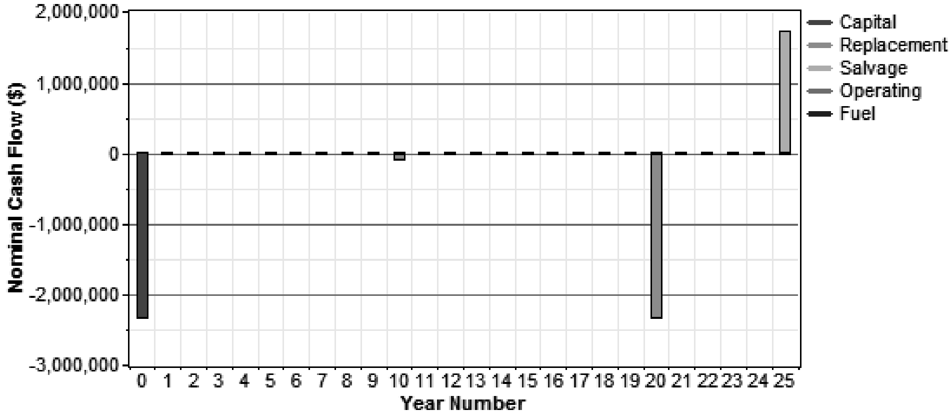
For the energy storage, the battery energy storage system (BESS) is used in this paper in order to fed the microgrid demand with the energy during the night period especially in Case-2, where the BESS is the only sources available during night. Moreover, for the long run of microgrid the energy storage can open the doors to clean energy solutions as indicated in [6]. Therefore, in this work, the combination of renewable energy and BESS is studied. Therefore, the proposed modeling framework is generic and demonstrates its effectiveness; any different configuration- including no BESS configuration, can be used, with its appropriate data and parameters to determine the least cost configuration (optimal design of Arafat microgrid). However, in case of short term operation of Arafat microgrid the BESS may be removed and there is no significant for include such technology, and this raises an important research issue, which will be taken up at the next stage.

Figure 2, presents the annual cash flows for the four cases, respectively. It is seen that in the diesel based Arafat Microgrid (Case-1), the diesel generator and converter incur a capital cost at the beginning of the project which are the renting of these equipment, while the system incurs a regular stream of fuel and O&M cost. However, in Case-2, the solar PV with BESS based Arafat grid only incurs an initial investment cost while the replacement cost is sporadically distributed over its lifetime and the other costs are negligible. In Case-3, the cash flow pattern is similar to Case-2 with an additional regular stream accounting for cost of fuel and O&M arising because of the presence of diesel generator .

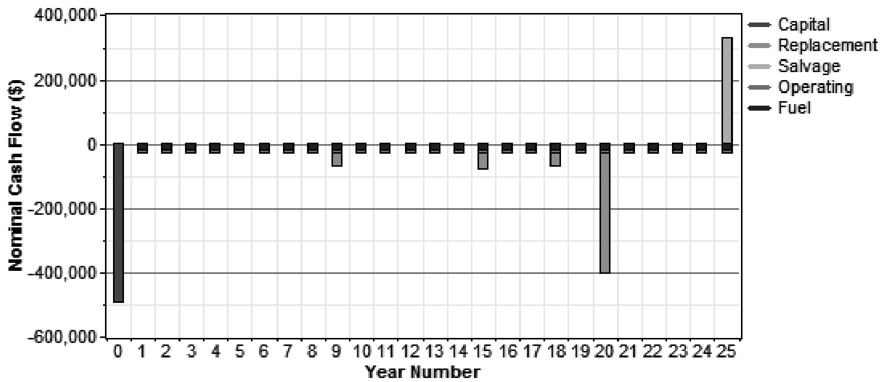
The annual cash flow of Case-4 is different because of the sellback power to the grid and associated revenue earnings by the operator of Arafat microgrid, the O&M cost is significantly reduced. Also, the system incurs a regular high stream of fuel and O&M cost as compared to Case-3, because of the significant increase in diesel generation capacity.



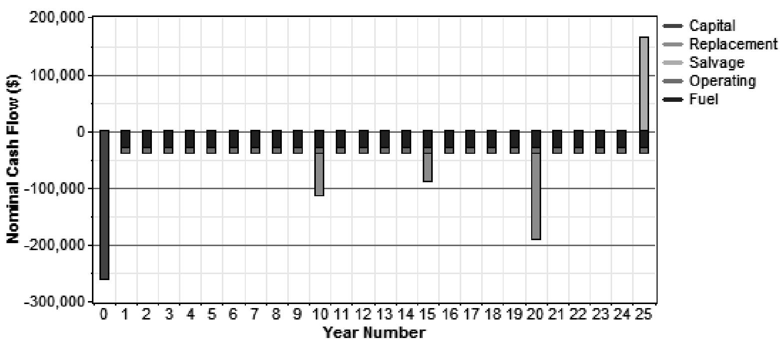
(a) Case-1 (Diesel based)



(b) Case-2 (Renewable energy based)



(c) Case-3 (Diesel-renewable mixed)



(d) Case-4 (Grid-connected Arafat microgrid)

Figure (2): Cash flow for all Cases

Summary:

This paper presented the optimal design and comparative studies for an isolated Arafat microgrid, and a grid connected Arafat microgrid as a smart energy hub configuration. Various supply options were included in this study such as diesel based, solar PV with BESS based and diesel-solar PV-BESS mix. Studies were carried out using the HOMER software which provides a very efficient tool for case studies and policy analysis. From the methodology, data, results, and discussion above, the following conclusions are drawn as follows:

Analysis revealed that if the Arafat grid operated as a smart energy hub with diesel-solar PV-BESS supply mix options, it was the most economically favorable option. The feasibility of isolated Arafat grid was studied in this work and from the analysis it was noted that the diesel-solar PV-BESS mix had the lowest NPC and a fairly small carbon footprint, when compared to a diesel-based Arafat grid. Although a fully renewable-based Arafat grid, which had no carbon footprint, was the most preferred, the NPC was higher . Although a solar PV with BESS-based Arafat grid had no carbon footprint, the NPC was higher and hence not selected However, if this case is calculated for the lifetime of the solar PV which are almost 20 years in most cases and the diesel generations capital cost as well as the emission cost are included that will defiantly will change the optimal design. Finally, it was noted that the solar PV with BESS based isolated Arafat grid could benefit the most by grid connectivity, followed by the diesel-based isolated Arafat grid, because of their high costs.

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