DESIGN OF HYBRID SOLAR ENERGY SYSTEM FOR THE APPLICATION OF TRAIN LOCOMOTIVE POWER SOURCE FOR THE AALRT AND ETHIO-DJIBOUTI ROUTES

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ABSTRACT

The scarcity and environmental effect of the non-renewable energies and the abundance and opportunities of renewable energies lead to the development of a hybrid solar system with diesel and electric sources. This research has considered a PV solar cell to design a hybrid solar system for the railway train traction system. In this study, the widely known Angstrom correlation has been used to compute the daily radiation and energy utilization on the Ethio-Djibouti railway route. The data which has been used in the computation covers from 3 to 5 years sunshine hour data that was collected by the Ethiopian National Metrology Agency Service. This has been compared with the calculated value. Based on the technical proposal of the ERC; Box type, YZ25G, DFN7G and AALRT, tram train cars had been selected for the installation of solar panels at the top roof surface area of the car. To compute and to model the hybrid solar system, MATLAB, CATIA, Microsoft Visio and Microsoft Excel software were used. The amounts of solar energy generated for the traction, reduction of carbon emission and cost levelization of the system have been included in the research. The generated energy may cover 4.455 to 356.9% of required energy based on the sunshine hour duration, types of car and configuration;, Therefore, the excess energy shall be sent to the main grid for other purposes to reduce the wastage. For all selected trains, it was calculated that a total number of 2011 panels with a total of 30 years' service and life cost of 56,764,325bir will be required. Considering the minimum energy production and maximum configuration, the cost return time may be 12 years. Therefore, it will operate for 18 years with profit. The reduction of carbon emission which is found based on the amount of fuel consumed ranges from 214.63 kg to 6845.85 kg and 107.313 kg to 3447.02 kg per trip for freight and passenger transportation respectively. The research generally shows the possibility of application of solar energy through the selected route and the best solution for sustainable energy supply which helps the overall economic development and environmental protection in the country.

Keywords: *Photovoltaic, levlization, hybrid, dispatcher, rooftop-camber*

INTRODUCTION

The rising of cost and shortage of fuel together with the pressing need to reduce air pollution are the main motives that lead to the development of efficient, emission free, economic, environmental friendly and sustainable electrical vehicles in the world. The world agreed at the present time to use a solar energy extensively on many energy applications due to its abundance [1, 8].

Ethiopian solar and wind energy resource (SWERA) reported (2007) that the annual average daily radiation for the country is 3.74kWh/m2/day. In other cases the Ethiopian resource group study shows the radiation is 5.5 to 6.5 kWh/m2/day within an average of 345 days [3, 8].

Sharew (2007) predicts the monthly average totals of global radiation on a horizontal surface in Ethiopia. He had modeled and analyzed using Simple Model of Atmospheric Radiative Transfer of Sunshine (SMARTS) and Vapor Pressure Radiation Model (VP-RAD) .As a result, the monthly mean of the daily global solar radiation on a horizontal surface is about 19.5 MJ m^{-2} and 12 MJ m^{-2} respectively [12].

Tesfaye, *et al* (1989) estimates the solar radiation of Ethiopia 500 Wh/m2/day by using Angstrom score-relation [10].

The application of solar energy for the railway system is limited due to lack of advanced technology, but some countries plan to use the hybrid system for different uses in their railway system.

The Solar Century company is installing a total of 4400 Panasonic HiT solar panels on 6000 m2 Black friars railway bridge in England and it generates 900,000kWh of electricity and saves over 500 tons of carbon for the railway station system per year [5].

The Indian Railway, being the world biggest railway system,, has planned to use innovative technology to tap alternative sources of energy to reduce dependence on fossil fuel and the power grid by using solar energy for the nterior lighting and cooling [4].In this research it is possible to show that solar energy is used to operate the train based on the design of the system.

The Dubbed Vili tram, the first solar powered European rail car, fitted PV panels on the roof- top area of 9.9m2 and produce a power to derive two 7 kw motor with 25 km/h of the train [6].

The levelized costs of energy for large solar troughs with six hours of thermal storage ranged from below 20 to 30 US cents/kWh approximately for high heat generation. Technological improvements and cost reductions are expected, but the learning curves and subsequent cost reductions of solar technologies depend on production volume, research and the cyclic nature of the Sun affects.

Solar energy is the most abundant and none exhausted. Indeed, the rate of solar energy intercepted by the Earth is about15, 000 times greater than the rate at which humankind consumed energy [1, 4]. To capture the solar energy a photo-voltaic (PV) cell or concentrated solar power (CSP) cell may be used. The daily amount of generated solar power is dependent on the configuration of number of trains, geographical position and light radiation angle, solar radiation intensity, PV performance, length of sunshine hour, weather condition, efficiency and size of solar panel. The main objective of this study is to design a hybrid solar energy system by installing the PV at the roof-top area of the configured train cars for the application of locomotive traction system that operates through AALRT and Ethio-Djibouti railway route. In turn to compute the amount of energy added to the system, reduction of fossil fuels, main grid electrical energy consumption, carbon emission and levelize the cost. The significance of the present study is to provide a general information on solar energy resource of Ethiopia, to introduce and increase the potential usage of alternative energy efficiency in the railway transportation as well as other industries, to increase the gross energy sources in the country and to reduce the Co2 emission which is a serious problem in our planet.

METHODOLOGY

The methodologies followed in this study are reviewing different literatures, collecting data, model analysis of radiation, cost estimation and carbon emission.

a. Collecting Data

In this study, the data mainly collected from Ethiopian Meteorology Agency Service (EMAS) and Ethiopian Railway Corporation (ERC) proposed train specification and other related sources. Based on the EMAS information 3-5 years' sunshine hour and day duration data was collected and it is tabulated as follows:

In the analysis of a hybrid solar energy system, a commercial monocrystal silicon panel with a1.9558 m X 0.9906 m and efficiency of 28% has been installed at the top roof of the train. The number of solar panel installed is different based on the size and configuration of the train, and the effective top surface area. According to ERC proposal, the overhead contact power supply system's uses a 750v with 1050A and 132 kV with 508A and power factor of 0.95 for AALRT and Ethio-Djibouti route respectively. For the selected trains, the power consumption varies from 787.5 to 1564 kw of maximum service load. Other information taken from the proposal is the types of train car AALRT tram, Box type, YZ25G and DFN7G which have different functions, size and operating systems that help to compute the top surface area and the power consumption.

b. Modeling and Computation of Irradiation at the Surface of the Earth

Modeling of a data is a technique used to represent the reality of the things considered in the studying process. In this study a mathematical and physical model has included using application and language softwares such as CATIA, MaTLab, Microsoft Visio and Microsoft Exel.

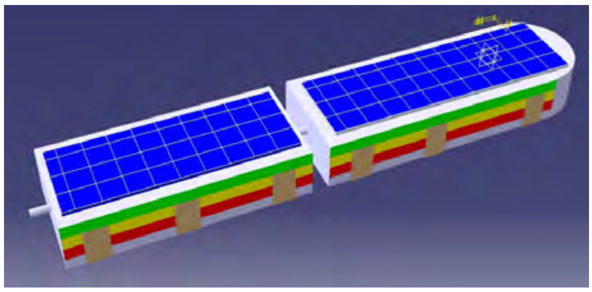

Figure 1 Physical model of the train roof-top area

In the modeling and computation of radiation and sunshine hour, the known angstrom correlation has been used that relates the latitude, angle of radiation and angle of earth declination. The calculated sunshine hour and day duration was compared with the actual data collected from the Ethiopian Meteorology Agency.

$$Sunrise = 12 - \frac{1}{15^0}\cos^{-1}\left(\frac{-\sin(\phi)\sin(\delta)}{\cos(\varphi)\cos(\delta)}\right)$$

$$Sunset = 12 + \frac{1}{15^0}\cos^{-1}\left(\frac{-\sin(\phi)\sin(\delta)}{\cos(\varphi)\cos(\delta)}\right) \quad (1)$$

Therefore, Sunshine hour duration

= sunset- sunrise

The monthly average daily global radiation intensity G on a horizontal surface (kwh.m^2.day^{-1}) is calculated using:

$$G = G_0\left(a + b\left(\frac{S}{S_{Max}}\right)\right) \quad (2)$$

Where; G_0 = the monthly average daily extra-terrestrial radiation on a horizontal surface (Kwh.m-2.day^{-1})

S = the monthly average daily hours of bright sunshine (hrs)

S_{max} = the monthly average day length (hrs), and "a" and "b" values are known as Angstrom Constants and are empirical.

;

$$a = -0.01 + 0.235\cos\phi + 0.323\left(\frac{S}{S_{Max}}\right)$$

$$b = 1.449 - 0.553\cos\phi - 0.694\left(\frac{S}{S_{Max}}\right) \quad (3)$$

For a given number of days starting from January (n) the solar declination (δ) and the mean sunrise hour angle *(W_s)* can be calculated using the following equations

$$\delta = 23.45° \times \sin\left(\frac{360(284+n)}{365}\right) \quad (4)$$

$$W_S = \cos^{-1}(-\tan\phi\tan\delta) \quad (5)$$

The values of the monthly average daily extra-terrestrial irradiation (G_0) can be calculated as

$$G_0 = \left(\frac{24}{\pi}\right)I_{SC}\left[1 + 0.033\cos\left(\frac{360n}{365}\right)\right] \times \left[\cos\phi\cos\delta\sin w_s\left(\frac{2\pi w_s}{360}\right)\sin\phi\sin\delta\right] \quad (6)$$

Where I_{SC} is the solar constant (=1367 W m^{-2}), ϕ is the latitude of the site.

c. Daily Solar Energy Obtained

In the computation of daily solar energy, assume that the effect of aerodynamic, boundary condition near the surface of the top roof, the camberness/ curvature of the roof, the property of the connected wire used in the power systems, are negligible.
The calculation of daily solar energy has been based on the clear sunshine hour duration. According to the ERC proposal the AALRT operates 14 hours per day with a maximum speed of 120 km/hr

Table 1 The average monthly day duration (S_{max} (hr)) and bright sunshine hour(S (hr))

	Addia Ababa		Debirezeit		Natheret		Metehara		Dire Dawa		Mieso	
Months	**S (hr)**	**S_{max} (hr)**	**S (hr)**	**S_{max} (hr)**	**S (hr)**	**S_{max} (hr)**	**S (hr)**	**S_{max} (hr)**	**S (hr)**	**S_{max} (hr)**	**S (hr)**	**S_{max} (hr)**
Jan	9.5	11.61	9.2	11.64	9.4	11.64	9.6	11.63	9.3	11.59	9.1	11.61
Feb	10	11.82	8.4	11.83	8.8	11.83	8.7	11.83	9.7	11.8	5.8	11.81
March	8.6	12.08	8.4	12.07	8.2	12.07	8.7	12.07	9.3	12.08	6.3	12.08
April	6.8	12.32	7.4	12.3	7.8	12.29	8.2	12.3	7.2	12.34	7.8	12.32
May	6.8	12.49	7.7	12.46	7.4	12.45	8.6	12.46	8.8	12.52	7.8	12.49
Jun	5.2	12.52	6.3	12.49	8.1	12.48	7.6	12.49	7.7	12.55	7.7	12.52
Jul	5	12.4	5.2	12.37	7	12.37	6.9	12.38	7.5	12.42	7.2	12.4
Aug	3.25	12.17	5.1	12.16	6.2	12.16	6.8	12.16	7.5	12.18	6.7	12.17
Sept	4.8	11.92	6.4	11.92	7.6	11.93	7.5	11.92	6.6	11.91	6.5	11.92
Oct	7.65	11.67	9.5	11.69	10.2	11.70	9.4	11.69	8.4	11.65	9.1	11.67
Nov	9.3	11.51	9.1	11.54	9.6	11.55	9.3	11.54	9.7	11.48	8.1	11.51
Dec	9.45	11.48	9.2	11.52	9.1	11.53	9.5	11.51	9.8	11.45	9.1	11.48

and the cross country passenger and freight train operates with a maximum speed of 160km/h and 120km/h for 14 and 28 hour respectively. The daily irradiance depends on a lot of variables such as geographic location, time, train orientation, weather conditions and albedo that represents the reflection on the ground surface.

$$G_{day\ density} = \frac{G_{max} T_{day}}{\pi/2} \eta_{wthr} \quad (7)$$

The daily generated power is dependent on the daily irradiation distribution and can be calculated as follows:

$$GA_{sc}\eta_{sc}\eta_{wthr}\eta_{mppt} \quad (8)$$

Where $P_{elec\ tot}$ = *power generated from the solar /day,*

A_{sc} = effective roofarea

η_{sc} = solar cell efficiency=28%,

$G_{per\ day}$ = solar radiation (KW/m^2/day),

n = number of cars in a train set,

η_{wthr} = day condition factor=1,

η_{mppt} = the maximum power point tracer

Coefficient = 0.98

d. Computation and Analysis of the Diesel Power Generation

The technical specification of the Ethiopian Railway Corporation (ERC) shows a DFN7G multipurpose train uses two diesel generators with maximum service power of 1564 KW and 782 KW/ engine. The train has consumed 207+3%g/KWh of fuel with a speed of 120 km/hr for freight and 160 km/h for passenger and the journey takes 14 hours and 7 hours from Addis Ababa to Djibouti respectively.

The total energy content of the diesel fuel generated from one kg of fuel is:

$$P_{per/kg} = m_{diesel} \times LHV_{diesel} \quad (9)$$

Where m_{diesel}= is the kg of fuel consumed by the generator, according to the ERC, is 0.213 kg/KWh at rated power, but here in the computation the service power is considered.

LHV_{diesel} = the lower heating value of diesel fuel, which is 43MJ/Kg (11.979 kwh/kg), and the efficiency of the diesel generator ranges from 40 - 80%. For this study, 75% has been taken.

$$P = m_f \times \gamma \times P_{per/kg} \quad (10)$$

Total fuel consumed = $\frac{m_f}{h} \times T(h)$, consider the density of the diesel fuel used for train as 860 kg/m^3;

e. Energy Storage, Control Units and Junctions

i. Design of Battery for Hybrid System

The main selection criteria for solar energy storages are the energy and power density, the response time, the lifetime, the efficiency, cost, the gravimetric energy density in Wh/kg, and the peak power. For this study, a sealed maintenance free 48 batteries with 2V and 500Ah per battery were used, which is compatible to the technical specification of ERC. The battery charging capacity B_{rc} can be calculated as:

$$B_{rc} = \frac{E_{c(AH)} D_s}{(DOD)_{max} \eta} - \frac{500Ah \times 5}{0.75 \times 0.9} = 3703.704Ah \quad (11)$$

Where DOD = battery depth of discharge =0.75

D_S = battery autonomy or storage days

η = temperature correction factor= 0.9

$E_{c(AH)}$ = energy ampere in hour

Assume the charging autonomy is 5 hours, then the possible total power delivery from the battery can be

$$P_{b\,single} = B_{rc} + V_b = 3703.704 \times 2 = 7.407kwh \qquad (12)$$

Therefore, the required number of battery to store the energy required will be:

Number of battery required

$$= \frac{Power\,use\,for\,traction}{P_{b\,single}} \qquad (13)$$

Control Unit and Converters

The VVVF control units and converter with a capacity of output power that is greater than 1000 KW is selected as it is similar to the proposed type for ERC trains. The other unit used in the system is a four battery charge and discharge controller with a capacity of 280 VAC output voltage with a charging span of 10,000 times.

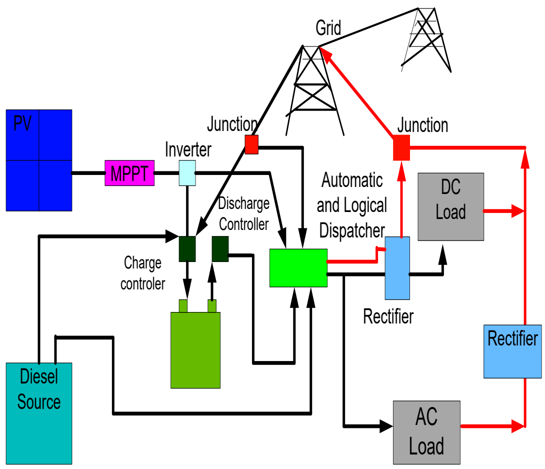

Figure 2 PV, Diesel and Grid Connected hybrid system circuit schematic diagram

Cost Levelization And Cost Comparison of The Hybrid System

According to the world battery market, the price of the single battery is $350, therefore, the total price of the battery used for this analysis will be:

Total price of battery = total number of battery X price/ battery = 529x350 = $188,650 which is equivalent to 3,886,190 ETB. The present selling price of the Ethiopian electrical power corporation is 1.75 ETB per KWh. Then, the total price for one trip from Addis Ababa to Djibouti will be:

$$C_{total} = P \times H \times C_{per\ KWH} \qquad (14)$$

Where C_{total} = total price of consumed power;

P= power consumed;

H= number of driving hours and

$C_{per\ KWH}$ = price per KWh

The selected inverter, MPPT, junction, and charge and discharge controller are $525, $600, $87 and $52 respectively. The price of all other necessary components of the system is included in the total cost of a panel. Based on the manufacturer information, a monocrystal silicon solar cell panel has a potential of 27 to 30 years of service life. Consider 30 years life span and the battery shall be replaced within 15 years at average cost of $188,650 (3,867,325Birr) in life.

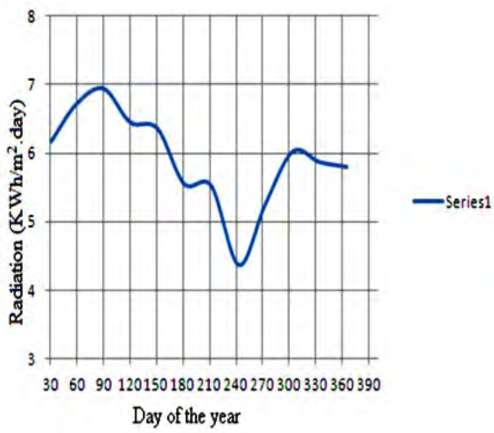

Figure.3. Radiation distribution throughout the year at Addis Ababa

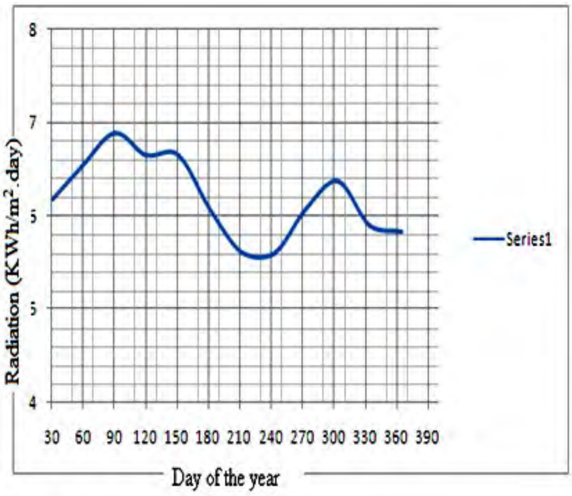

Figure 4 Radiation distribution throughout the year at DebireZeit

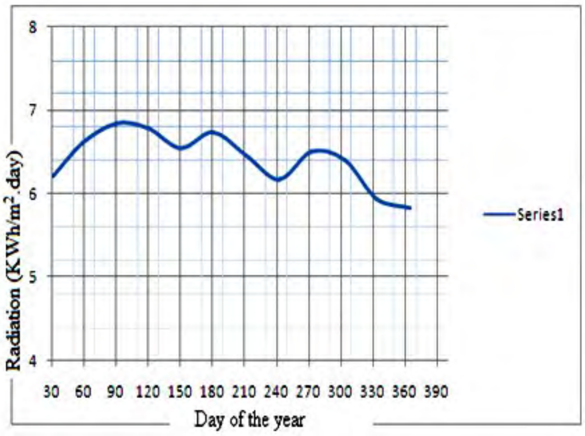

Figure 5 Radiation distribution throughout the year at Natherat

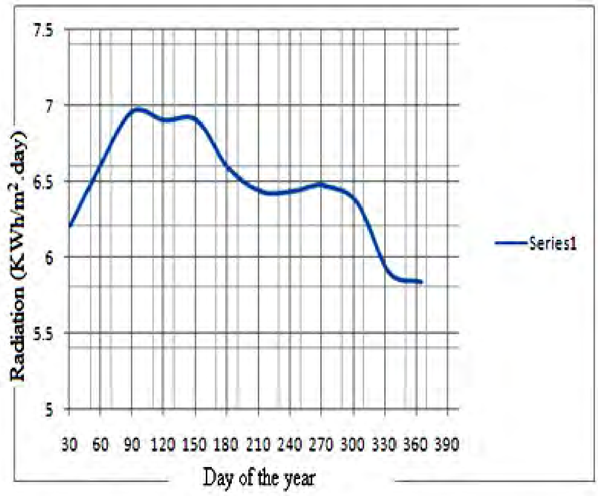

Figure.6. Radiation distribution throughout the year at Metehara

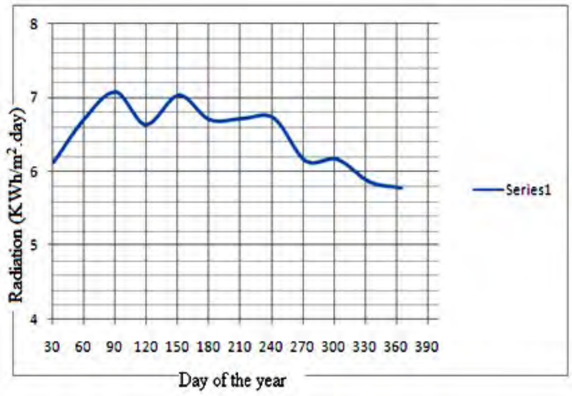

Figure 7 Radiation distribution throughout the year at Dire Dawa

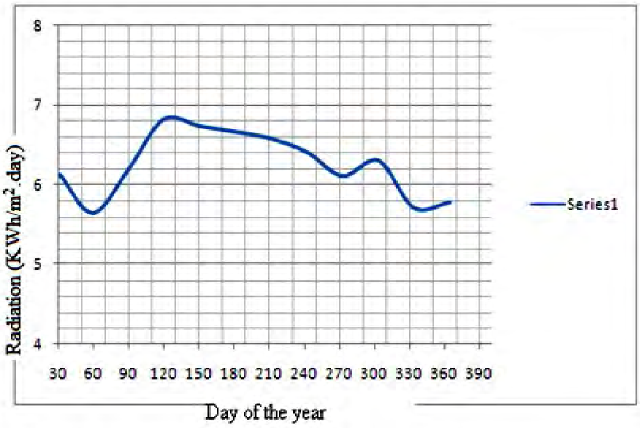

Figure 8 Radiation distribution throughout the year at Mieso

The daily radiation of the route varies based on the day length, weather factors, position of the site and inclination of the sun. As seen from the Table and graph bellow, the longest day duration is recorded in June; and the longest sunshine result has a long sunshine hour and also 345 average sunshine days. This is recommended for Industries but due to the low stage of the solar technology, the industry is forced to use a hybrid system for different applications.

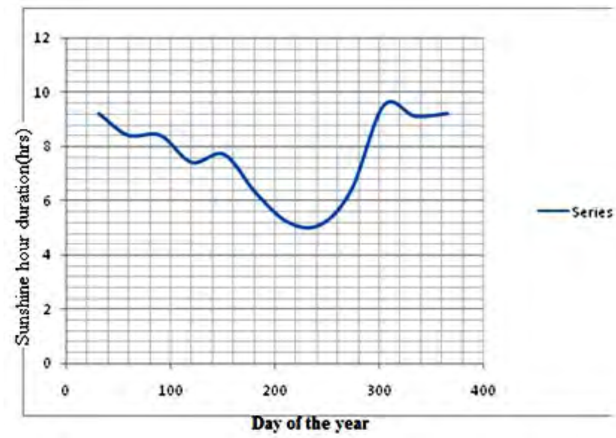

Figure 9 Sunshine hour variation in a year

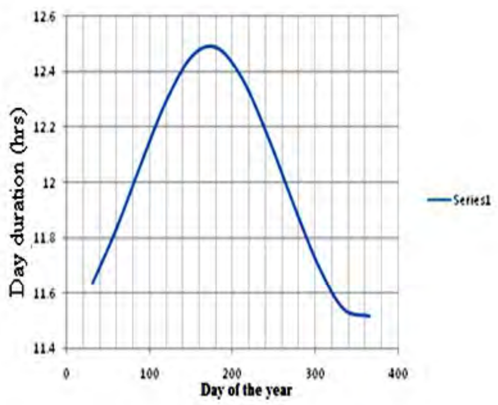

Figure 10 Day duration in a year

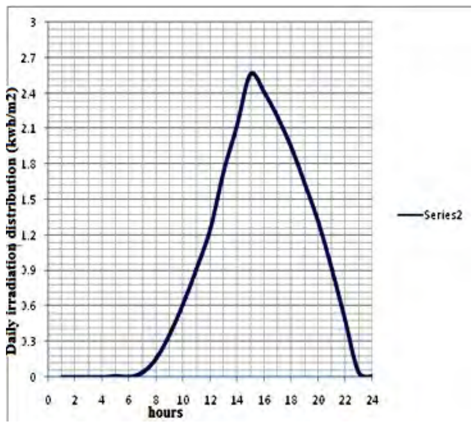

Figure 11 Approximation of irradiance as a sinusoid distribution in a day

Table 2 The hourly distribution of radiation

Hour	η_{wthr}	G_{max}	Irradi-ancedist.
0:00	0.0001	6.898	0
1:00	0.0005	6.898	8E-05
2:00	0.0009	6.898	3E-04
3:00	0.001	6.898	5E-04
4:00	0.005	6.898	0.003
5:00	0.059	6.898	0.035
6:00	0.04	6.898	0.039
7:00	0.125	6.898	0.143
8:00	0.25	6.898	0.327
9:00	0.375	6.898	0.552
10:00	0.5	6.898	0.818
11:00	0.625	6.898	1.125
12:00	0.795	6.898	1.561
13:00	0.895	6.898	1.903
14:00	1	6.898	2.29
15:00	0.875	6.898	2.147
16:00	0.75	6.898	1.963
17:00	0.625	6.898	1.738
18:00	0.5	6.898	1.472
19:00	0.375	6.898	1.166
20:00	0.25	6.898	0.818
21:00	0.125	6.898	0.429
22:00	0.01	6.898	0.036
23:00	0.0006	6.898	0.002
0:00	0.0001	6.898	4E-04

It is observed that the energy generated from solar is sometimes more than the power required by the locomotive. Therefore, the energy generated from the solar and main grid has to be hybridized into a single system. It is governed by different dispatchers in such a manner that priority is given more to solar energy consumption than the grid. The remaining unused energy will be stored in batteries and, when the battery becomes full, the excess energy can be turned to the grid system through the return line. Based on the equation (12), the total number of batteries required for these four types of train set is 539. In other case the train car may be parked at the station but it continuously generates energy so that the total energy shall be sending to the main grid and bf used for other purposes.

DFN7G multipurpose train consumes a diesel fuel for its traction system. Therefore, it was found that the amount of fuel used 4874.31kg(5667.8lit), 2437.15kg (2833.9lit) per trip for freight and passenger train and its cost it is estimated to be $4858.114 and $2429.057 respectively. But one of the problems of our earth is pollution due to the release of carbon emission from the diesel fuel. Therefore, when the train uses this hybrid solar system, it reduces 214.63 kg to 6845.85 kg and 107.313kg to 3447.02 kg per trip for freight and passenger train application respectively.

The total investment and operating cost will be 56,764,325 Birr and it returns back with 12 year for a minimum energy production and maximum allowable train configuration. Therefore, it operates 18 years with profit. This implies the use of this hybrid energy system has a significant contribution for the growth of the country's economy, and it will constitute a milestone in an attempt to see alternative and renewable energy in the transport industry.

The other economic advantage of using the hybrid system is reducing fuel cost and making the investment needed on environmental protection.

see alternative and renewable energy in the transport industry. The other economic advantage of using the hybrid system is reducing fuel cost and making the investment needed on environmental protection.

Table3The summarized minimum and maximum energy generated and percentile coverage of the total consumption

			Box type Freight Car		YZ25Gpassenger car		DFN7G multipurpose		AALRT passenger	
			A/car=50.35 No. Car=1&20 P_{grid} (KW)= 815.4 No. panel/ car= 26/ Power/panel=200w		A/car=75.54 No. Car=1&20 P_{grid} (KW)=815.4 No. Panel/ car= 39 Power/panel=275w		A/car=58.11 No. Car=1&20 P_{grid} (KW)=1564 No. panel/ car= 30 Power/panel=275w		A/car=71.669 No. Car=1&3 P_{grid} (KW)=787.8 No. panel/ car= 37 Power/panel=300w	
Stations	**Month**		P_{SC} (KW)	% coverage	P_{SC} (KW)	% coverage	P_{SC} (KW)	% coverage	P_{SC} (KW)	% coverage
A.Aa	Aug	Min	60.39	7.41	90.59	11.11	69.68	4.455	85.947	10.91
	Mar	Max	1919.77	235.44	2881	353.4	2216	141.7	409.8	52.04
D/Zeit	Aug	Min	77.43	9.81	116.3	14.26	89.45	5.72		
	Mar	Max	1944.55	238.48	2861	350.8	2200	140.7		
Natherat	Dec	Min	80.75	9.87	118.8	14.57	91.37	5.842		
	Mar	Max	1930.51	236.76	2844	348.8	2188	139.9		
Metehar	Dec	Min	80.75	9.903	120.6	14.8	92.8	5.934		
	Mar	Max	1923.87	235.94	2890	354.4	2223	142.1		
D/Dawa	Dec	Min	79.86	9.79	126.7	15.53	97.43	6.229		
	Mar	Max	1955.71	239.85	2910	356.9	2239	143.1		
Meiso	Feb	Min	77.93	9.56	118.4	14.52	91.05	5.821		
	Apr	Max.	1884.98	231.17	2827	346.8	2175	139.1		

Table 4 The Energy produced from PV and Cost computation

Type	Max. No. of cars	No. panel / car	Total No. of panel	Panel capacity (watt)	Total cost/ panel system	Total price (Birr)	Min. average P_{SC}	Energy price of solar/year (Birr)	Consumed Energy price /year (Birr)
AALRT	3	37	111	300	35,000	3,885,000	116.47	223,185.64	6,038,487
Box type	20	26	520	200	22,600	11,752,000	87.185	1,113,788.38	10,987,515
YZ25G	20	39	780	275	27,000	21,060,000	131.25	1,676,718.75	10,947,090
DFN7G	20	30	600	275	27,000	16,200,000	100.28	1,281,077.0	27,521,216
Total	20		2,011	516,800		52,897,000		4,294,769.77	55,494,308

CONCLUSION

The purpose of this research work has been to compute the possible amount of solar energy produced from the roof-top of the train car, for both the percentage reduction of energy consumption and carbon emission.

Based on the data collected and mathematical computation Ethiopia has an average radiation of 5.87kW/m^2/day, which indicates the country has a great potential to generate electric power from the sun for the application of train traction system and other applications to reduce fuel dependency, main electric consumption and carbon emission.

It is observed from Table 2 that the minimum radiation is 4.37KW/m^2/day obtained at Addis Ababa in August and the maximum obtained at Dire Dawa which is 7.o79KW/m^2/day in March. The amount of energy generated varies with the radiation and number of cars configured as a result, AALRT, Box type, YZ25G and DFN7G with the percentile consumption coverage of 10.91 - 52.04%, 7.41 - 239.85%, 11.11 -356.9% and 4.455 -1 43.1% being computed respectively. Therefore, 10,14,9 and 18 number of cars shall be configured to cover all the required power with minimum energy production. But for AALRT, the maximum allowable configuration of a car is three and it remains as a supplemental system.

According to the analysis, there is a potential to produce excess energy. Therefore this will be sent to the main grid for other application that support the overall economic development of the country.

It was observed that, with a minimum energy production, the cost of return time takes 12 years and it is expected to operate 18 years with profit. Moreover, the carbon emission from DFN7G multipurpose diesel train cars might be reduced from 214.63 kg to 6845.85kg and 107.313kg to 3447.02 kg per trip for freight and passenger application respectively. Generally, it is possible to conclude that the use of this hybrid system for railway train traction system has an enormous advantage for the country's economic growth and environmental protection.

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