Chapter 7

Optimization of Hybrid Energy Efficiency in Electrical Power System Design

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Additional information is available at the end of the chapter

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1. Introduction

Evaluation of economic and technical feasibility of a large number of technology options, accountability for variations in technology costs and energy resource availability, could easily be carried out using the hybrid optimization model for electrical renewable (HOMER). A power system designer can use HOMER to provide an important overview that compares the cost and feasibility of different configurations and evaluate the technical performance of the power system [1]. A hybrid system is an electricity generation system, based on the integration of various energy sources (such as photo voltaics, wind turbines, small hydro power or diesel generators) [2]. Hybrid configurations can potentially deliver improved performance and better economic values for a given electrification situation [3].

Among the various energy modeling software available, the capabilities provided by the HOMER software is the best option for modeling and investigating various hybrid systems. The program first runs an hourly simulation of all possible configurations of system types. Due to the speed of processing these simulations, there is room for the evaluation of thousands of combinations. This hourly simulation also provides improved accuracy over statistical models that typically evaluate average monthly performance of a system. HOMER also models the partial load efficiency of diesel generators. This more accurately simulates the lower efficiency of a generator when it is not operating at full capacity. When the simulations have be run, HOMER sorts the feasible cases in order of increasing net present (or lifecycle) cost. This cost is the present value of the initial, component replacement, operation, maintenance, and fuel costs. HOMER lists the optimal system configuration, defined as the one with the least net present cost, for each system type. The sensitivity analysis of HOMER then repeats this optimization as user-defined factors, such as fuel price, load size, reliability requirement, and resource quality [4, 5]. Furthermore, the HOMER analysis simplifies the task of evaluating designs of both off-grid and grid-connected power systems for a variety of applications. In designing a power system, many decisions about the configuration of the system are to be made: components to include in the system design, size of each component to use etc. The large number of technology options and the variation in technology costs and availability of energy resources make these decisions difficult [6].

In [6-8], the authors limited the use of the HOMER software to only the solar resources, while in [8, 9], an analysis was carried out proposing an optimization solution of a hybrid system of renewable energy by using the Homer software for remote areas. The Hybrid systems reported in these papers involve combination of different energy sources like wind/battery, PV/battery, wind/PV/battery, wind/PV /diesel/battery. However, various sizes of the system configurations were not taken into account and the focus was not on the best operating conditions and combination of the power systems, in terms of optimized energy efficiency. This chapter presents the use of HOMER software in the analysis of a power system comprising a wind turbine, solar photo voltaic, AC generator, converter, primary load and battery system. Various sizes of the sources were considered for all possible configurations of system types. The optimized energy efficiency based on the least net present cost was used as the basis for the selection of the best operating condition of the power system. Also, a further investigation was carried out considering two cases with two different load profiles to show that the load profiles affects the responses of the renewable energy system and the cash flow summary of some of the system equipments. In light of this, a wind turbine is integrated into the PV, battery, converter and AC diesel generator system.

2. System model considered

The model system used for this study is shown in Figure 1, where a primary load of 157kwh/d, 22kW peak is connected to the AC bus. The ENAIR 70 wind turbine type and a diesel generator (Keno) used in the study are connected to the AC bus. A converter system is in between the AC and DC bus, while the photo voltaic (PV) solar panel and battery H1500 are connected to the DC bus respectively. A brief detailed presentation of the model system parameters is given in subsequent section of this chapter. Table 1 shows some of the merits and limitations of using the HOMER software [10].

Merits	Limitations
Simulates a list of real technologies, as a catalogue of available technologies and components	Quality input data needed (sources)
Very detailed results for analysis and evaluation.	Detailed input data (and time) needed
Determines the possible combinations of a list of different technologies and its size.	An experienced criterion is needed to converge to the good solutions
It is fast to run many combinations.	HOMER will not guess key values or sizes if there are missed.

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Merits	Limitations
Results could be helpful to learn a system configuration and optimization.	Could be time consuming and onerous

Table 1. Merits and limitations of HOMER

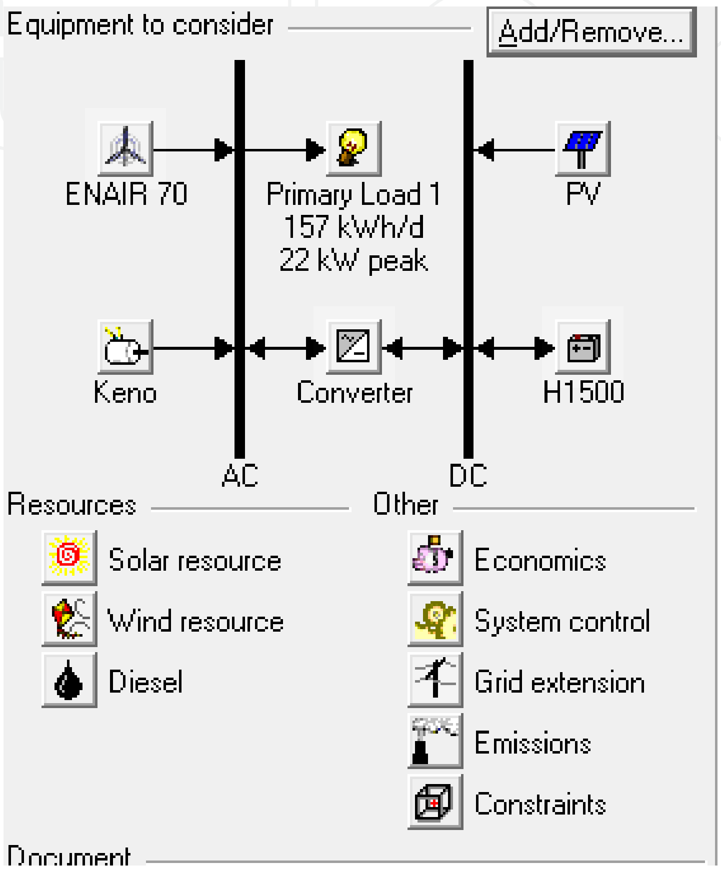

Figure 1. Model system

3. Inputs and assumptions of system model

AC load: Primary **load 1**

The load profile used for this study is shown in Figure 2, where there was a peak of 8.2kW at the early hours of the morning and dropped to 4kW until around 6am, where a slight peak of above 6kW was observed. Just before noon and after noon, the load profile slightly increased and decreased respectively and a gradual peak was observed in the evening between 6pm and about 11pm going as high as 13kW. A scaled annual average of 160, 147kWh/d, scaled peak load of 12.8, 11.7kW and a load factor of 0.522 was considered in this study as shown in Table 2.

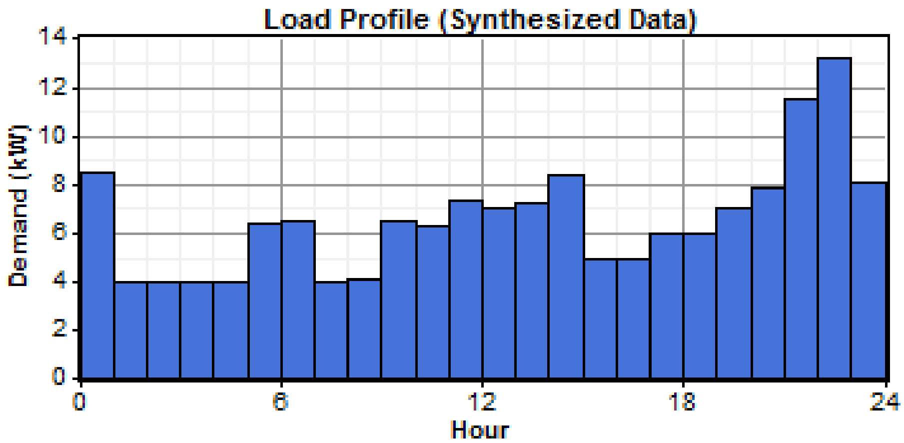

Figure 2. Load profile of study

AC Load: Primary Load 1

Data source:	Synthetic
Daily noise:	15%
Hourly noise:	20%
Scaled annual average:	157 kWh/d
Scaled peak load:	21.6 kW
Load factor:	0.303

Table 2. AC Load Parameters

PV

The detail of the PV system is shown in Table 3. A 20 year lifetime and derating factor of 80% were considered. The slopes were 14, 24 degs, with a ground reflectance of 20%.

PV

Size (kW)	Capital ($)	Replacement ($)	O&M ($/yr)
0.240	420	420	42

Sizes to consider:	21, 22, 23, 24, 25, 30, 40, 50 kW
Lifetime:	20 yr
Derating factor:	80%
Tracking system:	No Tracking
Slope:	14, 24 deg
Azimuth:	0 deg
Ground reflectance:	20%

Table 3. PV Parameters

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Solarresource

Table 4 shows the parameters of the solar resource, where the maximum average radiation occurred in the month of April. The scaled annual average is 6.04kWh/m^2/day.

Solar Resource

Latitude: 14 degrees 0 minutes North
Longitude: 23 degrees 0 minutes West
Time zone: GMT -1:00

Data source: Synthetic

Month	Clearness Index	Average Radiation (kWh/m^2/day)
Jan	0.611	5.100
Feb	0.632	5.790
Mar	0.670	6.720
Apr	0.668	7.050
May	0.660	7.030
Jun	0.622	6.590
Jul	0.598	6.330
Aug	0.587	6.180
Sep	0.590	5.990
Oct	0.608	5.700
Nov	0.609	5.180
Dec	0.598	4.820

Scaled annual average: 6.04 kWh/m²/d

Table 4. Solar Resource Parameters

The daily radiation and clearness index of the solar resource is shown in Figure 4.

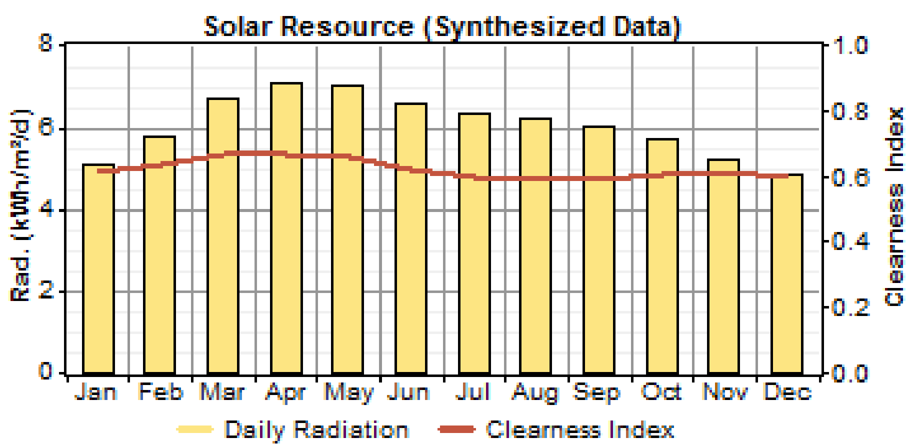

Figure 3. Solar resource radiation and clearness index

AC wind turbine: ENAIR70

ENAIR wind turbine with different quantities and hub height of 15m was used in this study. The details and power curve of the wind turbine are shown in Table 5 and Figure 4 respectively.

AC Wind Turbine: ENAIR 70

Quantity	Capital ($)	Replacement ($)	O&M ($/yr)
1	16,000	16,000	160

Quantities to consider:	1, 2, 3
Lifetime:	15 yr
Hub height:	15 m

Table 5. Details AC Wind Turbine

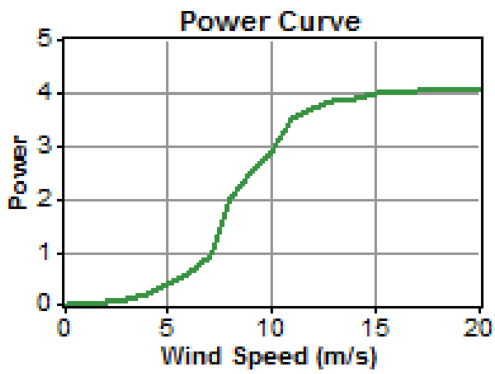

Figure 4. Power Curve of ENAIR 70 Wind Turbines

Windresource

The wind resource data used for this study is shown in Tables 6 and 7, with the peak wind speed occurring in January, while the least wind speed in August, while a plot of the wind speed for the various months is shown in Figure 5.

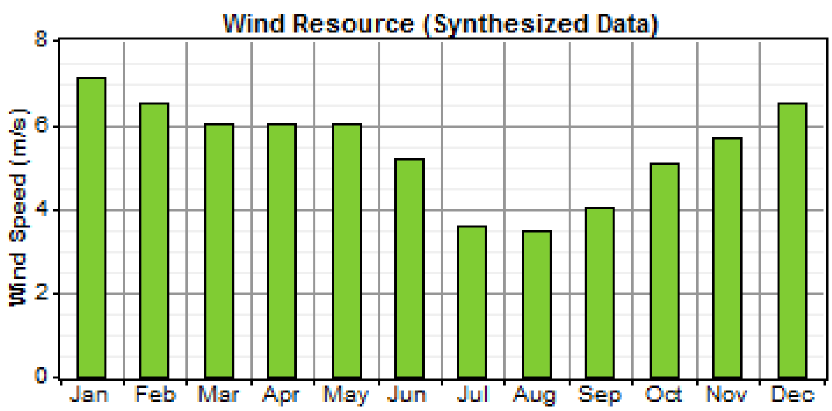

Figure 5. Wind Resource

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Wind Resource

Data source: Synthetic

Month	Wind Speed (m/s)
Jan	7.1
Feb	6.5
Mar	6.0
Apr	6.0
May	6.0
Jun	5.2
Jul	3.6
Aug	3.5
Sep	4.0
Oct	5.1
Nov	5.7
Dec	6.5

Table 6. Wind speed distribution

Weibull k:	2.00
Autocorrelation factor:	0.850
Diurnal pattern strength:	0.250
Hour of peak wind speed:	15
Scaled annual average:	5.43 m/s
Anemometer height:	10 m
Altitude:	0 m
Wind shear profile:	Logarithmic
Surface roughness length:	0.01 m

Table 7. Details of Wind Resource

ACgenerator:Keno

The details of the AC generator details are given in Table 8, while its efficiency is shown in the simulation results.

AC Generator: Keno

Size (kW)	Capital ($)	Replacement ($)	O&M ($/hr)
36.000	6,000	6,000	2.000

Sizes to consider:	36 kW
Lifetime:	15,000 hrs
Min. load ratio:	30%
Heat recovery ratio:	0%
Fuel used:	Diesel
Fuel curve intercept:	0.08 L/hr/kW
Fuel curve slope:	0.25 L/hr/kW

Table 8. Details of AC Generator

Fuel:Diesel

The fuel details are shown in Table 9.

Fuel: Diesel

Price:	$ 1.6/L
Consumption limit:	5,000 L
Lower heating value:	43.2 MJ/kg
Density:	820 kg/m3
Carbon content:	88.0%
Sulfur content:	0.330%

Table 9. Details Fuel Type

Battery:Hoppecke12OPzS 1500

The Hoppecke 12 OPzS 1500 battery parameters used are shown in Table 10. A battery spring of 24 was considered in the study.

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Battery: Hoppecke 12 OPzS 1500

Quantity	Capital ($)	Replacement ($)	O&M ($/yr)
1	1,369	1,369	50.00

Quantities to consider:	1, 2
Voltage:	2 V
Nominal capacity:	1,500 Ah
Lifetime throughput:	5,136 kWh

Table 10. Battery Parameters

Converter

Table 11 shows the parameters of the converter system.

Converter

Size (kW)	Capital ($)	Replacement ($)	O&M ($/yr)
15.000	5,975	5,975	50

Sizes to consider:	15 kW
Lifetime:	15 yr
Inverter efficiency:	90%
Inverter can parallel with AC generator:	Yes
Rectifier relative capacity:	100%
Rectifier efficiency:	85%

Table 11. Converter Parameters

4. Grid extension/ economics/generator control

A grid extension was compared to stand alone system to know if it is cheaper to use the grid or the stand alone system. Details of the grid extension, economics of the system and generator control are shown in Table 12.

Grid Extension

Capital cost:	$ 15,000/km
O&M cost:	$ 160/yr/km
Power price:	$ 0.134/kWh

Economics

Annual real interest rate:	6%
Project lifetime:	20 yr
Capacity shortage penalty:	$ 0/kWh
System fixed capital cost:	$ 0
System fixed O&M cost:	$ 0/yr

Generator control

Check load following:	No
Check cycle charging:	Yes
Setpoint state of charge:	80%

Allow systems with multiple generators:	Yes
Allow multiple generators to operate simultaneously:	Yes
Allow systems with generator capacity less than peak load:	Yes

Table 12. Grid Extension/Economics/Generator Control Parameters

5. Emissions/Constraints

The emissions and constraints in running the system are described in Table 13. It would be discovered that the emissions are zero due to the renewable energy level of operation.

Emissions

Carbon dioxide penalty:	$ 0/t
Carbon monoxide penalty:	$ 0/t
Unburned hydrocarbons penalty:	$ 0/t
Particulate matter penalty:	$ 0/t
Sulfur dioxide penalty:	$ 0/t
Nitrogen oxides penalty:	$ 0/t

Constraints

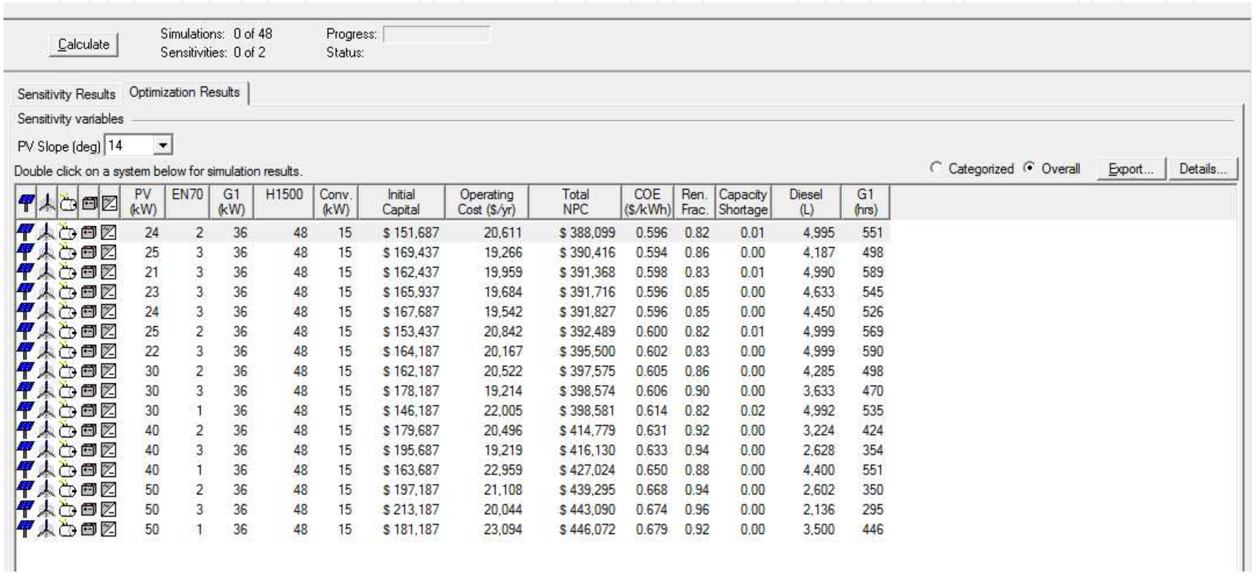
Maximum annual capacity shortage:	2%
Minimum renewable fraction:	0%

Operating reserve as percentage of hourly load:	10%
Operating reserve as percentage of peak load:	0%
Operating reserve as percentage of solar power output:	25%
Operating reserve as percentage of wind power output:	50%

Table 13. Emissions and Constraints of the System

6. Simulation results and analysis

Simulations were run in the HOMER software for various configuration system types of the power system, in order to obtain the most efficient system configuration that would give the lowest net present cost to determine the basis of energy efficiency. Figure 6 shows all the possible configurations and results that can be obtained using the various power sources.



PV (kW)	EN70	G1 (kW)	H1500	Conv. (kW)	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Capacity Shortage	Diesel (L)	G1 (hrs)
24	2	36	48	15	$ 151,687	20,611	$ 388,099	0.596	0.82	0.01	4,995	551
25	3	36	48	15	$ 169,437	19,266	$ 390,416	0.594	0.86	0.00	4,187	498
21	3	36	48	15	$ 162,437	19,959	$ 391,368	0.598	0.83	0.01	4,990	589
23	3	36	48	15	$ 165,937	19,684	$ 391,716	0.596	0.85	0.00	4,633	545
24	3	36	48	15	$ 167,687	19,542	$ 391,827	0.596	0.85	0.00	4,450	526
25	2	36	48	15	$ 153,437	20,842	$ 392,489	0.600	0.82	0.01	4,999	569
22	3	36	48	15	$ 164,187	20,167	$ 395,500	0.602	0.83	0.00	4,999	590
30	2	36	48	15	$ 162,187	20,522	$ 397,575	0.605	0.86	0.00	4,285	498
30	3	36	48	15	$ 178,187	19,214	$ 398,574	0.606	0.90	0.00	3,633	470
30	1	36	48	15	$ 146,187	22,005	$ 398,581	0.614	0.82	0.02	4,992	535
40	2	36	48	15	$ 179,687	20,496	$ 414,779	0.631	0.92	0.00	3,224	424
40	3	36	48	15	$ 195,687	19,219	$ 416,130	0.633	0.94	0.00	2,628	354
40	1	36	48	15	$ 163,687	22,959	$ 427,024	0.650	0.88	0.00	4,400	551
50	2	36	48	15	$ 197,187	21,108	$ 439,295	0.668	0.94	0.00	2,602	350
50	3	36	48	15	$ 213,187	20,044	$ 443,090	0.674	0.96	0.00	2,136	295
50	1	36	48	15	$ 181,187	23,094	$ 446,072	0.679	0.92	0.00	3,500	446

Figure 6. Display of all Possible System Configuration

From Figure 6, HOMER has been able to optimize the energy efficiency of the system using various conditions, by displaying the results from the most cost effective system to the least cost effective configuration. The best solution obviously is the first array, where the most effective system of the solar panel, wind turbine, ac generator, battery and converter configuration, would use 24kW PV system, 2 wind turbines, 36kW AC generator, 48 H1500 battery system, and 15kW converter system. The initial cost of the optimized system is $151,687, with an operating cost per year of $20,611, giving a total net present cost (NPC) of $388,099 and cost of energy per kWh of 0.596 and renewable fraction of 0.82.

6.1. Details of optimized results

From Figure 6, the details of the optimized results are shown in Figures 7 to 20.

Figure 7 shows the cash flows for the system. The negative values indicate expenditures, while the positive value is the salvage value of the system in the expected life of the project. The battery state of charge is shown in the frequency histogram in Figure 8, while Figures 9 and 10 show the battery bank state of charge on an hourly basis for the various months of operation. The AC generator output is shown in Figure 11 in the course of operation, while Figure 12 displays its response of efficiency.

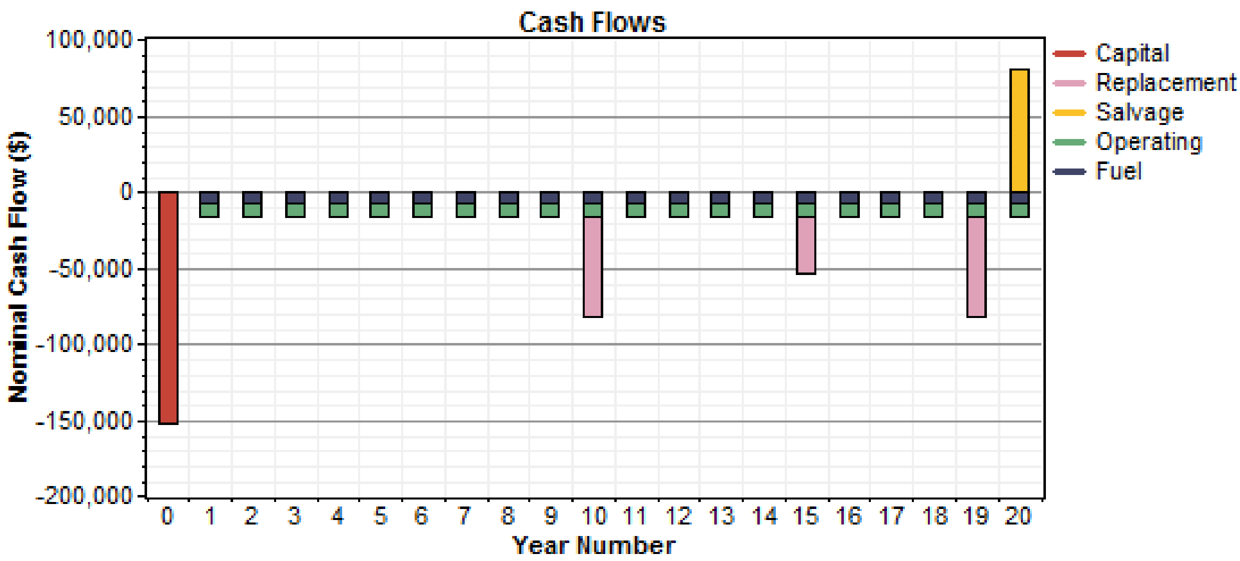


Figure 7. Cash flows

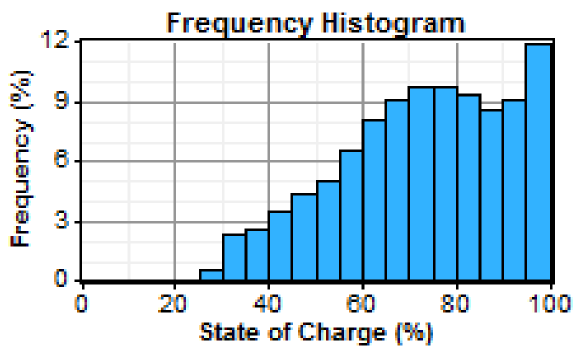


Figure 8. Battery state of charge

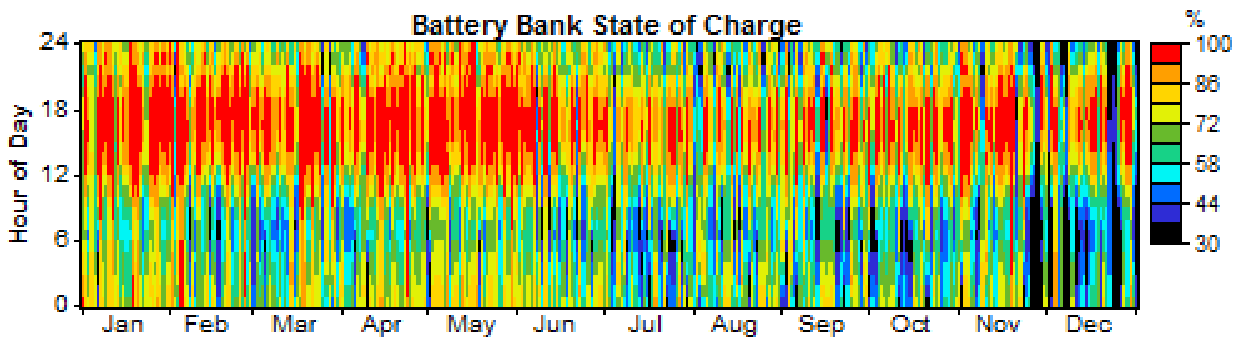


Figure 9. Battery bank SOC

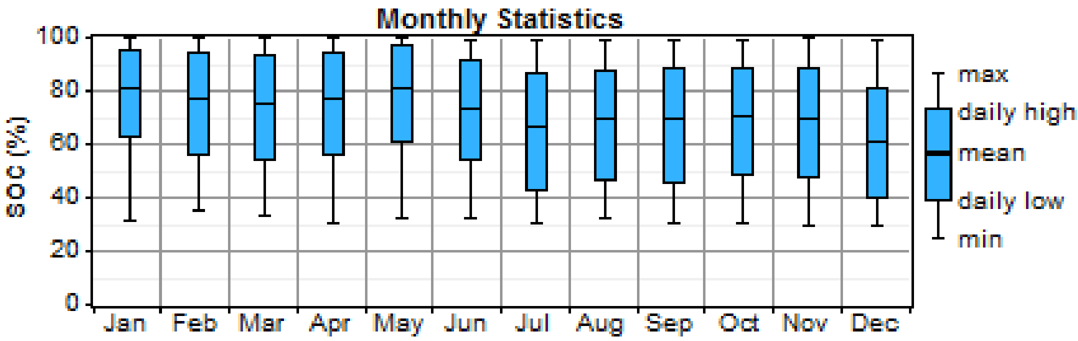


Figure 10. SOC monthly statistics

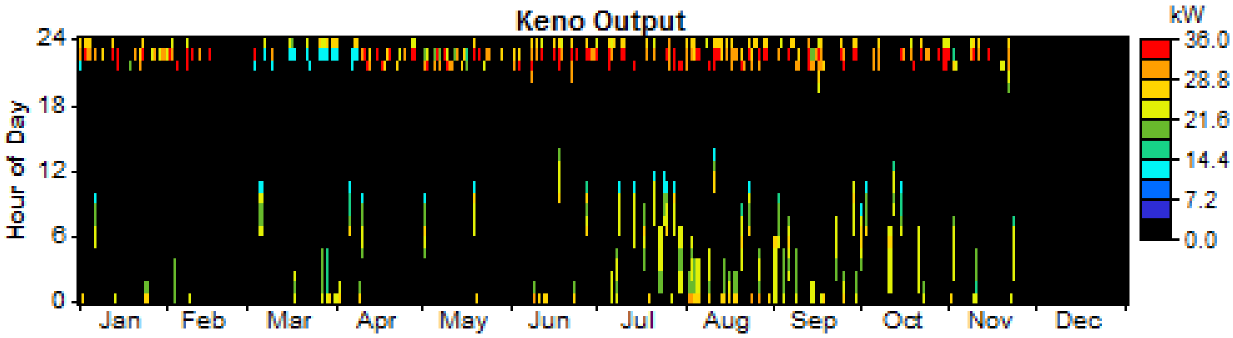


Figure 11. Generator Output

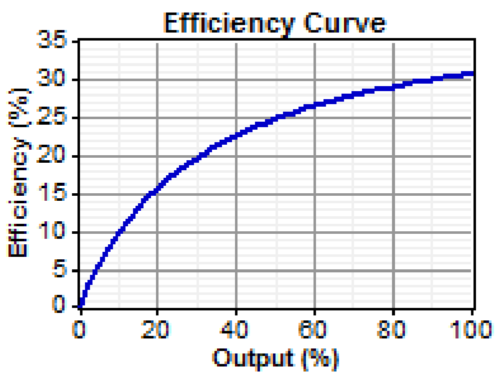


Figure 12. Efficiency curve of the generator

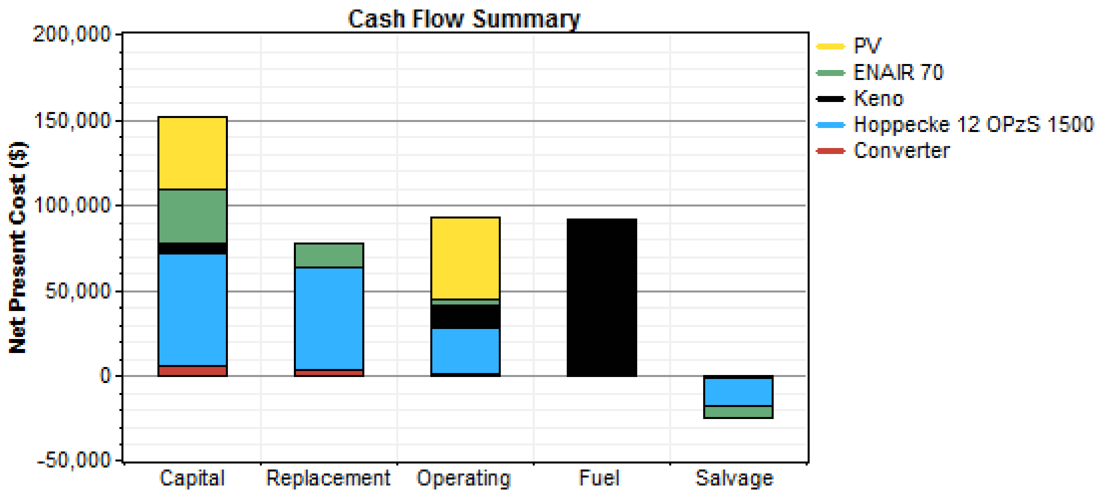


Figure 13. Cash flow summary

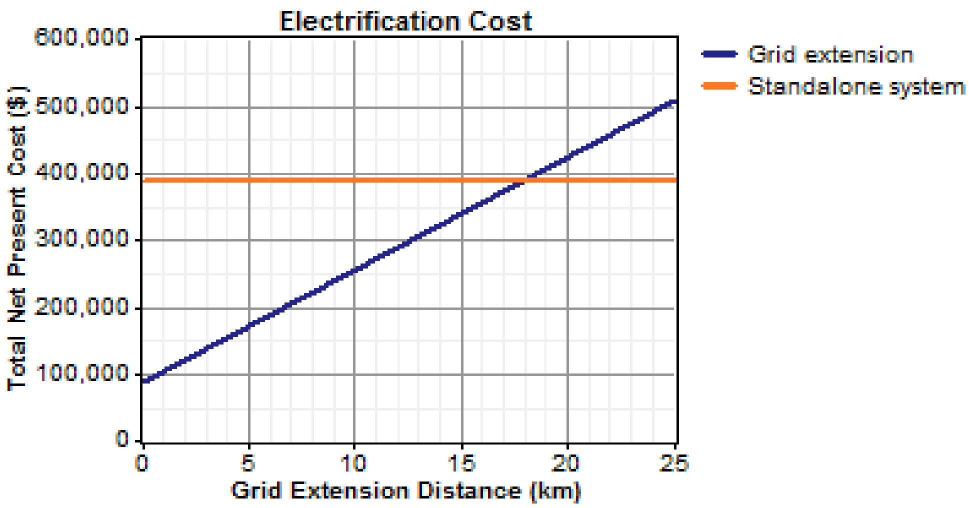


Figure 14. Grid system

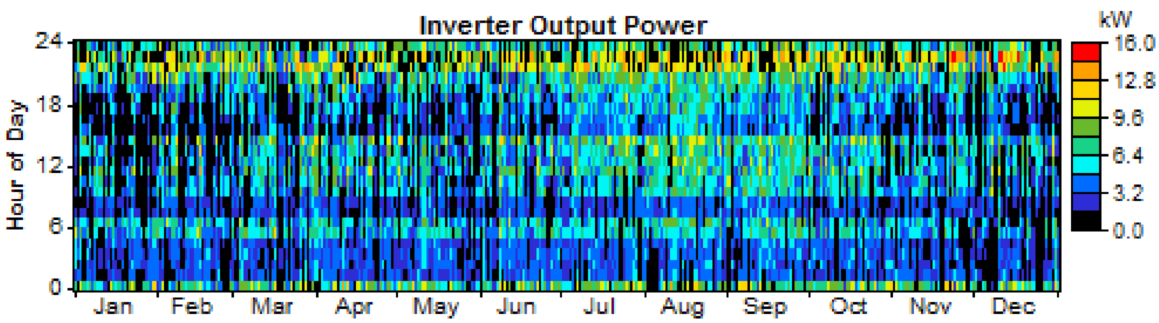


Figure 15. Inverter output power

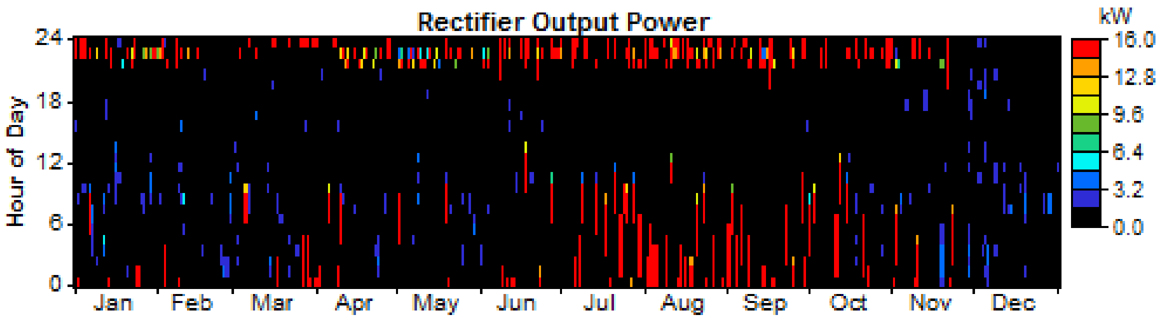


Figure 16. Rectifier output power

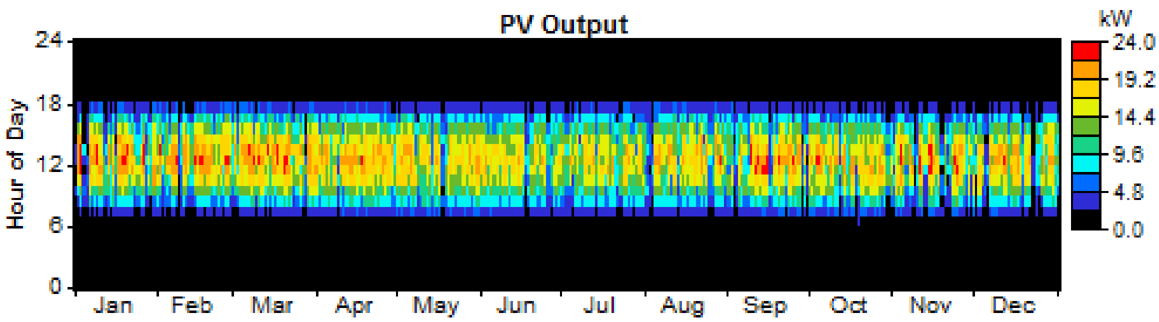


Figure 17. PV output

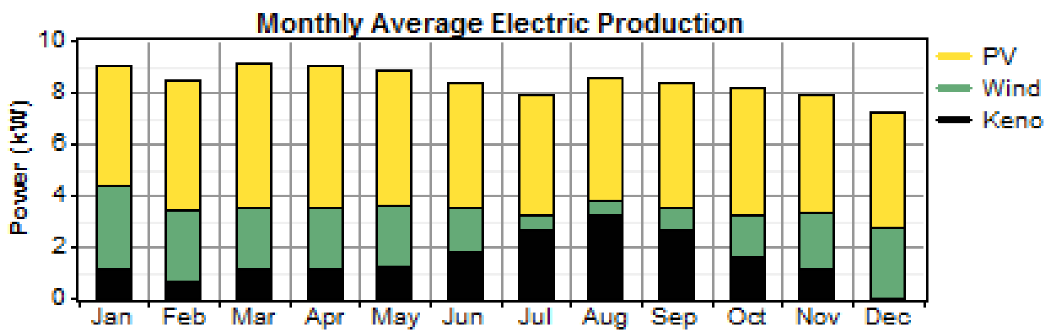


Figure 18. Monthly average electric production

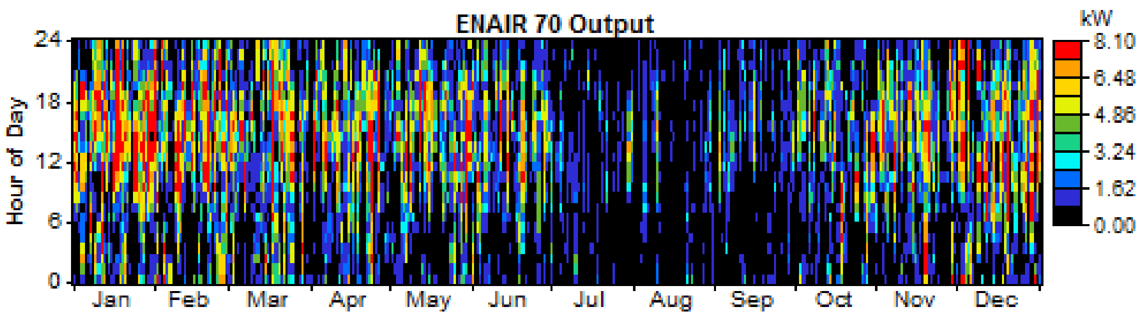


Figure 19. Wind turbine output

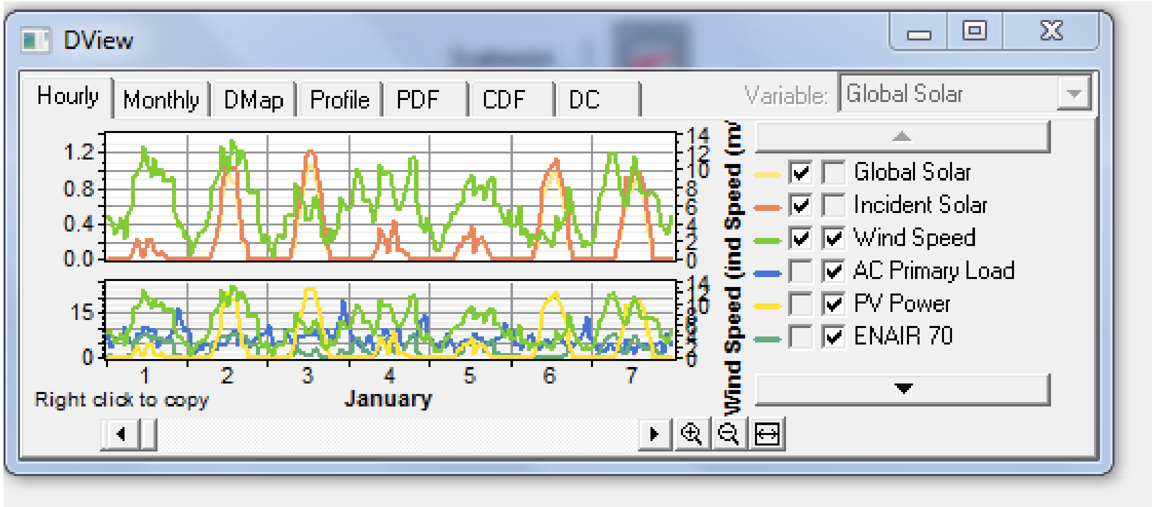


Figure 20. Hourly plot for sources for the month of January

A detailed cash flow summary of the PV, wind turbine, AC generator, converter and battery system is shown in Figure 13, with much consumption coming in from the use of the diesel fuel. Figure 14 shows the electrification cost of using the grid or stand alone system. It can be deduced from Figure 14 that the use of the grid system is more economical than the stand alone system until a grid extension distance of 17.8km, after which a break even occurs and is more economical to use the stand alone system. The inverter, rectifier and PV output are shown in Figures 15 to 17 respectively. The monthly average electric production for the wind, solar and AC generator are shown in Figure 18, with more power been produced by the PV system due to high average radiations. The wind turbine output power is shown in Figure 19, while an hourly plot DView of the wind speed, PV, wind turbine and AC primary load for the month of January is shown in Figure 20. Due to the fact that the wind speed is highest in January for the wind resource used in this study, its effect has greater impact than the other power sources for that particular month.

7. Investigating the effects of different load profiles on the system

Two cases using two load profiles shown in Figures 2 and 21 respectively were also considered with the model system shown in Figure 1. A comparison and investigation of the effects of the two load profiles on the equipments in the model system was carried out. Load profile 2 shown in Figure 21 is skewed towards the right where a maximum load of about 17kW is used towards the late hour of the evenings, while the load profile in Figure 2 is roughly and evenly distributed with a peak load of 13kW observed also in the late evenings.

From Figures 22 and 23, it is seen that the load profile has a great influence in the cash flow summary of the system. Lower load profile shown in Figure 21 requires lower capital, replacement, and operating, fuel and salvage value of the project for the PV, wind turbine, diesel and battery system as compared to higher load profile shown in Figure 2. However, the cost of operating the converter system remains the same despite the variation in the load profiles.

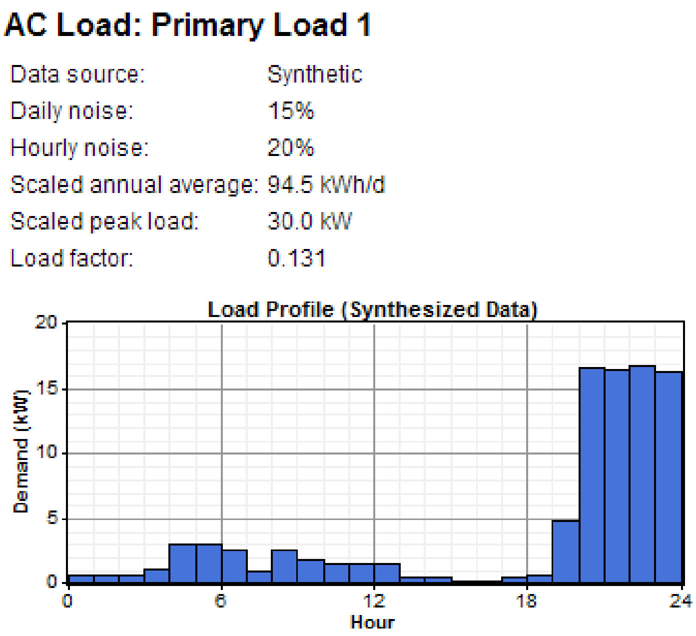
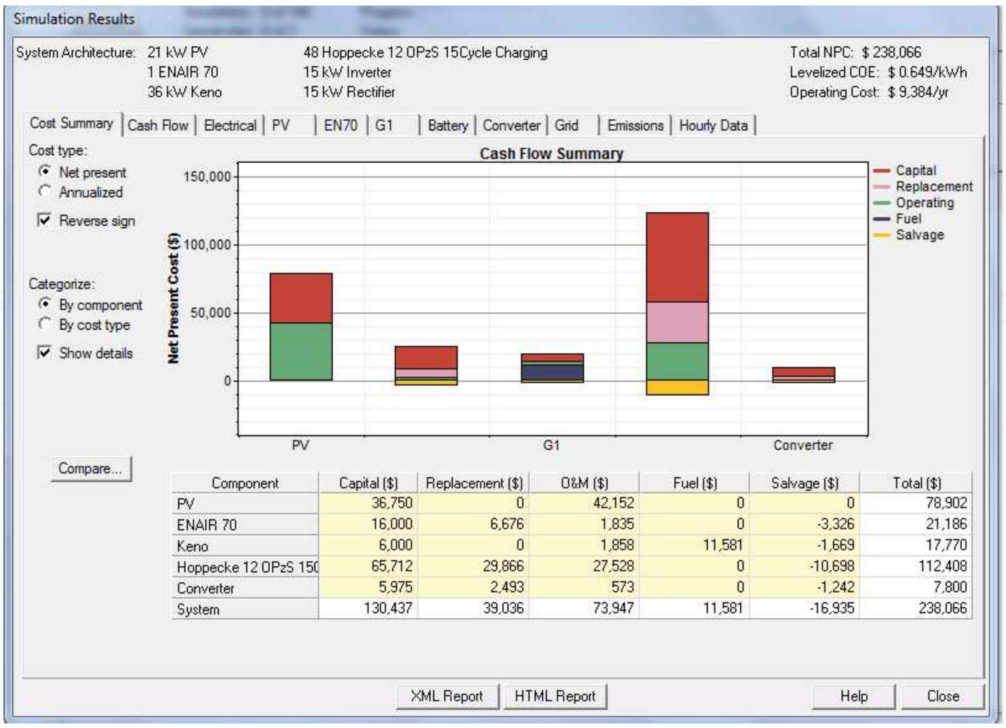


Figure 21. Load profile 2



Component	Capital ($)	Replacement ($)	O&M ($)	Fuel ($)	Salvage ($)	Total ($)
PV	36,750	0	42,152	0	0	78,902
ENAIR 70	16,000	6,676	1,835	0	-3,326	21,186
Keno	6,000	0	1,858	11,581	-1,669	17,770
Hoppecke 12 OPzS 150	65,712	29,866	27,528	0	-10,698	112,408
Converter	5,975	2,493	573	0	-1,242	7,800
System	130,437	39,036	73,947	11,581	-16,935	238,066

Figure 22. Cash flow summary of lower load profile

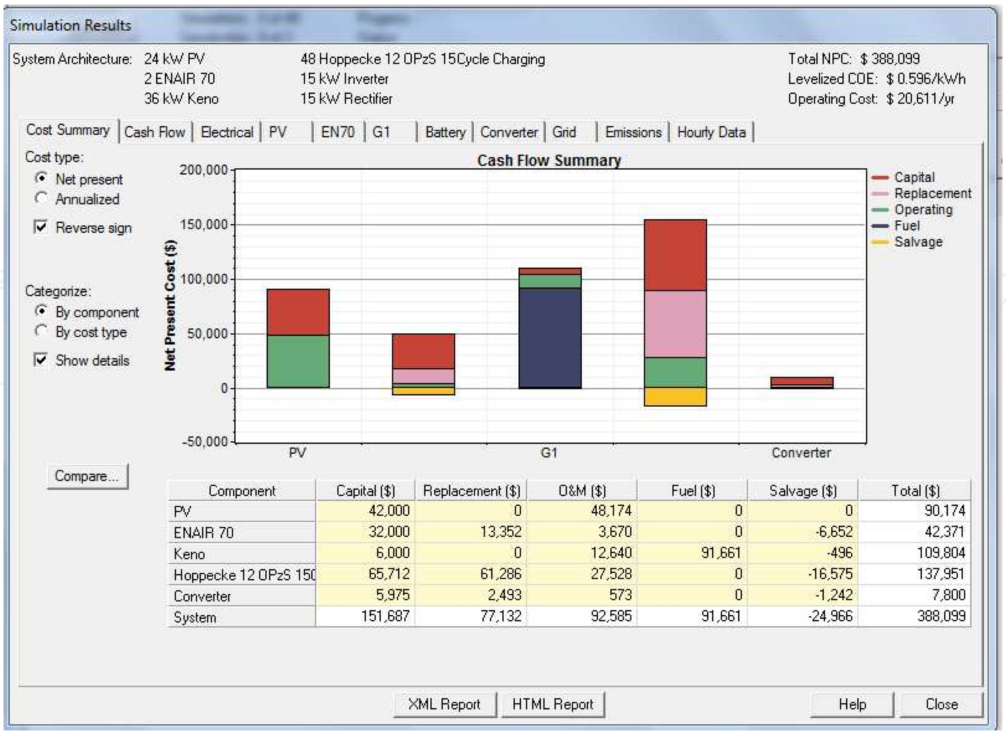


Figure 23. Cash flow summary of higher load profile

8. Levelized cost of electricity and demand side management loading scheme

The Levelized cost of electricity (LCOE) is also the levelized cost of energy (LCOE) or the levelized energy cost (LEC). It is a common metric for comparing power generating technologies as used in the model system of this study. The full life-cycle costs (fixed and variable) of a power generating technology per unit of electricity (MWh) are often called levelized costs of electricity. In contrast to the tendency of increasing energy prices for conventional power sources, like the AC diesel generator used in this study, the levelized cost of electricity of all renewable energy technologies (the PV and wind turbine) have been falling continuously for decades. This development is driven by technological innovations such as the use of less expensive and better performing materials, reduced material consumption, more-efficient production processes, increasing efficiencies as well as automated mass production of components [11, 13]. It can be defined with the following equation [10, 12, and 14].

$$LEC = \frac{\sum_{t=1}^{n} \frac{I_t + M_t + F_t}{(1+r)}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}} \quad (1)$$

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Where

- LEC is the average lifetime levelized electricity generation cost
- I_t is the investment expenditures in the year t
- M_t is the operations and maintenance expenditures in the year t
- F_t is the fuel expenditures in the year t
- E_t is the electricity generation in the year t
- r is discount rate
- n is life of the system

The LCOE of this study, for the best HOMER configuration option are shown in Figure 6 with value range of $0.596/kWh to 0.679/kWh. The LCOE, as shown in Figures 22 and 23 respectively are $0.649/kWh and $0.596kWh. It could be observed that the lower load profile gives a higher LCOE, lower net present cost of $238.066, and lower operating cost of $9,384/yr compared to results obtained in the higher load profile, with higher net present cost and operating cost.

Moreover, the costs of constructing and operating a new capacity generation unit are increasing everyday as well as transmission and distribution and land issues for new generation plants. This leads to the utilities to search for another alternative without any additional constraints on customers comfort level or quality of delivered product. Demand side management (DSM) therefore encompasses load reduction strategies as well as load growth strategies and flexible energy service options. This can be defined as the selection, planning, and implementation of measures intended to have an influence on the demand or customer-side of the electric meter, either caused directly or stimulated indirectly by the utility. DSM programs are peak clipping, valley filling, load shifting, load building, energy conservation and flexible load shape [15, 16]. Considering the model system of study, with respect to the two load profile scenarios, the second load profile in Figure 21 is said to have a better demand side management compared to first load profile of Figure 2. Thus, more energy would be saved in the lower load profile, with less pressure on the renewable energy sources based on effective load or energy management system.

9. Conclusion

The use of hybrid optimization model for electrical renewable (HOMER) software has been presented in this chapter for design of a power system mainly composed of electric renewables. Hybrid Optimization Model for Electrical Renewable (HOMER), is a micro power optimization model, that simplifies the task of evaluating designs of both off-grid and grid-connected power systems for a variety of applications. The HOMER Hybrid Optimization Modeling Software is used for designing and analyzing hybrid power systems, which contain a mix of conventional generators, cogeneration, wind turbines, solar photovoltaic, batteries, fuel cells and other inputs. In order to determine the optimized system configuration that would be more energy efficient, the net present cost was used as the basis for the selection of the best operation conditions considering a system made up of a PV, wind turbine, AC diesel generator, battery and converter systems. The lowest net present cost of the various solutions was chosen as the optimized configuration.

Also, HOMER would give idea of the best rating of the PV, the number of wind turbines, the rating of the AC diesel generator, number of battery springs, rating of the converter system, initial cost, operating cost, total net present cost, cost of energy per kWh, renewable energy fraction, capacity storage, diesel consumption in liters, and the generator hours of operation. HOMER contains a powerful optimizing function that is useful in determining the cost of the various energy project scenarios as shown in the text of this chapter. This functionality allows for minimization of cost and optimization of scenarios based on various factors.

Furthermore, a model system consisting of wind turbine, PV system, diesel ac generator, battery and converter system was investigated using different load profiles. The cash flow summary results demonstrates that increase load profile leads to more capital, operating, replacement, increase fuel, and salvage value of the project for the wind turbine, PV, diesel and battery systems. However, the converter system was found to be independent of the load profiles.

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