Design and Analysis of PV-DIESEL Hybrid Power System Case Study Sudan, El Daein (East Darfur)

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Abstract- This paper aims to design and to compare between four hybrid systems combination build from solar photovoltaic, battery and diesel generators to provide El Daein city east of Darfur state in Sudan with electric power, where most of electrical power supplied Darfur's regions are mainly generated by diesel generator units isolated from the national grid. Homer software is used in simulation, the most optimize case is scenario 1, which consists of solar photovoltaic, diesel generator and battery. By comparing the base case which consists of diesel generators and the least cost scenario 1, the achievement is appeared in reducing diesel generators capacity only to 5,000 KW comparing with 7000 KW capacity, 2000 KW PV capacity besides a storage capacity of 2000 kwh, the initial capital cost of scenario 1 system is only $5.64M and the levelized cost of the whole PV system is 0.0584 $/kwh, also as an achievement a 11% reduction in fuel consumption by the diesel generator (DG) with the solar hybrid system, a 14% can be reduced as well on the operation and maintenance cost (OPEX). In Carbon footprint savings of 11% are also achieved as a result of the reduction in the burning of fossil fuel.

Keywords— *Solar Photovoltaic, El Daein city, Hybrid systems, Electricity in Sudan, Homer software Minimum, Sudan adopted the combination of PV with diesel.*

INTRODUCTION

Sudan is an agricultural country with fertile land, plenty of water resources, livestock, forestry resources, and agricultural residues. Energy is one of the key factors for the development of national economies in Sudan and Electric power is a key driver of economic growth and prosperity, put in Sudan although the utility of electricity was working hard to supply electrical power to rural areas, but still access to electricity remains dream for majority of the population living in remote and arid rural areas [1]. According to [2] there are seven large isolated grids in Sudan, named after the towns they are serving: Neyala, El Daein, Al Fashir and Al Genena in Darfur states, Wadi Halfa in North State, Kadogly and Al Nuhood in Kordufan. In total, these isolated grids make up about 2% of the grid connected energy consumption and 3% of all grid-connected customers, their cumulated peak load is about 4% of the annual peak load of the national grid.

Recently the electricity sector authority in Sudan adopted the combination of PV with diesel to offer a distinct environmental and economic benefits compared with a diesel generator on its own. Each energy source is used to best advantage, taking account of its special features. Substantial savings on diesel fuel and maintenance can be realized in those hybrid systems where a diesel generator remains the most realistic option for meeting occasional high load demands and providing security of supply.

The installation of a solar power system to replace or offset a portion of the diesel electricity generation is an option to consider for remote residential homes. A complete replacement of diesel generation with solar power is usually not feasible, due to low solar input during the rainy season. However, a solar/diesel combination system known as hybrid system can prove to be very reliable and cost effective given the right conditions (such as optimal sizing) [3].
In Sudan although the utility of electricity was working hard to supply electrical power to rural areas, but still access to electricity remains dream for majority of the population living in remote and arid rural areas. Darfur region is one of these areas who have a low percentage of electrification ratios. One of the primary attributable factors in Darfur's economic development is the deficit in ready access to electricity. Most of electrical power supplied Darfur's regions are mainly generated by diesel generator units isolated from the national grid, although those generating units has also received a complete maintenance overhaul. However, capacity problems, such as generator-overheating and fuel supply shortages, force these power stations to apply load-shedding practices to balance the distribution of the daily electricity supply to Localities between the hours of 5:00 pm to 2:00 am. As a result, the region is plagued by

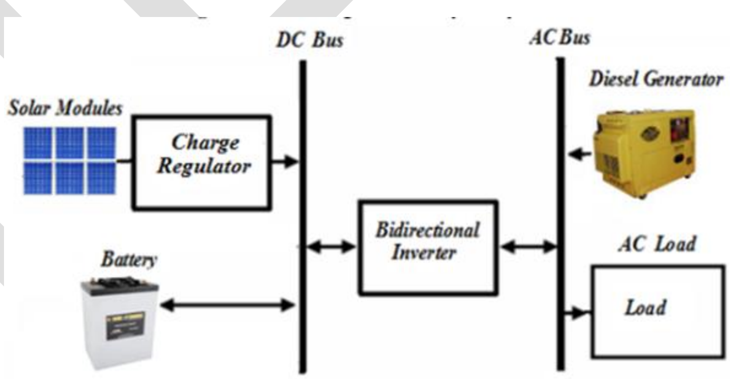
inefficiencies that severely limit opportunities to generate economic activities, jobs and additional incomes. The maximum generating capacity is currently insufficient to exceed six hours per day. Correspondingly, the environmental effects of gas/fuel-powered generators, such as noise pollution and health-related concerns to people who work in the plant [4].
Significant amounts of research have lately been devoted in the optimal design and operation of hybrid diesel and renewable system. Recently [5] proposed and designed a small hybrid power system consists of a 2,750 kW solar photovoltaic (PV), a 21,600 kWh battery storage, a 1,500 kW power electronic converter, and a 1,000 kW diesel generator to meet an average demand load of 9.422 MWh/day with a peak load of 1.3 MW for a village in eastern Nigeria, research presented in [6] a hybrid system composed of three generators, two on renewable energy (solar and wind power) and one on combustible energy (diesel generator).has been modulated and simulated, this system is composed with three generators, two on renewable energy (solar and wind power) and one on combustible energy (diesel generator) to supply a small village located in southwest of Algeria for 24 hours during both seasons winter and summer, the authors of [7] deal with the design, performance analysis, and optimization of a hybrid microgrid for the hospital complex located on Eskişehir Osmangazi University (ESOGU) campus using Hybrid Optimization of Multiple Energy Resources (HOMER) software, the performance of the microgrid was investigated via simulation using five operating scenarios. Reference [8] reviewing the research on the unit sizing, optimization, energy management and modeling of hybrid renewable energy system components.

Recently the authority of electricity in Sudan contracted to install a PV system to be integrated with the existing isolated diesel generator units located in two cities in Darfur state east of Sudan, one of this cities is El Daein city the capital of east Darfur, where the existing unreliable diesel generator power system units are generating power with two types of generation, one generation belong to IPP procedure and the remaining small capacity units belong to the Sudanese Thermal Generating Power Company. Recently the authority of electricity in Sudan is contracted with a local contractor on a base of EPC contract to deliver and install 5 megawatts PV system to be integrated and synchronizing with the existing diesel generator system size with a total cost of $ 6,862,846.25M, they contracted without carrying out a pre-design or feasibility study to determine the suitable PV system size.

This paper aims to design and size the optimize hybrid system components and to compare between the basic system (existing diesel generator units) and the new proposed hybrid system for the most optimize hybrid system to reduce diesel consumption, importing and transporting of fossil fuel used in generation of electricity and to increase the reliability of electrical supply system.

SYSTEM DESCRIPTION

The hybrid system proposed in this study to meet the load demand needs of El Daein city which is located in eastern Darfur state in Sudan, the hybrid system consists of (i) Existing unreliable Diesel generators units supplying the city demand load consuming mainly two types of fuel oil, namely Diesel oil and Gas oil with a total fuel consumption approximately 9,888,327.78 Liter per a year (3,492.03 Tons) all together (ii) photovoltaic (PV) system included PV panels, Convertors, controllers and storage batteries. As shown in figure 1 [10].



HOMER DESCRIPTION:

HOMER Energy is the global standard for optimizing microgrid design in all sectors, from village power and island utilities to grid-connected campuses. Homer Pro, or HOMER (Hybrid Optimization of Multiple Electric Renewables), simplifies the task of evaluating designs for both off-grid and grid-connected power systems and is the software developed by the National Renewable Energy Laboratory (NREL). By using Homer Energy Software you can find out which components are best for this system and How many and what size of each components are most efficient. HOMER Pro 3.11.2 software was used to simulate hybrid energy system for off-grid with different schedules and compared with a system that run with diesel generator. In doing the simulations system designs, several parameters have to be taken into consideration for proper decisions. Input information to be provided to HOMER includes: electrical loads (1 year of load data), renew- able resources (such as 1 year of solar radiation data), component technical details/costs, constraints, controls, type of dispatch strategy, etc. HOMER is a simplified optimization model/code, which performs hundreds or thousands of hourly simulations over and over (to ensure best possible matching between supply and demand) to design the optimum system [9]. HOMER simulates the system over 8760 h, therefore Homer performs three principle tasks; (i) in the simulation process, HOMER models the performance of a particular micro power system configuration each hour of the year to determine its technical feasibility and life cycle cost, in the optimization process, HOMER simulates many different system configurations in search of the one that satisfies the technical constraints at the lowest life-cycle cost. In the sensitivity analysis process, HOMER performs multiple optimizations under a range of input assumptions to gauge the effects of uncertainty or changes in the model inputs; (ii) optimization determines the optimal value of the variables over which the system designer has control such as the mix of components that make up the system and the size or quantity of each;(iii) sensitivity analysis helps assess the effects of uncertainty or changes in the variables over which the designer has no control, such as the average wind speed or the future fuel price [11].

Therefore HOMER calculates the following four costs for every simulation Result [12]; (i) COE (Cost of Energy); (ii) NPC (Net resent Cost); (iii) O&M (Operations and Maintenance Cost); (iv) Initial Capital Cost.

INPUT DATA AND ANALYSIS METHOD

The resources available for the Global Horizontal Irradiance (GHI) of the selected location El Daein, Sudan (Longitude 11.4613°, Latitude 26.1241°) is downloaded from National Renewable Energy Lab Database. The daily solar irradiation ranges between 5.980 kWh/m2 and 5.879 kWh/m2; whereas, the annual average daily solar irradiation for this area is 6.12 kWh/m2 as illustrated in Table1 and Figurer 2.

TABLE 1: GLOBAL HORISONTAL IRRIDANCE (GHI)

	sources Available *Global Horizontal* Irradiance (GHI)	
Solar Resources	Annual Average	6.12 kwh/m2/day
	Maximum (April)	6.8 kwh/m2/day
	Minimum (August)	5.3 kwh/m2/day
	Downloaded from National Renewable Energy Lab Database	

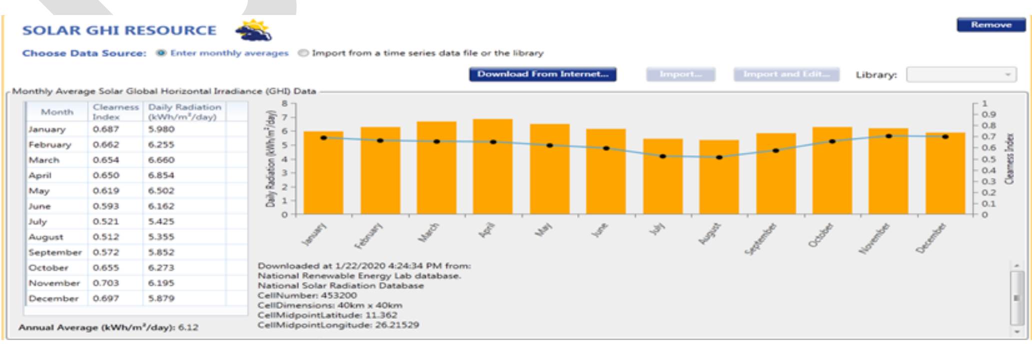


Figure. 2. Global Horizontal Irradiance (GHI)

TABLE 2: ELECTRIC LOAD PARAMETERS

Electric Load Parameters	
Average (kwh/day)	100,144.5
Average (KW)	4,172.68
Peak load (KW)	5,500
Load Factor	0.76

System optimization and method of analysis is represented by the flowchart in Figurer 3. It starts with selecting the solar resource data as input, followed by simulation and optimization, and desired result at the end. Beside the load, the system consists of four other components: the generator, DC to AC converter, solar PV array, and battery system as presented in Figureure 4.1. The weather input data were provided by NASA's Surface meteorology and Solar Energy database along with other real data that were collected in the early stages of this project from STPG. Figurer 4 shows the hourly electric load (January/winter and June/summer) for this system and the peak load that occurs during summer in June. The stand-alone PV system model has been designed and followed by technical and economic investigation for the studied configure rations [13].

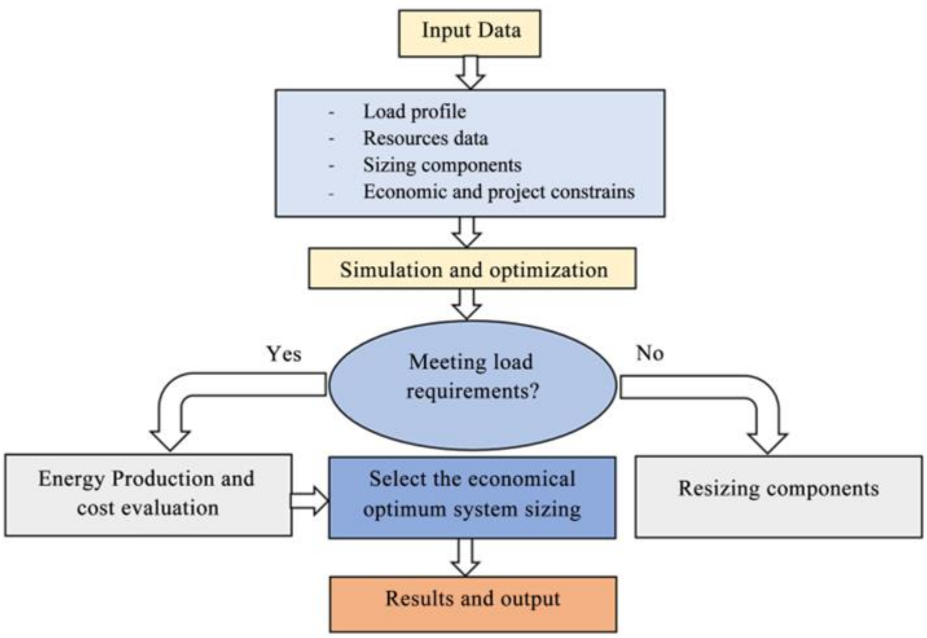


Figure. 3. Flowchart

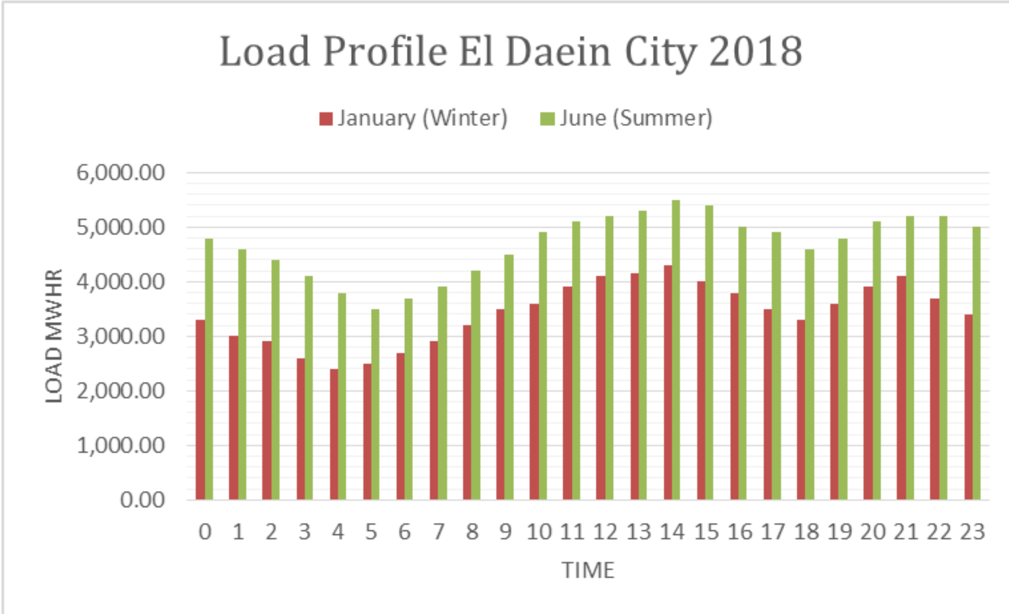


Figure. 4. Hourly Load Profile El Daein City

The specification of the input parameters of the components system proposed is shown in following Table 3, and the proposed system components also illustrated within Homer program blow Figurers (5-9).

TABLE 3: PARAMETERS OF THE PROPOSED SYSTEM COMPONENTS

Component	*Parameter*	*Value*	*Unit*
PV	Capacity	1	KW
	Life Time	25	Year
	Capital	1370	$
	Replacement	600	$
	O&M	10	$/year
Convertor	Capacity	System	KW
	Life Time	15	Year
	Efficiency	95	%
	Capital	Included in PV	$
	Replacement	300	$
Generator	Initial Capacity	300	$/KW
	Replacement	300	$/KW
	O&M	0.02	$/op. hour
	Life Time	15,000	hours
	Off hours/weekends	10	hours
	Diesel fuel price	1	$/L
Idealized Battery	Life time	15	Year

Model 1MWh Li-Ion	Quantity per string	2	Batteries
	Bus voltage	600	V
	Capital	700,000	$
	Replacement	5,000	$
	O&M	10,000	$/year
Economical Parameters	Project Life Time	25	Year
	Real Discount Rate	0	%
System Size	PV	2,000	KW
	Generator	5,000-7,000	KW

RESULTS AND DISCUSSIONS

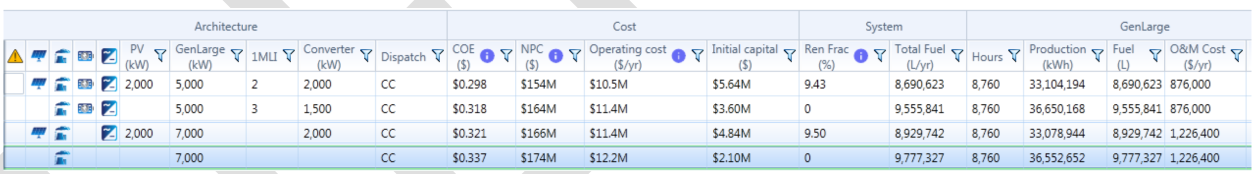
The categorized optimization results obtained for the proposed hybrid power plant by HOMER software are illustrated in Figurer 10: and tabulated in table 4; this optimization has produced four results in different scenario combinations.

Scenario 1: In the first row which is represented the first category (scenario 1), the optimization uses the PV, Diesel Generator source, Storage Battery and Inventor.

Scenario 2: In the second row, which it's the second category (scenario 2), the optimization uses Diesel Generator source, Storage Battery and Inventor.

Scenario 3: In the third row (scenario 3), it uses PV, Diesel Generator source and Inventor.

Scenario 4: In the fourth and last row (scenario 4) the case represents the Diesel Generator source as an optimization basic case.



Architecture					Cost				System		GenLarge			
PV (kW)	GenLarge (kW)	1MLI	Converter (kW)	Dispatch	COE ($)	NPC ($)	Operating cost ($/yr)	Initial capital ($)	Ren Frac (%)	Total Fuel (L/yr)	Hours	Production (kWh)	Fuel (L)	O&M Cost ($/yr)
2,000	5,000	2	2,000	CC	$0.298	$154M	$10.5M	$5.64M	9.43	8,690,623	8,760	33,104,194	8,690,623	876,000
	5,000	3	1,500	CC	$0.318	$164M	$11.4M	$3.60M	0	9,555,841	8,760	36,650,168	9,555,841	876,000
2,000	7,000		2,000	CC	$0.321	$166M	$11.4M	$4.84M	9.50	8,929,742	8,760	33,078,944	8,929,742	1,226,400
	7,000			CC	$0.337	$174M	$12.2M	$2.10M	0	9,777,327	8,760	36,552,652	9,777,327	1,226,400

Figure: 10. Categorized optimization results

TABLE 4: CATEGORIZED OPTIMIZATION RESULTS

Category	PV (KW)	Diesel Generator (KW)	Battery (kwh)	Convertor (kw)	Net Present Cost ($M)	Cost Energy $ (COE)	Operating Cost ($M/year)	Initial Capital (M$)	Renewable Fraction
Scenario 1	2000	5000	2000	2000	154	0.298	10.5	5.64	9.43
Scenario 2		5000	3000	1500	164	0.318	11.4	3.60	0
Scenario 3	2000	7000		1500	166	0.321	11.4	4.84	9.50
Scenario 4		7000		2000	174	0.337	12.2	2.10	0

Scenario 1: ***PV, Diesel Generator source, Storage Battery and Inventor.***

i. The categorized optimization results shows that the most optimum and least cost regarding cost of energy and total net present cost is category 1 or scenario 1, in the first row which uses the PV, Diesel Generator source, Storage Battery and Inventor. This least cost category only uses 5,000 KW diesel generator capacity and 2000 KW PV besides a storage capacity of 2000 kwh and the initial capital cost of $5.64M and total cost of energy (COE) is 0.298 $/kwh as shown in table 4..

ii. The advantage of scenario 1, over the base case is that the net present cost is reduced by 11% of the base case net present cost, cost of energy (COE) reduced by 12% and accordingly the operating cost is reduced by 14%. All this improvement happened due to sharing of PV flat plate by a fraction of 9.4% in the total energy served (kwh) and a penetration of 46.7 % in the average load demand (KW) as illustrated in Table 5: below

TABLE 5: SCENARIO 1 AND BASE CASE COMPARISION

Evaluation Criteria	Basic case (scenario 4)	Scenario 1	% of saving
Net Present Cost (NPC M$)	174	154	11
Cost of Energy (COE) ($)	0.337	0.298	12
Operating Cost (M$/yr)	12.2	10.5	14
Renewable Fraction (%)	0	9.4	
Renewable penetration (%)	0	46.7	

i. In table 6, by using Scenario 1, the saving in fuel consumption per a year is 11% which equal to 1,086,704 Liter/year and this is approximately equivalent to 962 Ton/year and 24,043 Ton in 25 years the project life time.

ii. Also for Carbon Dioxide (Co2) emission, a save of 11% is obtained by using Scenario 1, this saving percentage is equal to 2,849,581 kg/year and in 25 years the saving of Carbon Dioxide emission will be 71,239.6 Ton, table 6 shows this comparisons.

TABLE 6: FUEL CONSUMPTION AND EMISSION COMPARISON

Evaluation Criteria	Basic case (scenario 4)	Scenario 1	% of saving
Total Fuel Consumption (L/year)	9,777,327	8,690,623	11
Carbon Dioxide Emission (kg/year)	25,638,355	22,788,774	11

Scenario 2: ***Diesel Generator source, Storage Battery and Inventor.***

In scenario 2, Comparison of the basic system and Scenario 2 in terms of optimization results is given in Table 7, where the optimization use of scenario 2 comparing with the basic case results in capacity reduction of the Diesel generator from 7000 KW to only 5000 KW as illustrated in Table 5.37, causing a percentage reduction about 29%. This optimized capacity led to a saving of 5.75% in the net present cost, 5.64% in cost of energy and a saving of 6.56% in operating cost, also besides the mentioned optimization results advantage, there is another's positive effect concerning the environment concerns, the use of storage system results in fuel consumption saving about 8.67% and reduction in Carbone Dioxide emission by amount of 580,786 kg/year Table 8.

The nature of the served demand load reaches its maximum during summer season 5,500 KW where the battery through Invertor sharing in supplying the demand load by 500 KW, the remaining power delivered by the diesel generator as shown in Figurer 11.

TABLE 7: CATEGORIZED OPTIMIZATION RESULTS

Evaluation Criteria	Basic case (scenario 4)	Scenario 2	% of saving
Net Present Cost (NPC M$)	174	164	5.75%
Cost of Energy (COE) ($)	0.337	0.318	5.64%
Operating Cost (M$/yr)	12.2	11.4	6.56%
Renewable Fraction (%)	0	0	

TABLE 8: BASIC CASE SCENARIO 2 CAPACITY KW)

Evaluation Criteria	Basic case (scenario 4)	Scenario 2		
		DG	INV	BAT
Capacity (KW)	7000	5000	1500	3000 kwh

TABLE 9: COMPARISION FUEL CONSUMPTION AND EMISSION OF BASIC CASE AND SCENARIO 2

Evaluation Criteria	Basic case (scenario 4)	Scenario 2	% of saving
Total Fuel Consumption (L/year)	9,777,327	9,555,841	8.67%
Carbon Dioxide Emission (kg/year)	25,638,355	25,057,569	8.67%

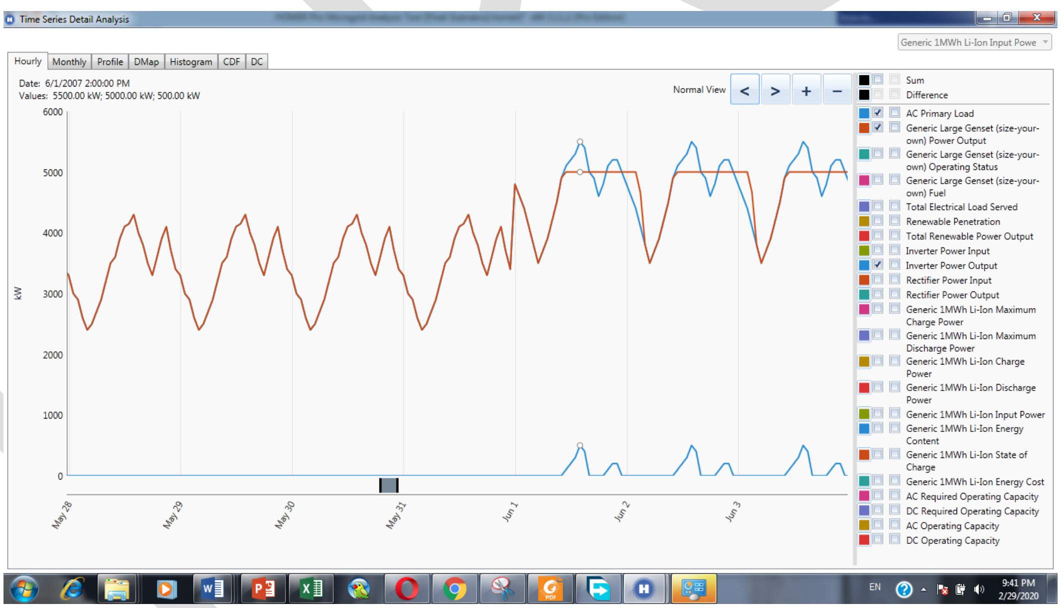


Figure: 11. Load sharing between Diesel generator and PV Scenario 2

Scenario 3: ***PV-Diesel Generator and Inventor.***

The optimized case of scenario 3- uses PV-Diesel Generator and Inventor as shown in Table 10, the comparison between the basic system and Scenario 3 in terms of optimization, results in a percentage reduction of 4.60% in net present cost, 4.75% in energy cost shown in Table 11, and a saving of 6.56% in operating cost, also there is a positive effect concerning the environment concerns, the use of PV systems results in fuel consumption saving about 8.67% and reduction in Carbone Dioxide emission by amount of

2,222,557 kg/year as shown in Table 12, which equivalent to 2,222.5 Ton of Carbon Dioxide per a year. The penetration of the PV is 46.7% same as in Scenario 1, but with 0.1% increasing in renewable fraction percentage than scenario 1.

TABLE 10: BASIC CASE AND SCENARIO 2 CAPACITY (KW)

Evaluation Criteria	Basic case (scenario 4)	Scenario 3		
		DG	INV	PV
Capacity (KW)	7000	7000	2000	2000

TABLE 11: CATEOGRAIZAION OPTIMIZATION RESULTS (SCENARIO 4&3) COMPARISION

Evaluation Criteria	Basic case (scenario 4)	Scenario 3	% of saving
Net Present Cost (NPC M$)	174	166	4.60%
Cost of Energy (COE) ($)	0.337	0.321	4.75%
Operating Cost (M$/yr)	12.2	11.4	6.56%
Renewable Fraction (%)	0	9.50	
Renewable Penetration (%	0	46.7	

TABLE 12: COMPARISION FUEL CONSUMPTION AND EMISSION OF BASIC CASE AND SCENARIO 3

Evaluation Criteria	Basic case (scenario 4)	Scenario 3	% of saving
Total Fuel Consumption (L/yaer)	9,777,327	8,929,742	8.67%
Carbon Dioxide Emission (kg/year)	25,638,355	23,415,798	8.67%

Figure.12. Load sharing between Diesel generator and PV Scenario 3

CONCLUSION

The main goal of this paper is to design and optimize a photovoltaic system integrated with an already existing diesel- grid system for supplying El Daein city situated in east of Darfur state in Sudan with electric power by using hybrid power plant.

A comparison of the four different combinations hybrid systems by using HOMER PRO 3.11 software, reveals that the hybridization of 2000 kW PV, 5000 kW DG, 2 batteries (1000 kWh nominal capacity each) and 2000 kW power converter is the optimal and better techno-economic performance among all investigated four cases and known as scenario 1 to produce the required energy demand with the efficient techno-economic performance. With this hybrid solution, the following is achieved;

It's not recommended to install PV systems as a part of hybrid plant without defining the required PV size to avoid reliability constraints, if the penetration of PV is high will cause stability problems. The optimization results shows that the optimized PV penetration to cause system stability is about 46.7% of the average demand load which in this study case is 4,172.6 KW.

The selected design with least cost category only uses 5,000 KW diesel generator capacity and 2000 KW PV besides a storage capacity of 2000 kwh and the initial capital cost of $5.64M compared with the contracted ≈ $6.8M, the levelized cost of the whole system of PV is 0.0584 $/kwh.

With hybrid solution an 11% reduction in fuel consumption by the diesel generator (DG) with the solar hybrid system. 14% can be reduced as well on the operation and maintenance cost (OPEX). Carbon footprint savings of 11% are also achieved as a result of the reduction in the burning of fossil fuel.

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