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Design of Solar PV Energy System for Wajir Town, Wajir County, Kenya

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Abstract: Solar PV systems are suitable for areas where grid connections are unavailable. Northeastern Kenya being an off grid area requires an alternative to close the gap of electricity shortages. This study provides proactive measure to resolve the potential energy issue in the near future. The Study present the development of an effective approach of designing, assessing, analyzing and determining economic viability of solar energy availability in Wajir town. Located in the north-eastern part of Kenya with population of 0.7million, the county receives about 300 sunny days in a year. Mostly, the daytime is extremely long in the summer time from 7:00am to 6:00pm. The unique weather profile favors the adoption of the solar energy technology. Solar Radiation was recorded for three month (October, November and December 2016) and also from the meteorological headquarters from the year 2000 to 2010. Results revealed that Wajir has an average daily insolation of 6.6 kWh/m^2. Energy demand survey of 20 households, 20 shops and the main hospital were conducted and later on design using Sunny Web design software was used to model by assuming 300 households, 20 shops and the main referral hospital. Sizing for PV array, inverters and modules were necessary to attain 122.25 kWp system for households, 25 kWp system for shops and 239 kWp system for the hospital.

Keywords: Solar radiation, Sizing, Assessment, Insolation, Energy demand, Photovoltaic.

I. Introduction

Wajir as a county experiences massive blackouts. This is due to insufficient power from Diesel power plant manned by Kenya Power Lighting and Company. Constant use of biomass sources such as charcoal and firewood results serious Environmental degradation. Climate change and energy security also pose threat, therefore the need for clean, reliable energy, alternative, new and renewable sources of energy in the rural areas of the country. Solar energy is reliable and more environmentally friendly. This resource is therefore one of the better energy alternatives for Wajir county for socio-economic development.

More than 1.6 million women and children die every year because of respiratory diseases caused by indoor air pollution from cooking fuels. In developing countries, poor people spend a higher share of their income on energy services than people in developed parts of the world. Costs per energy unit are also higher. Candles and batteries prove to be the most expensive forms of energy per unit. Four out of five people without access to electricity live in rural areas. Several developing countries like Kenya have abundant renewable energy resources including solar energy, but are not effectively utilized. According to International Energy Agency (IEA), (IEA,2015), Modern energy services are crucial to human well-being and to a country's economic development; and yet globally 1.2 billion people are without access to electricity and more than 2.7 billion people are without clean cooking facilities. More than 95% of these people are either in sub-Saharan African or developing Asia, and around 80% are in rural areas.

1.1 SOLAR ENERGY

Solar energy is radiant light and heat from the sun harnessed using a range of ever-evolving technologies such as solar heating, solar photovoltaic, solar thermal electricity, solar architecture and artificial photosynthesis. Solar power has the extraordinary ability to give us an abundance of energy just by hitting the earth's surface. The spectrum of solar light at the Earth's surface is mostly spread across the visible and near-infrared ranges with a small part in the near-ultraviolet.

1.2 Technologies used to convert solar energy

There are several kinds of solar techniques that are currently available. However, each one of them is based on quite different concepts and science and each has its unique advantages. Analysis and comparison between different technologies will help to adopt the most efficient and beneficial technology given a specific set of conditions of solar energy. These range from solar collectors on house roofs for space and water heating to solar power plants, with large arrays of mirrors concentrating solar energy to heat water and drive turbines to produce electricity. The type of solar energy conversion system installed in an area depends on the prevailing climate. Generally speaking, non-concentrated photovoltaic solar panels (PV) and concentrated solar power (CSP) are the two most mature technologies, they have been commercialized and expected to experience rapid growth in the future, and thus emphasis will be on these two technologies. Solar thermoelectricity systems (STS), dye sensitized solar cell (DSPV) and concentrated photovoltaic systems are emerging technologies and under intensive study (Arun *et al.*, 2008). Eventually, they may claim a significant share of the solar energy market if they achieve the necessary technical breakthroughs to make them sufficiently competitive to be commercialized.

II. Methodology

Various instruments, methods and materials were used in assessing and designing of solar energy in Wajir town. Assessment and Sizing were carried out separately. Solar Energy resources comprising of Radiation were first recorded for three months, a model design was done using the observed radiation so as to design solar energy for Wajir town. Design based on the daily energy demand assessment for selected institutions such as (Wajir hospital, households and shops) were described.

In order to assess solar energy availability reaching the earth's surface, measurements of solar radiation is crucial. The solar radiation reaching the earth being direct or diffuse, the component record diffuse so as to know the exact measurement. Data from Wajir County was measured directly using Hukseflux pyranometer.

For purpose of designing solar PV for 20 households, 20 shops and the main hospital, energy demand was investigated and recorded.

III. Results, Analysis and Discussion

3.1 Monthly Radiation for October, November and December 2016

The monthly solar radiation for Wajir town (October-December, 2016) is presented in table1. It was observed that the minimum recorded monthly value was 6.1 kWh/m^2/day and maximum value recorded 7.4 kWh/m^2/day. The data was first recorded in W/m^2 then converted to MJ/m^2/d and finally to kWh/m^2/d. Average daily insolation of Wajir Town for the three months record was 6.6 kWh/m^2/d. December has the maximum average value of 6.8 kWh/m^2/d followed by October of 6.6 kWh/m^2/d and November with 6.5 kWh/m^2/d. It was noted that December had the maximum average due to a constant dry and there was hardly cloudiness. During this month the season was dry and hot. During the months of October and November there was significant of cloudiness and little rain which makes the values to decrease. The average of the radiation readings was slightly lower than that of the meteorological which was 6.8 kWh/m^2/d. the result conquers with Milanzi 2013, Omwando 2012, and Okoola 2008. Which says that September-November there was little rain and from December it is hot and dry.

Table 1: Solar Radiation in Wajir County for a period of three months (Oct, Nov and Dec 2016)

	October		November		December		Average
	MJ/m^2/d	kWh/m^2/d	MJ/m^2/d	kWh/m^2/d	kWh/m^2/d	MJ/m^2/d	kWh/m^2/d
1	23.76	6.6	23.41	6.5	23.76	6.6	6.6

2	24.45	6.8	23.07	6.4	24.45	6.8	6.7
3	23.41	6.5	23.76	6.6	23.41	6.5	6.5
4	24.88	6.9	23.76	6.6	24.45	6.8	6.8
5	23.41	6.5	24.45	6.8	24.88	6.9	6.7
6	23.06	6.4	23.06	6.4	23.41	6.5	6.4
7	22.72	6.3	22.72	6.3	24.45	6.8	6.5
8	23.41	6.5	23.76	6.6	24.88	6.9	6.7
9	23.76	6.6	23.41	6.5	25.57	7.1	6.7
10	23.41	6.5	23.06	6.4	24.88	6.9	6.6
11	23.41	6.5	23.76	6.6	23.41	6.5	6.5
12	23.76	6.6	23.41	6.5	24.45	6.8	6.6
13	22.29	6.2	23.76	6.6	23.76	6.6	6.5
14	24.45	6.8	22.72	6.3	24.45	6.8	6.6
15	23.41	6.5	24.45	6.8	24.1	6.7	6.7
16	24.88	6.9	23.41	6.5	25.57	7.1	6.8
17	23.41	6.5	23.76	6.6	24.45	6.8	6.6
18	23.06	6.4	22.29	6.2	24.88	6.9	6.5
19	23.41	6.5	21.95	6.1	23.41	6.5	6.4
20	23.76	6.6	23.06	6.4	24.45	6.8	6.6
21	23.41	6.5	23.06	6.4	23.41	6.5	6.5
22	23.41	6.5	23.41	6.5	24.88	6.9	6.6
23	24.45	6.8	23.06	6.4	25.92	7.2	6.8
24	23.76	6.6	22.29	6.2	25.57	7.1	6.6
25	22.72	6.3	23.41	6.5	26.61	7.4	6.7
26	23.41	6.5	23.06	6.4	25.92	7.2	6.7
27	23.06	6.4	23.41	6.5	24.88	6.9	6.6
28	23.41	6.5	22.72	6.3	24.45	6.8	6.5
29	23.41	6.5	23.41	6.5	24.45	6.8	6.6
30	23.76	6.6	24.45	6.8	24.88	6.9	6.8

31	24.45	6.8			23.76	6.6	6.7

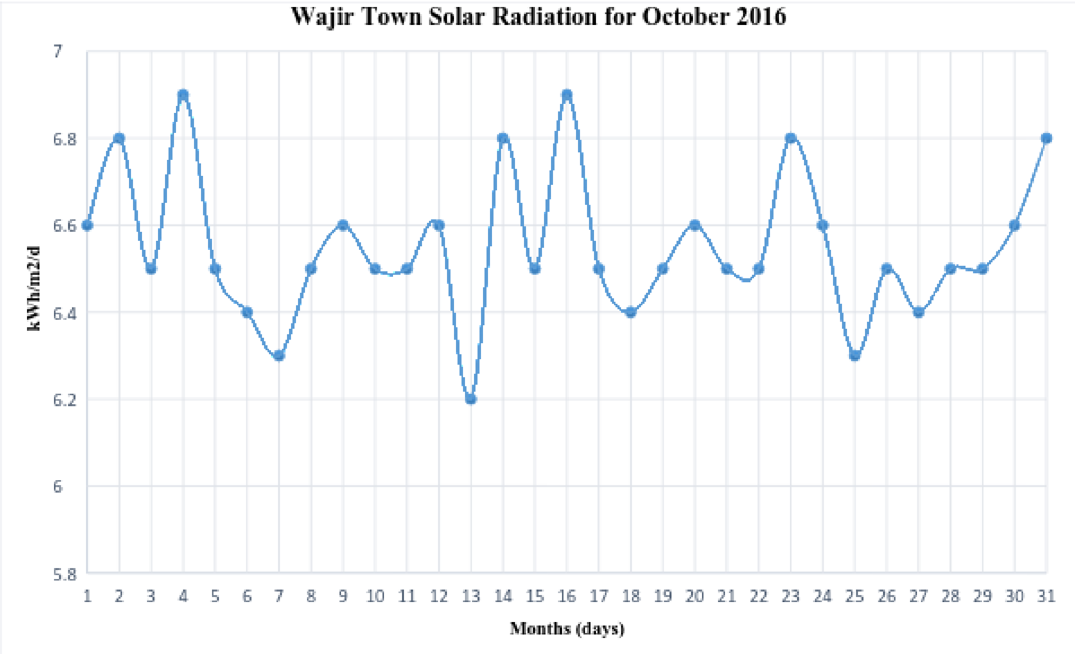

Figure 1: Wajir solar radiation for October 2016

Figure 1 shows the radiation penetration in October is moderate compared to November. The highest recorded was 6.9 kWh/m^2/d and the minimum value observed was 6.2 kWh/m^2/d, throughout the month of October there was little rain in Wajir town. September to November seasons there was significance of clouds therefore moderate penetration of solar radiation reaching the earth. Recorded values are in close range. In this month there are six peaks; 2nd, 4th, 14th, 16th, 23rd and 31st during this peaks there was no rain and scattered clouds were constant. October is the only month Wajir town experienced short rain. Throughout the year there was no rain in Wajir town. Due to the short rain that started late October till early November, penetration of solar radiation was reduced. September to November are rainy seasons (Okoola, 2008) but in Wajir town the rain was short and existed only few days therefore the results in October agrees to that of Okoola and Omwando.

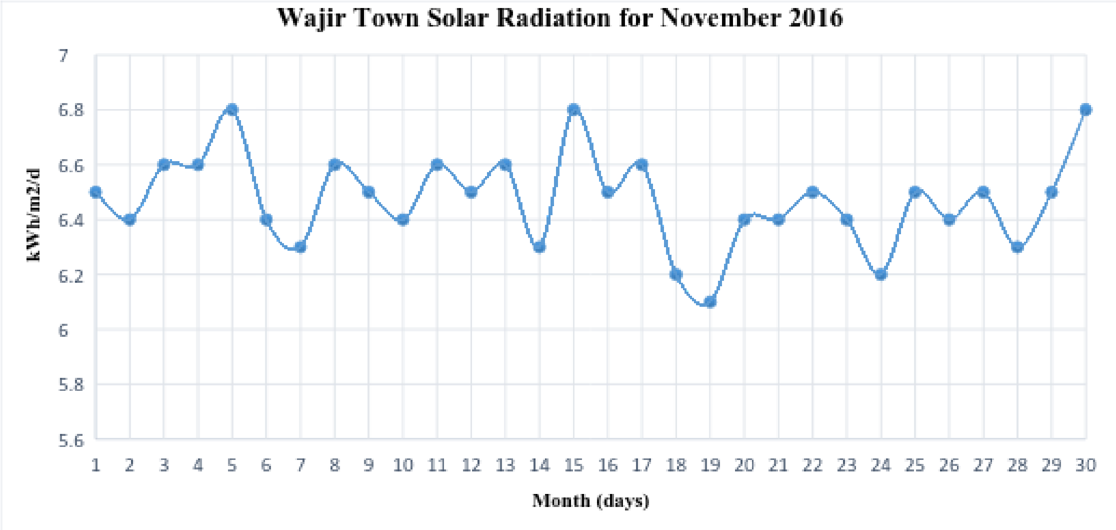

Figure 2: Wajir solar radiation for November 2016

Figure 2 shows the radiation penetrations are low compared to other months (October and December). The highest value observed was 6.8 kWh/m^2/d while the minimum recorded value was 6.1 kWh/m^2/d. In this month there are three picks, day five, fifteen and thirty first respectively. (5th, 15th and 30th). During this month, cloud and short rain was observed for few days and this made low solar radiation penetration on 19th day of the month. After every peak there was rain and scattered clouds formed, therefore November had low penetration of radiation. After date 30th of November the rain stopped and the weather changed to hot and dry. (Milanzi, 2013) in his research in Malawi shows that the highest radiation peak was received after November, the result confirms that after this month Wajir also experienced hot and dry.

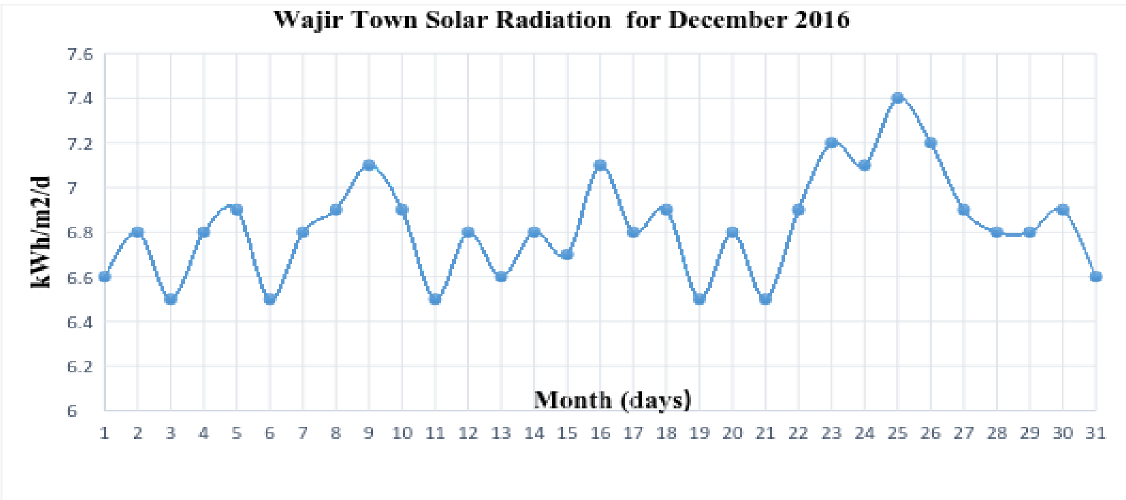

Figure 3: Wajir Solar Radiation for December 2016

In figure 3, it was observed that the highest value obtained for December was 7.4 kWh/m^2/d and the lowest value recoded was 6.5 kWh/m^2/d, radiation penetration during this month as compared to the other months was high. A total of 212 kWh/m^2 was observed in this month which equivalent to 762MJ/m^2. Radiation record for December was increasing gradually day by day. From 11th to 14th, 16th to 21st and 26th to 31st of the month, low values of solar radiation were observed. It is evident that after 21st day, the values keep on increasing until they reached maximum threshold value of 7.4 kWh/m^2/d. The high value was due to lack of cloud cover throughout the day and the sky was clear. During this month, there was no significant of rain and cloud. The town experienced total drought and radiation was reaching the earth with no obstructions. December is known for its hot and dry properties. Omwando, 2012 confirms that hot and dry is experienced during

December to February season. The result from Wajir town agrees that December was the month with highest solar radiation reaching the earth.

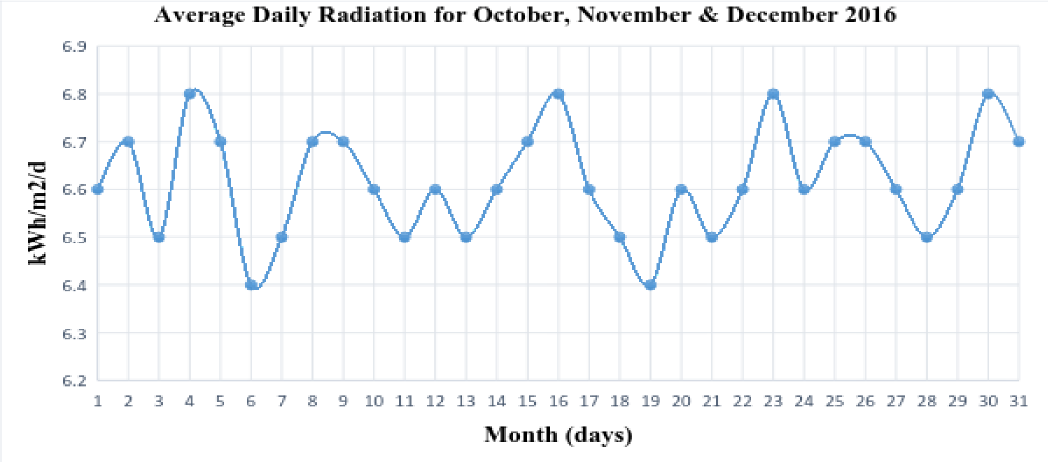

Figure 4: Average Daily Radiation for October, November and December 2016

Figure 4 depicts the average daily radiation of the three months. It was observed that the maximum value was 6.8 kWh/m^2/d and the minimum average was 6.4 kWh/m^2/d. It is evident that the region has reliable solar energy potential. The average radiation for the three months was 6.6 kWh/m^2/d and it represents the entire town of Wajir. When compared the average daily radiation of the three months and that of data recorded from the meteorological department (Table 3), it is evident that Wajir has an average of between 6.6 kWh/m^2/d and 6.8 kWh/m^2/d.

3.2 Monthly Radiation from Meteorological department

Table 2: Annual Insolation Averages for Wajir County

Monthly Radiation Averages in kWh/m^2/day (2000-2010)													
Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	**Average**
2000	7.4	7.6	6.8	6.1	5.6	4.9	4.8	5.6	6.5	6.1	5.7	6.7	**6.2**
2001	7.3	7.4	7.5	6.5	6.1	5.1	5	6.3	7.4	5.9	5.7	7.3	**6.5**
2002	7.4	7.5	7.6	6.1	6.5	6.5	5.9	6.4	6.9	5.9	7.2	7.2	**6.8**
2003	7.5	7.4	7.4	6.4	6.5	6.2	6.6	7.5	7.2	6.8	7.3	7.1	**7**
2004	7.3	7.6	7	7.5	6.8	7.3	6.8	7.1	7.4	7.4	6.7	7.6	**7.2**
2005	7	7.2	7.5	7.3	6.4	6.5	6.6	6.5	7.6	7.4	6.8	7.3	**7**
2006	7	7.5	7.4	6.2	6.8	7.2	7.3	7.5	7	7.4	6.8	7.6	**7.1**
2007	7.6	7.7	7.6	6.7	6.4	6.9	6.1	6.6	6.6	6.2	6.8	7.1	**6.8**
2008	7.6	7.7	7.4	6.3	6.3	6.6	6.5	6.8	6.6	7.3	6.5	6.7	**6.8**
2009	7.4	7.6	7.5	6.7	6.9	6.9	6.4	5.6	6.8	7.3	6.6	7.3	**6.9**
2010	7.8	7.7	7.3	6.9	7.4	6.5	6.6	6.6	6.4	6.8	7.1	7	**7**
Average	7.4	7.6	7.4	6.6	6.6	6.4	6.3	6.7	7	6.8	6.7	7.2	**6.8**

Table 2 shows the insolation values from meteorological department for Wajir town (2000-2010). It was observed that the minimum recorded monthly value was 4.8 kWh/m/d and maximum value of 7.8 kWh/m/d. February has the maximum average of 7.6 kWh/m/d while July had the minimum of 6.3 kWh/m/d. The penetration was high during the month of February due to the hot and dry season from December to February. During June- August season low penetration was observed due to cold dry season. Kenyan seasons are classified into: December- February, dry hot season; March-May, long rains season; June-August, dry cold season and September-November, short rains season (Okoola *et al.*, 2008). The result confirms that Wajir receives high solar radiation during December-February and low penetration during June-August season.

3.3 SEASONAL RADIATION ANALYSIS

The climate system in Kenya has four seasons namely: December-February, hot season; March-May, rainy season; June-August, cold season and September-November, short rains season (Okoola *et al.*, 2008).

3.3.1 Dec-Feb seasons

From the observation in table 3, January has the highest value of 7.8 kWh, February with7.7 kWh and December 7.6 kWh. The result shows that during December to February season solar radiation reaching Wajir town was high.

Table 3: Radiation values for Dec-Feb season 2000-2010

	Dec	**Jan**	**Feb**
Max recorded value (kWh)	7.6	7.8	7.7
Min recorded value (kWh)	6.7	7	7.2
Mean daily value (kWh)	7.2	7.4	7.6
Monthly mean value (kWh)	**223.2**	**229.4**	**216.6**

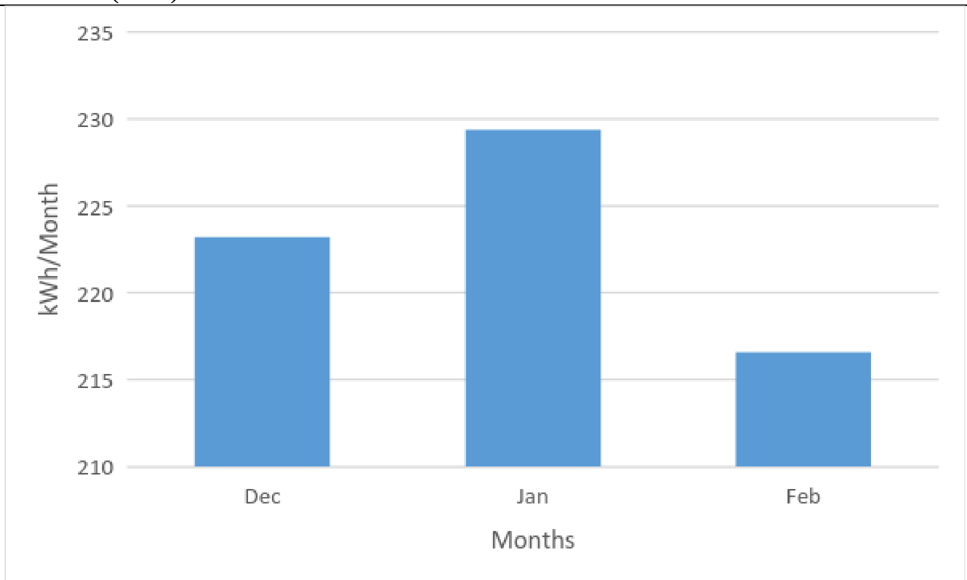

Figure 5: Dec-Feb Season in kWh/month 2000-2010

3.3.2 Mar-May Season

From the observation in table 4, March has the highest value of 7.6 kWh, April with 7.5 kWh and May 7.4 kWh. The result shows that during March-May season solar radiation reaching Wajir town was not high due to rain. Figure shows the fluctuation in the penetrations of radiation.

Table 4: Radiation values for Mar-May season 2000-2010

		Mar	**Apr**	**May**
Max recorded value (kWh)		7.6	7.5	7.4
Min recorded value (kWh)		6.8	6.1	5.6
Mean daily value (kWh)	7.4	6.6	6.6	
Monthly mean value (kWh)		**229.4**	**198**	**204.6**

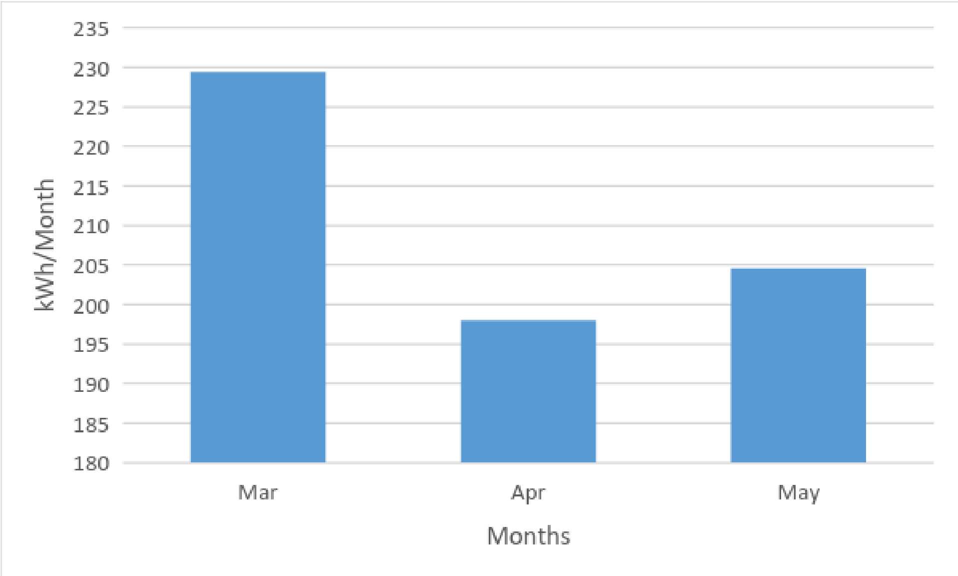

Figure 6: Mar-May Season in kWh/month 2000-2010

3.3.3 June-Aug Season

From the observation in table 5 August has the highest value of 7.5 kWh, June and July with 7.3 kWh each. The result shows that during June-August season solar radiation reaching Wajir town was moderate due to cold and dry throughout the season.

Table 5: Radiation values for June-Aug season 2000-2010

		June	**July**	**Aug**
Max recorded value (kWh)		7.3	7.3	7.5
Min recorded value (kWh)		4.9	4.8	5.6
Mean daily value (kWh)	6.4	6.3	6.7	
Monthly mean value (kWh)		**192**	**195.3**	**207.7**

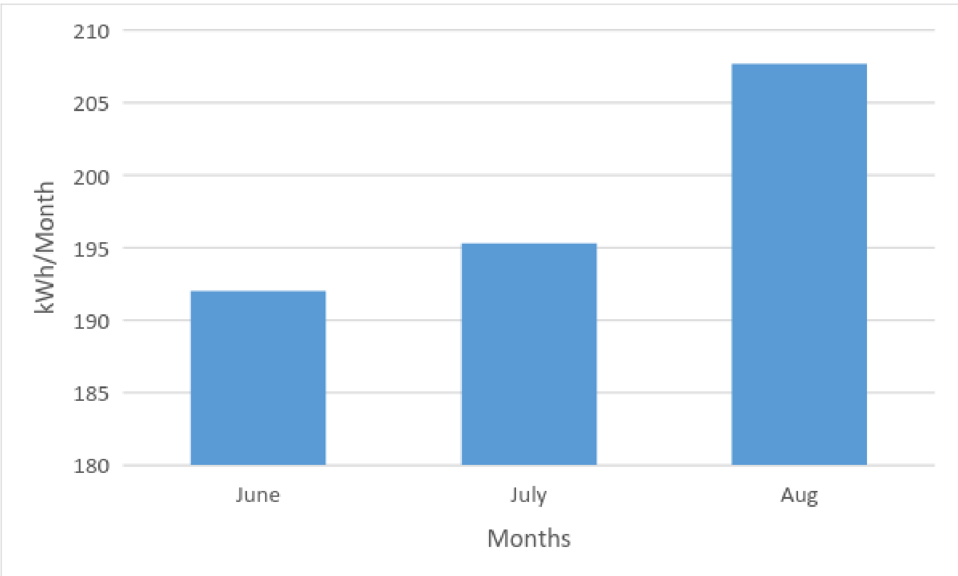

Figure 7: June-Aug Season in kWh/month 2000-2010

3.3.4 Sep-Nov Season

From the observation table 6 September and October have the highest values of 7.6 kWh each, November with 7.3 kWh. The result shows that during September- November season solar radiation reaching Wajir town was moderate of 7.3-7.6 kWh.

Table 6: Radiation values for Sep-Nov season 2000-2010

	Sep	Oct	Nov
Max recorded value (kWh)	7.6	7.6	7.3
Min recorded value (kWh)	6.4	5.9	5.7
Mean daily value (kWh)	7	6.8	6.7
Monthly mean value (kWh)	**210**	**210.8**	**207.7**

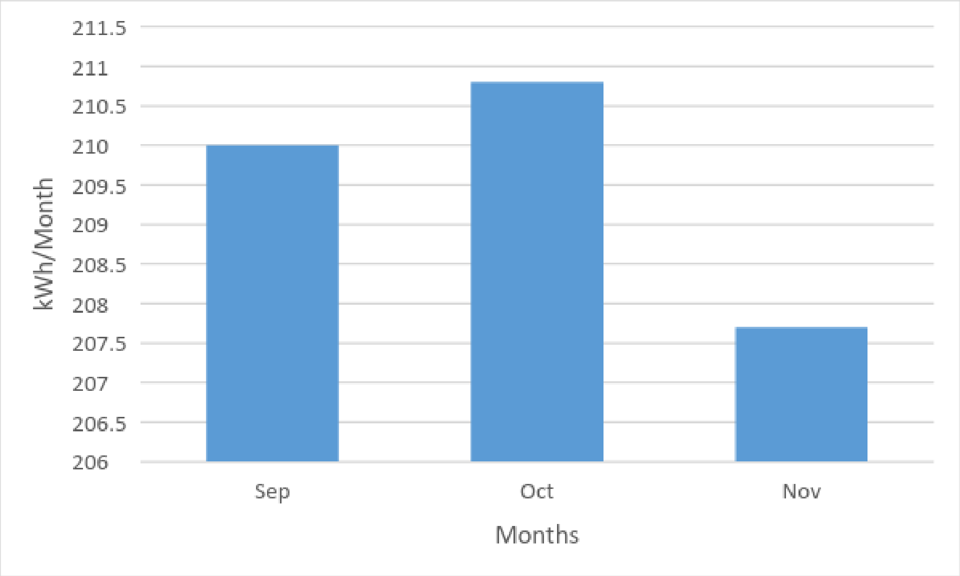

Figure 8: Sep-Nov Season in kWh/month 2000-2010

3.4 Solar energy design for Wajir Town using Sunny Design

The table 7 shows the total energy demand for the households. The total energy demand in kwh/day for the twenty households are 42.45kWh/day and 15494.25kWh/yr. 300 households were used for the design.

20 households =42.45kWh/d

300 households=?

$\frac{300\ households \times 42.45 kWh/d}{20\ households}$ = 636.75KWh/day ≈ 232413.75kWh/yr.

Table 7: Daily energy consumption for households

Appliances	Quantity	Amount of energy per unit	Usage hour per day	Daily use of electricity (kWh per day)
Lightings	120	60	5	36
Fun	12	75	6	5.4
TV	14	15	5	1.05

Table 8: Energy demand for the shops

Appliances	Quantity	Amount of energy per unit	Usage hour per day	Daily use of electricity(KWh per day)
Lightings	300	60	5	90
Fun	1(20)	75	4	6
Refrigerator	35	80	12	33.6
Mobile charger	2(20)	4	10	1.6

Due to the high temperature condition the region uses electric Fun continuously for four hours. It is clearly shown in table 8. The total energy demand in kwh/day for the twenty shops was 132 kWh/day and 48180 kWh/yr. Four mosques were observed with only lamps for lightning and fans. Each has a 4 hour twelve lamps of 60W each and a 6 hour 8 Funs of 75W each. It is shown in table 10 with the total daily use of the electricity in kilowatt-hour per day for the mosque. The total energy demand in kwh/day for the four mosques are 17.28 kWh/day and 6307.2 kWh/yr.

Table 9: Daily energy consumption for the mosques

Appliances	Quantity	Amount of energy per unit	Usage hour per day	Daily use of electricity(KWh per day)
Lightings	12(4)	15	4	2.88
Fun	8(4)	75	6	14.4

Wajir Town is served by one health Centre that as shown in table10.The total energy demand in kwh/day for the four mosques were 17.3 kWh/day and 6314.5 kWh/yr.

Table 10: Daily energy consumption for the health clinic center

Appliances	Quantity	Amount of energy per unit	Usage hour per day	Daily use of electricity(KWh per day)
Lightings	1500	36	11	594
Fun	750	75	10	562.5
Refrigerator	20	80	24	38.4
Desktop Computers	250	55	6	82.5

3.4.1 Households and mosques Demand

Total demand in a year for 300 households = 232413.75kWh/yr.
Total demand in a day for =636.75kWh/day.
Total demand in a day and year for the 4 mosques=17.3 kWh/day and 6314.5 kWh/yr.

Total demand for the mosques and households in a year =238728.25 kWh/yr.
Average daily sum =6.6h

$$\frac{238728.25 kWh/yr}{6.6h}$$

$$\frac{36170.95 kW/yr}{365}$$

$$\frac{99.1 kW}{0.8 \times 0.96 \times 0.74} = 174.4 kW$$

$Size of the Array \sim 70\% \; of \; 174.4 \; kW = 122.1 \; kW$

The number of modules are 488 modules

The rated capacity of each PV module used in the study was 250W whose initial capital cost is $195. 476 PV modules were used during the design with peak wattage of 116.16 kWp. The modules are ground mounted. The maximum available PV energy was 232413.75 kWh/yr. Using equation 4 the total number of inverters were 8 inverters with rating capacity of 25 kW

Inverters used were five Sunny Tripower type with Maximum AC active power of 22 kW, Maximum DC power 25.55 kW. It has nominal power ratio of 91%. The inverters are compatible with the size of the PV array. It has efficiency of 91.2% with integrated DC surge arrester.

3.4.2 Shops Demand

Total demand in a year =48180 kWh/yr.
Average daily sum =6.6

$$\frac{48180 kWh/yr}{6.6h}$$

$$\frac{7085.3 kW/yr}{365}$$

$$\frac{20 kW}{0.8 \times 0.96 \times 0.74} = 35.2 kW$$

$Size of the Arry \sim 70\% \; of \; 35.4 kW = 25 kW$

The total number of modules were 100 modules.

The rated capacity of each PV module used in the study is 250W whose initial capital cost is $195. PV modules are connected in series in order to generate the desired output. And as such, several units' sizes were put to be considered in the project for optimization of the whole system. 100 PV modules was used during the design. The modules are ground mounted. Using equation 4 the total number of inverters was 1 inverter with rating capacity of 20 kW.

Inverter used was only one of Sunny Tripower type with Maximum AC active power of 20kW, Maximum DC power 25.00 kW with maximum input voltage of 1000V and rated voltage of 600V. It has nominal power ratio of 110%.

3.4.3 Health Centre Demand

$$\frac{466251 kWh/yr}{6.6h}$$

$$\frac{70644.1 kW/yr}{365}$$

$$\frac{194 kW}{0.8 \times 0.96 \times 0.74} = 341.36 kW$$

$Size of the Arry \sim 70\% \; of \; 341.36 \; kW = 239 kW$

The total number of modules were 956 modules.

The rated capacity of each PV module used in the study is 250W whose initial capital cost is $195. 956 PV modules was used during the design. The cost of a diesel generator depends on its size. For the present study, the DG capacity is rated as 304kW of 380kVA. Therefore, even though the design proposed in this study ensures the guaranteed electricity source from diesel generators, the aim always remains to reduce their operating hours. The fuel consumption by the generator was 80.0 I/h or 3.50kWh/l. The fuel cost is considered to be $0.85 per liter. The lifetime of DG is 15000 operating hours. The generator model is designed in such a way that it can operate in standalone mode to feed the load. The DG output is utilized to meet the load. Using equation 4 the total number of inverters were11 inverters with rating capacity of 25 kW

Inverters used are eleven Sunny Tripower type with Maximum AC apparent power 25.00 kVA, Rated power 25.00 kW. The inverters are compatible with the size of the PV array. It has efficiency of 98.4% with integrated DC surge arrester and has DC input voltage of up to 1000V.

IV. Conclusions

Results revealed that Wajir town has an average daily insolation of 6.6 kWh/m^2 however, the amount of solar energy available is season dependent with December-February season receiving the highest amount of 7.4 kWh/m^2 and June-August season receiving the least amount of 6.5 kWh/m^2.

The total energy demand for the twenty households are 42.45 kWh/day and 15494.25 kWh/yr. The total energy demand for the twenty shops is 132 kWh/day and 48180 kWh/yr. The main hospital had an average daily energy of 466251 kWh/yr. The rated capacity of each PV module used in the study is 250W whose initial capital cost is $195.In the case of the hospital hybrid system was necessary therefore the need to design standby diesel generator. The cost of a diesel generator depends on its size. For the present study, the DG capacity is rated as 304 kW of 380 kVA. Therefore, even though the design proposed in this study ensures the guaranteed electricity source from diesel generators, the aim always remains to reduce their operating hours. The fuel consumption by the generator is 80.0 I/h or 3.50 kWh/l. The fuel cost is considered to be $0.85 per liter. The lifetime of DG is 15000 operating hours. The generator model is designed in such a way that it can operate in standalone mode to feed the load. The DG output is utilized to meet the load.

Therefore it requires a PV system capacity of 239 kW for the hospital, 25 kW for the shops and 122.1 kW for 300 households with no battery since the design used sunny design, a technology that omits battery usage and instead tripower inverters were used which are smart and can work in both ac and dc applications.

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