

ADDIS ABABA UNIVERSITY
ADDIS ABABA INSTITUTE OF TECHNOLOGY
SCHOOL OF MECHANICAL AND INDUSTRIAL ENGINEERING
GRADUATE PROGRAM IN RAILWAY ENGINEERING



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

By:
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**A Thesis Submitted to the School of Graduate Studies of Addis Ababa University in Partial
Fulfillment of the Requirement for the Degree of Masters of Science in Mechanical Engineering
(Railway Engineering Stream)**

Advisor:
HABITAMU TKUBET

March 2015

ADDIS ABABA INSTITUTE OF TECHNOLOGY
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**Design of Hybrid Solar Energy System for the Application of Train
Locomotive Power Source for the AALRT and Ethio-Djibouti Routs**

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DECLARATION

I **declare** that the thesis report entitled “**DESING OF HYBRID SOLAR ENERGY SYSTEM FOR THE PPLICATION OF TRAIN LOCOMOTIVE POWER SOURCE FOR THE AALRT and ETHIO-DJIBOUTI ROUTS**” comprises of original work (except where indicated) carried out by me and due the acknowledgements have been made in the text to all other materials used. The dissertation does not contain any classified information and has not been submitted in any form for another degree at any other Institution/Universities.

SHIMELS KEBEDE

Date

This is to certify that the thesis entitled, submitted by candidate is in partial fulfillment of the requirements for the award of Master of Science degree in mechanical engineering (railway engineering stream). To the best of my knowledge, the matter embodied in the thesis has not been submitted to any other University / Institute for the award of any Degree or Diploma.

Advisor: Mr. **HABITAMU TKUBET**

Date

ACKNOWLEDGEMENTS

First and foremost, praise and thanks goes to my God for the blessing that has been bestowed upon me in all my endeavors.

I am deeply indebted to Mr. Habitamu Tikubt my advisor and guide, for the motivation, guidance and patience follow throughout the research work. I appreciate his broad range of expertise and attention to detail, as well as the constant encouragement he has given me over the years. There is no need to mention that a big part of this thesis is the result of work done by me under his guidance, without which the completion of the work would not have been possible.

I also want to thanks to my Friend Mr. Lema Mamo for his unlimited support and encouragement.

Finally, I wish to express sincere thanks to my lovely wife Frehiwot Meleaku for her moral support, tolerance and understanding while from the beginning to the final preparation of this thesis. You, my love Frehiwot and Yohanna, our angle daughter we are thousands of miles far but you are in my heart in each and every minutes I hope, as wish of God we will be together soon.

ABSTRACT

Revolutionary changes have been taken place in the life of the mankind since human beings acquired the capability of walking fast. Now a days rail transport become a cheap means of transportation system to any class of people and goods. The train uses a diesel or electrical energy for its propulsion based on its design but due to the raise of fuel price and environmental pollution factor, the modern train uses an electrical energy which is finally converted in to mechanical support for the propulsion. The electrical energy is generated from different form of energy sources among the various forms of energy, solar energy is the best form to use in the present situation due to its, abundablity, environmental friendly and sustainability.

In this study, the applications of solar energy to railway locomotive power propulsion system, using photovoltaic solar panels is analyzed and develop a grid connected system with a storage battery to store excess energy for emergency and night time, the rest excess generated energy is send back to the grid through the return line which is already build up by Ethiopian Rail way corporation power system directly through the line and as a form of regenerative energy during brake. The research mainly focuses on the conversion, the amount of electrical energy produced from the sun with the pre defined solar panel and its application for the railway propulsion system as a supplemental energy source for the electrical and diesel traction system for the selected newly build up Ethiopian rail way car and routs by maximize the solar source and minimizing the others. Therefore the different literatures was asses, important data was collected from different rail way companies and national meteorology agency and other sources, the amount of energy produced is mathematically calculated, the data which is collected was computed by using a Microsoft excel and Mathlab, the hybrid energy system layout and a physical model of a train car could be developed using a Microsoft Visio and CATIA software respectively. In this research, the well known Angstrom correlation, which used sunshine hour duration for the selected station through the Ethio-Djibouti railway rout, was used to compute the daily radiation and energy computation from a 3 to 5 years collected data. The result shows the minimum and maximum radiation distribution through the rout is 4.37kw/m^2 /day during August at Addis Ababa and 7.2kw/m^2 /day at Diredawa during May respectively. In general, Ethiopia has an average radiation of 5.87ke/m^2 /day, which indicates a great potential to generate electric power from the sun. Based on the technical proposal of the ERC, Box type, YZ25G and DFN7G and AALRT of train car had been selected for the installation of solar panels at the top roof surface area which is varying based on the number and size of the train car. For all selected trains a total number of 2011 panels with a total 30 years life cost of 56,764,325birr. 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 of it. Based on the minimum energy production and maximum configuration the cost return time may be 12 years. The research generally shows the possibility of application of solar energy through the selected route and the best solution for sustainable energy supply and for the overall economy development in the country

Table of Contents

DECLARATION.....	ii
ACKNOWLEDGEMENTS	iii
ABSTRACT.....	iv
LIST OF FIGURES	vii
LIST OF TABLES	ix
CHAPTER ONE.....	1
1. INTRODUCTION	1
1.1. Background	1
1.2. Solar Electricity Generation	3
1.3. Effect of Light Radiation Angle on Photovoltaic Power out Put	4
1.4. Solar Irradiance	5
1.5. Solar Cell Performance	6
1.6. Ethiopia Fact	7
1.7. Cost of solar energy production	8
1.8. Statement of the problems	9
1.9. Objectives of the Study.....	9
1.10.The Scopes the research	10
1.11. Organization of the Thesis.....	10
1.12.Research Methodology.....	10
1.13.Significance of the Research	11
1.14.Limitation of the Research.....	11
CHAPTER TWO	12
2. LITERATURE REVIEW	12
CHAPTER THREE	18
3. DESIGN AND ANALYSIS OF THE HYBRID SYSTEM.....	18
3.1. Theoretical Basis.....	18
3.2. Design of PV	20
3.3. Daily Solar Energy Obtained	32
3.4. Calculation of Solar Power That Can Be Harnessed By PV from the Top Roof of the Configured Train Car Set.....	37
3.5. Computation and Analysis of the Diesel Power Generation	46

CHAPTER FOUR	49
4. ENERGY STORAGE, CONTROL UNITES AND JUNCTIONS	49
4.1. Electrochemical Batteries	49
4.2. Control Unit and Converters	51
CHAPTER FIVE	53
5. COST LEVELIZATION AND COST COMPARISON OF THE ELECTRIC, DIESEL AND HYBRID SYSTEM.....	53
5.1. Cost Comparison of Electrical, Diesel and Solar.....	53
5.2. Cost Levelization of the Hybrid System.....	54
CHAPTER SIX	55
6. CARBON DIOXIDE EMISSION	55
6.1. Computing the Carbon Emission Reduced by Using the Solar Hybrid Energy Source	55
CHAPTER SEVEN	57
7. RESULT DISCUSSION, CONCLUSION AND RECOMMENDATIONS	57
7.1. Result Discussion.....	57
7.2. Conclusion	58
7.3. Recommendation and Suggestion of Future Work.....	59
8. BIBLIOGRAPHY	60

List of Figures

Figure. 1. A Solar Cell is Connected In Series and Parallel to form a Module Then a Solar Panel and Then wired to Produce a Required Solar Energy	4
Figure. 2. Solar Radiation Spectrum	5
Figure.3. Direct, Diffuse and Reflected Irradiance	5
Figure.4. The Global Solar Irradiance at the Surface Obtained from Satellite Imaging Radiometers and Averaged Over the Period 1983 to 2006.....	8
Figure.5. Solar Energy System Configuration.....	21
Fig.6.Physical Model of the Train Roof Top Area	22
Figure.7. Radiation Distribution Throughout the Year at Addis Ababa.....	27
Figure.8. Radiation Distribution Throughout the Year at Debire Zeit.....	28
Figure.9. Radiation Distribution Throughout the Year at Natherat.....	29
Figure.10. Radiation Distribution Throughout the Year at Metehara.....	30
Figure. 11. Radiation Distribution Throughout the Year at Dire Dawa.....	31
Figure.12. Radiation Distribution Throughout the Year at Mieso.....	32
Figure.13. Variation of Incidence Angle on the Solar Cells for a Roof Top Surface of the Train at Sunrise and Sunset.	33
Figure.14. Sunshine Hour Variation in a Year.....	35
Figure.15. Day Duration in a Year.....	36
Figure.16. Approximation of Irradiance as a Sinusoid Distribution in a Day at Debire Zeit.....	36
Figure.17. The Power Increment With the Number of Car Configured for AALRT.....	39
Fig.18. The Percentage Coverage of Power Based on the Number of Cars.	40
Figure. 19. The Power Increment With The Number of Car increase for Box Type Car.....	41
Figure.20. Percentile Coverage of Power for Box Type Car	42
Figure. 21. The Power Increment With the Number of Car Increase for YZ25G	43

Figure.22. Percentile Coverage of Power for YZ25G Car..... 44

Figure. 23. Power Increment of for DFN7G Multipurpose Train Configuration. 45

Figure.24. Percentile Coverage of Power of DFN7G Train Car.....46

Figure. 25. PV, Diesel and Grid Connected Hybrid System Circuit Diagram 52

List of Tables

Table .1. Specification of Selected Proposed Train Types	20
Table.2. Physical Characteristics of a Solar Cell And Application.....	22
Table.3. Summarized Yearly Distribution of Radiation at Addis Ababa.....	26
Table. 4. Summarized yearly distribution of radiation Table at Debire Zeit	27
Table.5. Summarized Yearly Distribution of Radiation at Natherat.....	28
Table.6. Summarized Yearly Distribution of Radiation at Metehara	29
Table.7. Summarized Yearly Distribution of Radiation at Dire Dawa.....	30
Table.8. Summarized Yearly Distribution of Radiation at Meiso.....	31
Table.9. The Hourly Distribution of Radiation Intensity.....	36
Table.10.The Amount of Power Generation and Percentile Coverage for AALRT Based on Train Set Configuration.	39
Table.11. Power Generated from the Solar Source and Possible Percentile Coverage of he Main Source Box Type Freight Car	41
Table.12. Power Generated from the Solar Source and Possible Percentile Substitution of the Main Source of YZ25G Passenger Car	43
Table.13. Power Generated and Percentage Substitution for DFN7G Multipurpose.....	45
Table. 14. Energy production from PV and Cost computation.....	54

CHAPTER ONE

1. Introduction

1.1. Background

The need to find energy sources other than fossil sources for vehicles is pushing towards the development of electrical vehicles, such types of energy is generated from different source. The rising costs and shortage of fuel together with the pressing need to reduce air pollution are the main motives leading to the development of efficient and sustainable electrical vehicles. Since electric vehicles can be powered by a variable set of sources of electrical energy (renewable and non-renewable), they shall be as much as possible an emission free, economical, environmentally friend and alternative to fossil fuels energy sources. However, autonomous electric vehicles have limited energy autonomy. This means that the time between recharges tends to be too small, resulting from the low energy density and high mass characteristics of batteries, in comparison to liquid fossil fuels that have high energy density, robust design, longer driving range and no battery charging requirements. In order to reduce the energy consumption and consequently increase the time between recharges and increase autonomy, two alterations can be implemented: First, vehicles can be built with lighter materials and with improved aerodynamics. Secondly, batteries can be placed onboard the vehicles so that they can be recharged continuously by using regenerative system and solar energy sources while moving. The solar powered train (SPT) can be an autonomous vehicle, powered exclusively by solar energy and rechargeable batteries as a supplemental energy source. To increase the vehicle autonomy, the train will also be equipped with regenerative braking and top roof solar panels with an optimized energy capture, which is achieved by maximum power point tracking system. This makes it an economical, emission free and attractive means of transportation.

Diesel trains are commonly used to transport passengers and goods from urban centers to leisure centers and cross country and continent. Even if the diesel train used a long time, it has an effect on the environmental pollution, which is crucial issue at present, in addition to this the non-renewable fossil fuel expected to will run out in the near future and its price has gone up. Therefore, engineers concentrate on finding an alternative and non-depleted energy sources. The world agreed at the present time to use a solar energy extensively on most energy applications [15].

Solar energy is the most abundant efficient and none exhausted of all energy resources. Indeed, the rate at which solar energy is intercepted by the Earth is about 15,000 times greater than the rate at which humankind consumes energy [1, 4]. Currently, there is no evidence indicating a substantial impact of climate

change on regional solar resources. In other word solar technologies offer opportunities for positive social impacts, and their environmental burden is small [4, 11].

Solar energy conversion consists of a large family of different technologies capable of meeting a variety of energy service needs. Solar technologies can deliver heat, cooling, natural lighting, electricity, and fuels for a host of applications. However, maximizing the absorbed solar energy and stopping it from escaping to the surroundings can take specialized techniques and devices such as evacuated spaces, optical coatings and mirrors. The technique is used depends on the application and temperature at which the heat is to be delivered with a range from 25°C (e.g., for swimming pool heating) to 1,000°C (e.g., for dish/Stirling concentrating solar power), and even up to 3,000°C in solar furnaces [8].

Passive solar heating is a technique for maintaining comfortable conditions in buildings by exploiting the solar irradiance incident on the buildings through the use of different glazing. Furthermore, solar driven systems can deliver process heat and cooling, and other solar technologies are being developed that will deliver energy carriers such as hydrogen or hydrocarbon fuels, known as solar fuels.

Hybrid power systems combine two or more energy sources such as diesel engines and solar panels, hydroelectric sources, wind powers etc. into a single plant to reduce long term generation costs, the dependency of fossil fuel and carbon emission, which is a severe problem on environmental and living habitat on earth. The principal advantages of a hybrid plant are its ability to affordably extend reliable energy access into the required load. A hybrid system uses advanced system control logic (also known as a dispatch strategy) to coordinate a different energy sources.

The real innovation of a hybrid power generation is the realization that cost savings do not come from using the most powerful solar panels or the most efficient diesel engines, but closely coupling and coordinating to matching , the cheapest energy production with the load to provide a more reliable and quality power at low cost.

Photovoltaic converters are used to convert a direct solar energy to electrical energy. They have some advantages such as low weight feasibility of small scales but they are more expensive compared to other types of energy converters. Therefore it is important to absorb the maximum solar energy in order to increase the efficiency of the energy converter.

Solar power cannot be relied upon to completely replace conventional fossil fuel and grid electrical energy rather to supplement the power generated by the engine and subsequently to reduce CO₂ emissions. Train coaches have a large roof area available for installing solar photovoltaic (PV) modules then

it is logical to extend the idea of automobile solar hybrid system. The energy generated from this scheme may excess of requirement in the coaches can be stored in batteries to use at night and cloudy day and send to the main grid for further use, thereby reducing the fossil fuel consumption.

The coaches have a longer span length to accommodate higher number of passengers and provide superior traveling comfort. Coaches are not self-generating (alternators driven by the moving wheels and axles) but have power cars which provide the required power for the propulsion of the coach and for required electrical load in the coaches. Therefore, it is necessary to use the long span area and to support the conventional source from the installed PV at the top roof surface area of the train.

In this study the power that can be harnessed from the train roof top using a solar PV module is computed and Wired together and supplied to motor directly and stored in the selected batteries for farther use, and if the generated energy is more than the direct use and batteries capacity, the excess energy is send to the main electric power grid. The formation of train set, the geographical position, the weather condition, solar intensity, the efficiency and size of the solar panel are the determinant factor in the generation and computation of solar energy required for the propulsion.

A train consists of one or more connected vehicles that run on the rails. Propulsion is commonly provided by a locomotive that hauls a series of unpowered cars that can carry passengers or freight. The locomotive can be powered by steam, diesel or by electricity supplied by trackside and over head systems. This research is focused to design a roof top solar panel installation and to assess the possible amount of electrical energy generated from the roof top of railways coaches, freight wagons and locomotives cars and percentage contribution for the propulsion.

1.2. Solar Electricity Generation

Generation of electricity can be achieved in two ways. In the first, solar energy is converted directly into electricity in a device called a photovoltaic (PV) cell. In the second, solar thermal energy is used in a concentrating solar power (CSP) plant to produce high-temperature heat, which is then converted to electricity via a heat engine and generator.

Solar Photovoltaic (PV): Photovoltaic is the technical term for solar electric. Photo means "light" and voltaic means "electric". PV cells are mostly made of silicon, silicon alloys and other similar elements, an element that naturally releases electrons when exposed to light. Amount of electrons released from silicon cells depend upon intensity of light incident on it. The silicon cell is covered with a grid of metal that

directs the electrons to flow in a path to create an electric current. This current is guided into a wire that is connected to a battery or DC appliance then can be used directly or can be convert to AC by using inverter.

PV tracking systems is an alternative to the fixed, stationary PV panels. PV tracking systems are mounted and provided with tracking mechanisms to follow the sun as it moves through the sky. These tracking systems run entirely on their own power and can increase output by 40%.

Back-up systems are necessary since PV systems only generate electricity when the sun is shining. The two most common methods of backing up solar electric systems are connecting the system to the utility grid and storing excess electricity in batteries or different types of capacitor to use at night or on cloudy days.

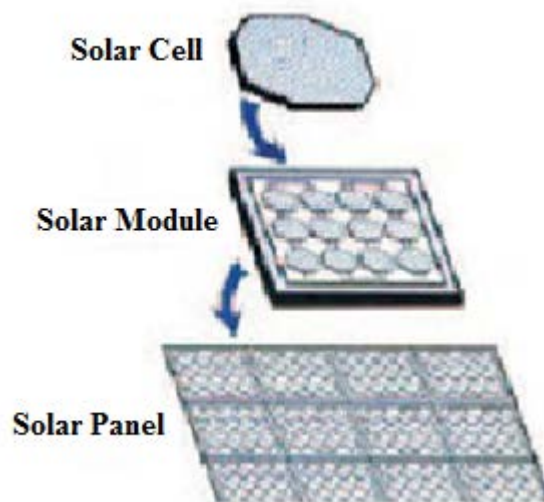


Figure. 1. A solar cell is connected in series and parallel to form a module then a solar and then to produce a required solar energy (world solar energy conference, 1990)

1.3. Effect of Light Radiation Angle on Photovoltaic Power out Put

The angle between the solar radiation and collector surface affects on the energy absorption and optimization of the conversion energy. Due to the motion of the earth; the sun light always radiate on the surface of the earth with different angle during the day, it is perpendicular for a fixed panel with a short time per day, therefore, it is required to design and installed the PV-array system with the maximum sunshine angle exposure to increase the efficiency of the PV electric production in a day.

1.4. Solar Irradiance

The energy coming from the sun depends on the wavelength, leading to the solar spectrum represented in figure 2. The reference solar spectral irradiance AM0 (Air Mass 0) represents the irradiance at the top of the atmosphere with a total energy of 1367W/m^2 . At sea level, it is referred as AM1.5 and the total energy equals 1000W/m^2 .

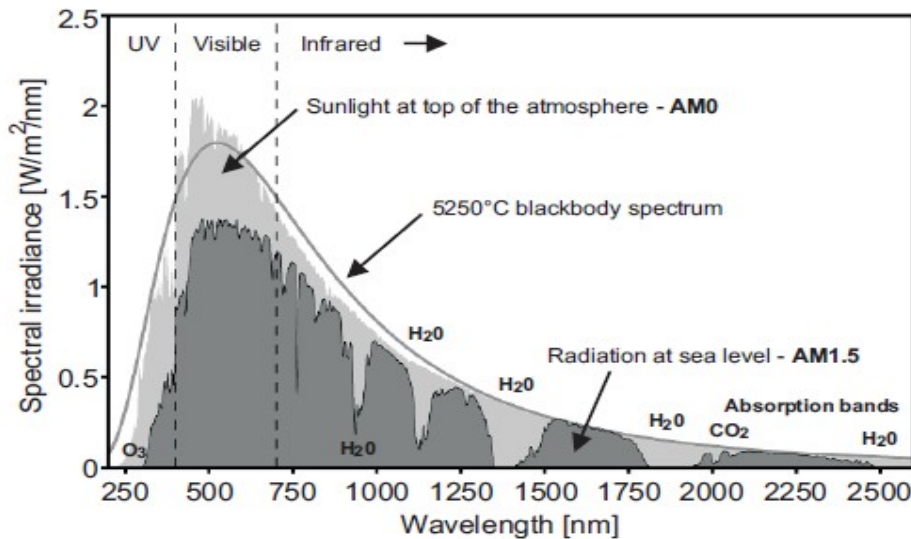


Figure. 2. Solar radiation spectrum (source: <http://www.physforum.com/solar> spectrum)

In addition to the direct irradiance, we also have to consider the diffuse irradiance, which is predominant on a cloudy day, and the reflected irradiance. Reflected irradiance is dependent on the albedo, which is a measure of the reflectivity of the Earth's surface. Fresh snow has an albedo of around 80 %, desert sand 40% and grass between 5% and 30 %.

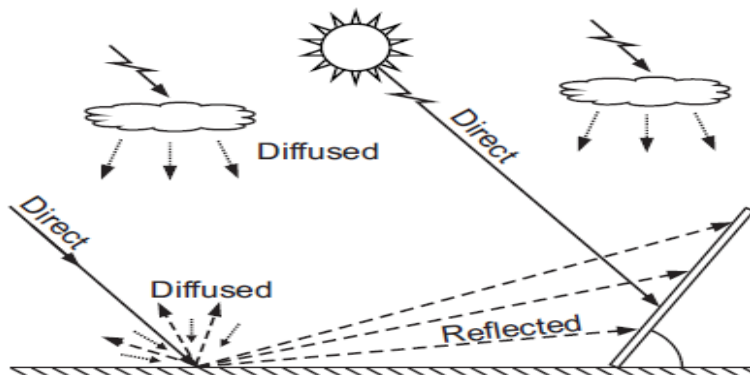


Figure.3. Direct, diffuse and reflected irradiance

1.5. Solar Cell Performance

Solar cells convert the energy of the lights photons to electric energy with efficiency between 5-28% without using thermodynamic cycle or active fluid. Now day's researchers have been doing in the laboratory to improve the efficiency of the cell up to 50% and above because in the universe the abundant and unlimited solar energy is exist, therefore increasing the efficiency of the collector and convertor is a non compromise measure to use the extensive energy. Solar cells can be light converter directly or can use light concentrators like mirror or convex lens to generate the solar electric power.

An ideal and perfect solar cell that would cover the entire spectrum and convert all this energy into electricity would have an efficiency of 100 %. In reality, depending on the semiconductors used, only a part of this spectrum is covered.

This photovoltaic converter is a developed energy converter with the advantages such as: relevant design and installation, silent energy conversion, long life time with less maintenance requirement, easy transportation and light weight. But compare to diesel generator and other it is more expensive, therefore, the optimum operation and the maximum energy absorption from the solar cells are important factors (1)

The performance of a solar cell is measured in terms of its efficiency at which converting sunlight into electricity. A variety of solar cell technologies can be used: most often polycrystalline silicon, monocrystalline silicon, or gallium arsenide and a synthetic cell are used. The power produced by the solar array depends on the weather conditions, the position of the sun and its intensity, and the size of the array. A typical commercial monocrystal silicon panel has an efficiency of 28% shall used in this study, which means that only this part of the incoming solar energy is in fact transformed into electric energy [15].

The various solar technologies have differing maturities, and their applicability depends on local conditions and government policies to support their adoption of energy sources to integration with the solar energy into broader energy systems which involves both challenges and opportunities. The performance of PV is also affected by the position of the area reference from the equator and the weather condition, the sunshine hour duration and day duration.

1.6. ETHIOPIA FACT

It is known that almost all forms of energies in our planet come from the sun. But the distribution of that energy on earth is different based on the rotation of the earth and the seasonal movement of the sun from the equator to the Capricorn and cancer which affects the irradiance angle of the solar system. The amount of solar energy reached to the earth is almost constant and high around the equator during the day time throughout the year.

In Ethiopia the National Meteorological Services Agency (NMSA) is responsible for installing, collecting, and archiving of meteorological and climatological data. It is also responsible for providing meteorological services including public weather forecast and conducting meteorological research.

Generally, northern Africa including Ethiopia is the areas where there is the maximum intensity and duration of sunshine over the globe, and as much as 4,000 bright sunshine hours are receive in a year. Based on the national meteorological agency and NASA satellite data information most parts of Ethiopia receive up to 11:00 hours of bright sunshine daily, and in the southeastern, 12:40 hours day duration depending on the rotation and tilting angle of the earth. It is only during summer rainy season in the highlands of central and south western Ethiopia, when there is much cloud cover, that the daily duration of sunshine hours is a minimum average of up to 5 hours [53].

Across Ethiopia the global horizontal irradiance (GHI) is high all throughout the year. The amount of radiation energy in a day is dependent on the duration of the sunshine hour, the temperature and the position of the station. Ethiopia receives 4.5 to 7.3kwh/m² of solar radiation per day.

This indicates the amount of energy that can be generated during the day from top roof of the coaches of trains during all seasons is high. So, it will result in considerable fuel savings as well as reduction of CO₂ emissions.

In Ethiopia the major portion of energy is utilized for economic and social development. Therefore to use this abundant and unlimited solar energy has a great contribution to the country's economic development by reducing the dependability of non renewable energy sources in which the country invest high budget on it and to keeping the environment safe.

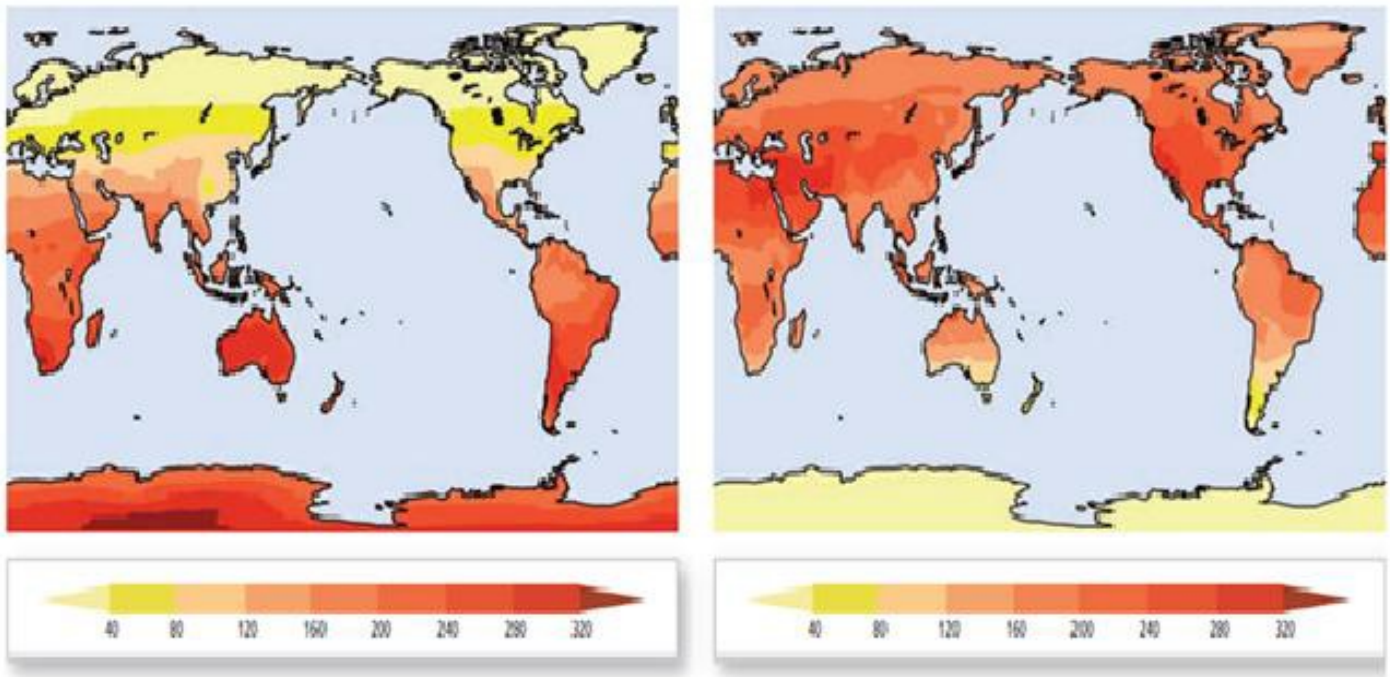


Figure.4. The global solar irradiance (w/m^2) at the surface obtained from satellite imaging radiometers and averaged over the period 1983 to 2006. Left panel: December, January, February. Right panel June, July, August (ISCCP Data Product 2006).

1.7. Cost of solar energy production

Over the last 30 years, solar technologies have seen very substantial cost reductions. The current levelized costs of energy (electricity and heat) from solar technologies vary widely depending on the upfront technology cost, available solar irradiation as well as the applied discount rates. Technological improvements and cost reductions are expected, but the learning curves and subsequent cost reductions of solar technologies depend on production volume, research and in pursuing any of the solar technologies, the variability and the cyclic nature of the Sun. The use of both these concepts of time and space, together with energy storage, has enabled designers to produce more effective solar PV systems is a better low price. Because of its inherent variability, solar energy is most useful when integrated with another energy source; to be used when solar energy is not available to make the operation the system is effective.

1.8. Statement of the problems

In the present time our world faces to the scarcity of energy, the run out of the non renewable energy source, the raising of fuel cost and environmental pollution problems. Therefore, countries have turned their eyes to the exploitation of renewable energy source. Among these sources solar energy is an abundantly available almost throughout the world specially in the middle east and sub-Saharan countries. Ethiopia is exist in the equatorial region, in which the sun is almost perpendicular throughout the year. So, there is sufficient and long time day light with an average temperature of 28°C and more than 340 to 355 sunshine days and have a potential of producing 4.5 to $7.3\text{kwh/m}^2/\text{day}$.

Therefore, there is a possibility to use this energy for the railway train traction by designing a hybrid grid connected power system, which helps to reduce the non renewable and hydropower source usage and the dependency on them. In addition to this it increases the potential to use alternative energy and future exploration of the solar energy towards the possibility of substitution of renewable source and to boost the country energy capacity and helping the growing of whole national economy.

1.9. Objectives of the Study

1.9.1. General Objective

The main objective of this study is to design a hybrid solar energy system for the application of train locomotive power source through the selected routes of Ethiopian rail way system and to supplement conventional energy source in turn to reduce the dependency of the fossil fuels and main grid electrical energy consumption and carbon emission from the fossil source.

1.9.2. Specific Objectives

The specific objectives of this research are as follows:

- Computing, Predicting and evaluating the amount of solar energy which will add to the traction and grid system
- developing a computer model for the integration system of the hybrid solar, diesel and electrical traction sources using CATIA, MATLAB, Microsoft Visio and Microsoft excel software.
- Analyze the fuel and electric cost.
- Analyze the fixed and operational cost of solar energy production system.
- Analyze a reduction of carbon emission.

- Recommending the possible future studies regarding the application of solar energy for railway system and factors related to its production.

1.10. The Scopes the research

The scopes of this study will be covered:

- Collecting data from national meteorological agency, energy bureau, and Railway Corporation the sunshine hour and altitude for the selected, renewable energy resource information and the rail way specification respectively which is used in the calculation of amount of energy production and comparison.
- Calculating and estimating the solar radiation using an angstrom correlation model for a selected station along the railway rout of Addis Ababa –Djibouti on a horizontal surface in turn to show the countries solar energy potential
- performing pre-design calculation for solar energy implementation on the roof top the rail car through the rout of the railways.
- Develop a complete model of the train using CATIA software, Put recommendation towards the application of solar technology on railway energy source and farther studies.

1.11. Organization of the Thesis

This thesis has organized in seven chapters, Chapter one is the brief introduction of the solar energy, chapter two the literature review, chapter three Design And Analysis Of The Solar Hybrid System, chapter four energy storage mechanism, chapter five cost levilization and comparison, chapter six carbon emission chapter seven result discussion, conclusion and recommendation finally the reference is included in the research process.

1.12. Research Methodology

The methodologies to be followed in this study are:-

- Review different literatures and theoretically analyzing.
- Collecting data from national meteorology agency, Ethiopian Railway Corporation and other sources
- Modeling the radiation mathematically and a physical system
- Computing and comparing the data obtained, the cost of the system and finally come to the conclusion and recommendation.

1.13. Significance of the Research

The significance of the present study is to provide a general information on solar energy resource potential of Ethiopia and to develop a hybrid solar system for the railway train traction, to increase the potential usage of alternative energy which help to increase the energy efficiency in the railway transportation as well as other industries, to increases the gross energy sources in the country by using the most abundant renewable energy source, solar energy and to reduce the CO₂ emission.

1.14. Limitation of the Research

This research is limited due to the following reasons:

- The data collected and station selection is limited, therefore the prediction of solar energy in the rout may not correctly represent
- The main constraint in this study is shortage of well organized information and data access.
- To develop a proto type model there is a material and time constraint.
- There is no previous worked data related with this title in ERC and Other international airway companies except some with limited information and researches which are undergoing.
- The analysis and modeling by using a software package might not match with the actual due to data evaluation error.

CHAPTER TWO

2. Literature Review

Solar energy is the most readily available and free source of energy since prehistoric times. It is estimated that solar energy equivalent to over 15,000 times the world's annual commercial energy consumption reaches the earth every year.

The Ethiopian solar and wind energy resource (SWERA) report on Country background information Solar and Wind Energy Utilization and Project Development Scenarios (2007). Based on the SWERA data, the mean annual average daily radiation for the country as a whole is $3.74 \text{ kWh/m}^2/\text{day}$. The annual average daily radiation for each woreda in the country is indicated using a GIS map. But when it compare with a NASA and The data generated for this research the prediction is almost half.

Sharew Anteneh Mekonnen (2007) predicts The monthly average totals of global radiation on a horizontal surface in Ethiopia had modeled and analyzed using Simple Model of Atmospheric Radiative Transfer of Sunshine (SMARTS) and for Vapor Pressure Radiation Model (VP-RAD). The monthly mean of the daily global solar radiation on a horizontal surface is about 12 MJ m^{-2} according to the VP-RAD model prediction and 19.5 MJ m^{-2} according to the SMARTS model prediction [53].

According to the Ethiopian resource group, Ethiopia receives 5.5 to $6.5 \text{ kWh/m}^2/\text{day}$ of solar insolation almost more than an average of 345 days. Solar energy availability is fairly constant (less than 10% of average) throughout the year in the lowland areas of the country but varies substantially in the highlands (more than 25% of average). The theoretical potential of solar energy is huge, 500 MWt/km^2 and 100 MWe/km^2 [15]. Therefore the country has huge potential to exploit more energy from the sun.

Tesfaye Bayou and Abebayehu Assefa (1989) estimates the solar radiation maps for Ethiopia by prepared measured solar radiation data from 6 sites and sunshine hour from 136 sites using Angstrom's correlation for inland region and schuepp's for the coastal region in which frequently low and high radiation and sunshine hour occurs. From the prepared map they found that $500 \text{ Wh/m}^2/\text{day}$ it shows the country receives a sizable and significant potential of solar radiation [54].

The project beneficiary installed amorphous silicon type photovoltaic tiles on passenger coaches, locomotives and freight coaches. The photovoltaic modules can be attached to the curved surfaces of

the coaches, locomotives and freight wagons and keeps the on-board accumulators charged even during stops. As well as providing energy cost savings, the photovoltaic technologies offer two significant environmental advantages over non-renewable energy sources:

1. Less greenhouse gas production: The solar panels keep the accumulators and auxiliary devices in charge during the stops, without depending on the main electrical system, with a reduction of 750 gram of carbon dioxide per KWh of produced energy compared to the traditional sources.
2. Longer life span of the accumulators: These are subjected to less wear and tear as a result of the photovoltaic cells being kept constantly charged. Longer lifecycles means less hazardous waste.

The energy produced by the photovoltaic panels can have different uses: they can be applied to the coaches and locomotives to charge the accumulators for the lighting and air conditioning, and they can also be installed on the freight carriages to recharge the accumulators so as to ensure the power supply for electric locks used to protect transported goods. Trials were carried out on the whole system to assess its validity. Energy yields were shown to have improved and carried out on the whole system to assess its validity which was tested in 2004 compared to the previous one, due to the streamlining of the capturing mechanism [8].

Solar car racing refers to competitive races of electric vehicles which are powered by solar energy obtained from solar panels located on the surface of the car. The two most notable solar car distance races are the World Solar Challenge and the American Solar Challenge [6]. The objective of these competitions is to promote research on solar-powered cars and with both alternative energy sources; environmental and advanced materials technology.

The solar contesting cars combine technology used in the aerospace, bicycle, alternative energy, and automotive industries. As a result, it becomes a priority to optimize the design to account for aerodynamic drag, vehicle weight, rolling resistance and electrical efficiency. Solar cars use a range of batteries including lead-acid batteries, nickel-metal hydride batteries (NiMH), nickel-cadmium batteries (NiCd), lithium ion batteries, and lithium polymer batteries. The batteries store solar energy produced when the vehicle is stationary or traveling with a given speed and slowly or downhill. In order to do this the engines must allow regenerative braking, i.e., power is fed back into the battery during deceleration [15].

The converter transforms the electric energy generated by the PV panels into electric energy suitable for the recharging of the batteries. For the observation period July 2003 to October 2005, the energy used by the prototype coach was 1378.42 kWh, the energy used by the prototype locomotives was 159.3 kWh (sufficient to keep the on-board accumulators going), the energy used by the prototype freight wagons was 540 kWh (sufficient for the electrical locks), resulting in reduction of 1033.82 kg, 119.95 kg and 405 kg of CO₂ emissions [2, 13]. Policy initiatives & intervention taken to harness green energy resources and implementation of energy conservation measures have yielded fruitful results. During 2011-12, capacity addition of about 326 MWp in solar energy was made which included provisioning of solar lighting system at 134 Railway stations, 734 Level Crossing gates, 10 office buildings, 306 street lights in colonies/training schools and 111 numbers of solar based water heaters in running rooms/hospitals/rest houses/canteens/base kitchens as a part of „The year of Green Energy“ initiatives. Besides, solar projects for capacity addition of 4.69 MWp by providing solar Photovoltaic modules at 200 railway stations, 21 administrative buildings and 1,000 level Crossing gates have been initiated, So far Indian Railway has harnessed about 4.5 MW of solar energy [3, 11].

The Indian Rail way, being the world biggest railway system, it plans 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 interior lighting and cooling [4]. In this research it is possible to show the solar energy is used to operate the train based on the design of the system.

Blackfriars railway bridge in England, Solar Century is installing total of 4400 Panasonic HiT solar panels are being installed on a 250m-long roof, covering 6000 m² and connected to 294 Solar Max MT 13 inverters from Sputnik Engineering. When installation is complete, the panels will generate 900,000 kWh of electricity a year, about half the energy required to run the station with an annual saving of over 500 tons of carbon for the station [5].

The first solar powered European rail, which is, the 760mm-gauge vehicle, dubbed Vili, is fitted with a bank of photovoltaic panels, which are mounted on the roof and cover an area of 9.9m². The panels feed batteries installed under the seats which are also fed by a regenerative braking system. The vehicle has a maximum speed of 25km/h and is driven by two 7kW microprocessor controlled asynchronous electric motors, which are mounted on each of the two axles. It is a narrow-gauge line with curves as tight as 50m radius [6].

According to the research on battery-driven light rail vehicle (LRV) developed by the Railway Technical Research Institute in Japan, their LRV consumes the electricity of 8.9MJ (about 2.5kWh) per kilometers at the maximum air conditioning load. It was assumed that interval between the stations is 500m; a railcar requires 4.5MJ (about 1.3kWh) to reach the next station. If a railcar arrives and departs every 10 minutes, 16kWh per hour is necessary for the station to transmit electricity to each railcar. Therefore, the electric power necessary for a day is 270kWh, for one year is 99000kWh. To supply all the required electric powers a 90kW rated solar cells are needed. When using the HIT solar cells (energy conversion efficiency: 19%), about 470m² is required. Roofless platforms or small roof platforms for tram are usual in Japan. If the roof of 2m in width and 30m in length, which is approximately equal to size of the new Ethiopian railway car, is installed at each station, and the whole surface is covered with HIT solar cells, about 13% of required electric power is obtained [7].

In order to estimate the amount of available energy the following sequential procedure must be done: get geographical position coordinates, get local solar incidence reference, calculate the power on each panel, estimate the total energy captured for the route, estimate the stored battery energy, calculate the optimum speed for the route and finally keep track of the average speed. A study of energy management system of electric vehicles has been developed by Jinrui N, Fengchun S, Qinglian R in [17] in order to improve the energy management of an urban electric bus. According to these investigators, current electric vehicles comprise on-board energy generation, an energy storage system, and a driving system in which to implement the solar energy.

There are many structures of energy sources for electric vehicles that result from combinations between fuel cells, power batteries and super-capacitors. As a result of the study, and aiming to reduce the deep charge/recharge cycle and battery size it is best to use the combination super-capacitor plus battery. A super-capacitor is an electrochemical capacitor that has an unusually large amount of energy storage capability relative to its size when compared to conventional capacitors. The system proposed by the authors is composed by a power battery group, DC-link, capacitor power converter, super-capacitor, motor power converter, and traction motor. The load current of an electric vehicle varies greatly during acceleration and deceleration and sometimes the load current exceeds the maximum charging or discharging current of the battery. The performance of electric vehicles with super capacitors was tested, and it was proven that they have a better performance than vehicles without it. The maximum speed with a super-capacitor is 96.17km/h and without it 68.77km/h. Furthermore, at any moment in time the optimal driving speed also depends on the remaining capacity of the batteries and other energy consumption parameters.

To capture as much solar energy as possible, the solar panels are generally directed so that they are perpendicular to the incident sun rays. Often the whole car is tilted for this purpose but it is practically impossible therefore using a maximum power point tracker is used to maximize the energy production efficiency of solar panel.

There have been several approaches to the implementation of control systems for vehicles running on limited energy sources. This system extracts the maximum electrical power from a distributed solar array that covers the surface of the vehicle. The energy transference is maximized by connecting each solar panel to a Maximum Peak Power Tracker (MPPT) that matches the panel impedance to the drive system. The ultimate goal for this vehicle is to achieve maximum average efficiency at the minimum weight. The average efficiency has to account for several external conditions such as road gradient and surface condition, predicted meteorological conditions and also the forces opposing motion, gravity, rolling resistance, and aerodynamic drag. The solar energy is either stored in onboard battery or flows directly to the motor, according to the demand imposed by the driving vehicle. For a given stored energy in the battery and the prediction for a certain amount to be collected, the speed is set to be as close as possible to the optimum value [15; 16].

Now a day the efficiency of the solar panel is highly improved up to 28%. The Low efficiencies mean that larger arrays are needed and higher investment costs. It should be noted that the first solar cells, built in the 1950s, had efficiencies of less than 4% but at the present the efficiency is increased, the required number of panel and area decreased, therefore the cost of the panel is dramatically decreased [10].

The levelized costs for solar thermal energy at a 7% discount rate range between less than USD 10 and slightly more than USD 20/GJ for solar hot water generation with a high degree of utilization in 2005. In China to more than USD 130/GJ for space heating applications in Organization for Economic Co-operation and Development (OECD) countries with relative low irradiation levels of $800\text{KWh/m}^2/\text{yr}$ is used. Electricity generation costs for utility-scale PV in regions of high solar irradiance in Europe and the USA are in the range of approximately 15 to 40 US cents /kWh in 2005 at a 7% discount rate, but may be lower or higher depending on the available resource and on other framework conditions. Current cost data are limited for concentrated solar power (CSP) and are highly dependent on other system factors such as storage.

In 2009, the levelized costs of energy for large solar troughs with six hours of thermal storage ranged from below 20 to approximately 30 US cents /kWh 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. [10].

As observed above from the different literatures many researches concentrate on the production of solar energy from the bridge cover and railway side installation and from the top of the roof for air conditioning and lighting system and office consumption. In this research a roof top surface area of the configured train car is considered for the installation of PV hybrid solar energy system. The generating energy from the installed PV system is added to the train power system to use for different purposes and the excess energy is sent to the main grid to use it for other purposes. The amount of electric energy produced from the solar system is computed based on the area available on the top roof for installation at selected stations through the Ethio-Djibouti route and at Addis Ababa using a sunshine hour duration and sun inclination based Angstroms correlation. The average daily solar intensity which hits the surface per meter square is modeled to determine the amount of produced energy. From the selected photovoltaic cell with specific efficiency and size the percentage reduction of conventional energy source, cost saving and carbon emission are analyzed and compared with the solar energy incorporated to the train traction system.

CHAPTER THREE

3. Design and Analysis of the Hybrid System

3.1. Theoretical Basis

To effectively solve the problem of urban and cross country transportation in Ethiopia, the government of Ethiopia decides to build a light railway system in the city of Addis Ababa and other parts of country with a different type and size capacity train for cross-country. The basis for design is plan position of the line, plan position of stations, the geographic report of some sections and the report of urban and cross country commuter passenger flow and the import and export capacity of the country, the power supply system and amount used are considered.

The power supply system shall be able to provide safe, reliable, economical and reasonable power source, with simple wiring, flexible operating mode, and convenient engineering execution, management and maintenance. The newly build up railway system in Ethiopia uses an electrical energy generated from hydropower source and a diesel fuel source.

The power supply system for adds Ababa is an electrical with a backup of diesel and the cross country has different mode of supplying, such as electrical and backup diesel, diesel source system. The power supply systems for the early tramcars were 550V, 600V. Currently most systems are 750V. Recently the mode of 1500V appears. Therefore, AALRT uses a 750v source because it is more mature and stabilized mode, even if the cost is higher. Traction inverter mainly consists of line contactor, IGBT inverter and chopper power unit, logic control unit and filter capacitor. The role of it is to convert DC voltage into 3-phase AC voltage with variable voltage and variable frequency, which will drive the traction motor to put vehicles into operation (motoring), and will convert the 3-phase AC voltage of traction motors into DC voltage to be fed back to the catenary (using regenerative braking system). For the cross country the single-phase power frequency (50Hz) AC 25kV/DC770v and the direct feeding system with return wire is applied for the power supply system. Distribution of the traction power supply facilities shall meet the requirements of long-term traction load and shall be designed with a capacity to meet passenger and freight transportation. The electric traction substation with Level-1 load shall be supplied by two independent and reliable power supplies and those two power supplies shall be hot backup for each other. Voltage of OCS shall be as follows: nominal voltage: 25kV; max. Working voltage: 27.5kV; min. short-time voltage: 29kV; min working voltage: 20kV and working voltage under abnormal conditions: 19kV. 132kV power supply is temporarily employed for the

traction substation with a contact wire current capacity of 508A and power factor of 0.95. It is temporarily suggested that: single-phase traction transformers shall be used in both SEBETA and MIESO (terminations) traction substations with conditions for 3-phase V/v connection reserved, and 3-phase V/v connection traction transformers shall be used in other traction substations. Fixed back-up shall be applied for all traction transformers. The source for the AALRT the power used for the traction system is 750 V with a current flow of 1050A supplied from the substation.

As we observe from the technical proposal to deliver a constant power a 132kv power supply station has been built. And for cross country the power used for traction will be different based on the type of car used and load capacity which varies from 815.4 to 1564kw of maximum service load.

The power used in the present is in scarcity due to the up running cost of fuel and the seasonal fluctuation of the water source and also in the near future the fossil fuel expected to run out. Therefore countries see different renewable energy sources such as wind, solar, and the like. Ethiopia is one of the countries which have a potential to generate high amount of energy from the renewable source especially from the sun and wind. In this study the design of solar energy to supplement the above non renewable source is carried out.

3.1.1. Technical Specification of the ERC Train Locomotives

According to the technical proposal of Ethiopian Railway Corporation, different types of railway locomotive and trailer are proposed. They grouped based on their purposes, power source, and shape and capacity. Therefore from the proposed types, the Addis Ababa light rail transports (AALRT), electrical freight and passenger locomotive (box type freight and YZ25G of passenger) DFN7G Diesel Locomotives are considered in this analysis.

Car strength complies with TB/T1355-1996 (railway vehicle strength design and test evaluation specification), Vehicle dynamic performance complies with GB/T 5599-1985 (railway vehicle dynamic performance evaluation and test identification norms), and Vehicle gauge complies with GB1461-198 (standard railway rolling stock gauge)

Table .1. Specification of selected proposed train types (source ERC technical proposal)

Locomotive parameter	AALRT	box car	YZ25G	DFN7G
Purpose of locomotive	Passenger	Freight	passenger	Multi-purpose
Length(mm)	28400	17400	25500	18800
Width(mm)	2650	3105	3105	3300
Power Source	Electric- DC750V	Electric- DC600V	Electric- DC600V	Diesel-electric Diesel and DC770
Voltage rated(V)	750	600	600	770
Rated current(A)	1050A	1359	1359	2389.61
Rated power (kW)	787.5	815.4	815.4	1840
Fuel consumption at rated power(gm)	-	-	-	207+3%g/kWh (469062gm)
Operating temperature	20-30 °C(28°C avr.)	-40 to 40 °C	-40 to 40 °C	-20 to 50°C
Max. configuration of car in train	3	20	20	20
Roof top area of each locomotive(m ²)/car	75.26	54.027	79.1775	62.0
Effective area of locomotive (m ²)/car	71.669	50	70	58
Total effective area(m ²)	210	1000	1400	1160

3.2. DESIGN of PV

The PV system design is based on the size, type and capacity of load used. The train is a combination of locomotive and trailers, which is operating in different conditions and combinations based on the purpose and load transported. According to the characteristics of the operation of the train, the energy used to propulsion of the train is varying. Here the roof top of the train car surface area is very determined parameters in the calculation and design of the hybrid solar system which is working with grid and diesel traction system as hybrid.

In the design of solar energy the geographical location, temperature, sunshine hour, duration of the day and the global rotation of the earth, the inclination of the earth, the efficiency and type of storage and collector, the size of the collector, the solar radiation are some of the factors considered in the design of the solar hybrid system. .

The solar panels, composed by solar cells connected in a defined configuration, cover a given surface of the roof top train cars. During the day, depending on the sun irradiance weather condition and elevation, they

convert light into electrical energy. A converter ensures that the solar panels are working at their maximum power point. That is the reason why this device is called a Maximum Power Point Tracker, that we will abbreviate MPPT. This power obtained is used firstly to supply the propulsion group and the onboard electronics, and secondly to charge the battery with the surplus of energy and it is connected to grid if there may be high enough wasted energy generated.

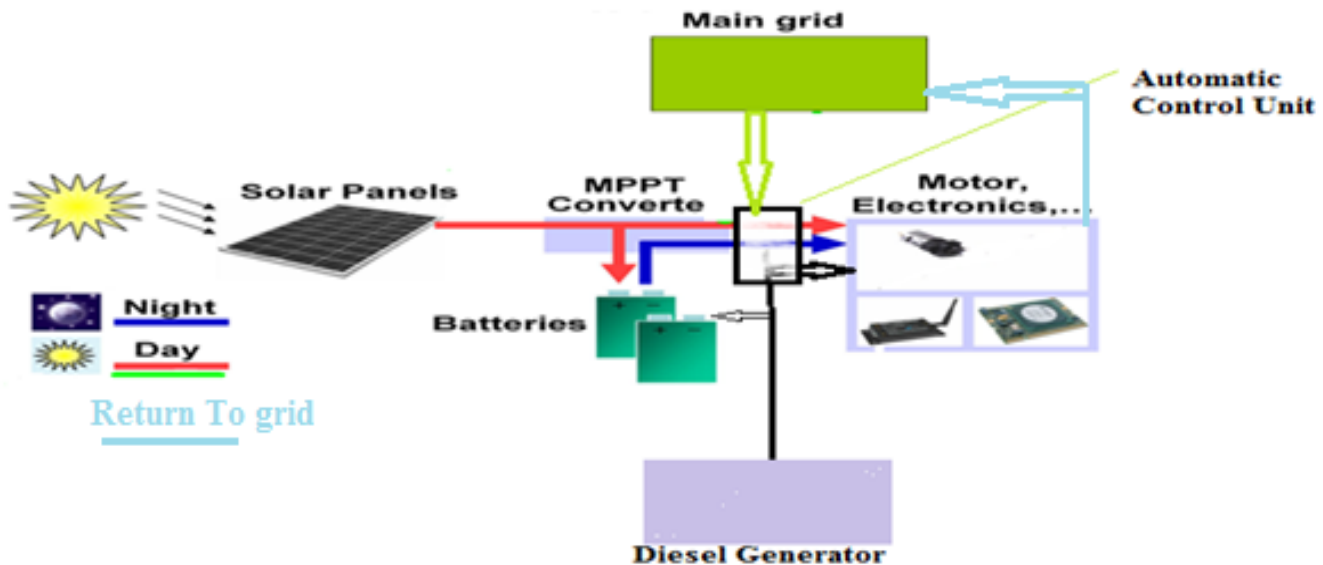


Figure.5. Solar energy system configuration

In this study the area of the roof top of the train is well known because the size of the train and locomotive is predetermined, the size of the collector also estimated based on the roof top area and the power calculated. Based on the countries market assessment different size and wattage of solar panels are available, 5w, 10w, up to 275W and the size is also differ. In this study the top roof surface area is fixed , therefore it is better to consider the size of the solar panel and for this research $1.9558 \text{ m} \times 0.9906 \text{ m} = 1.9374\text{m}^2$. Therefore, the parameter we calculate is the total power, $P_{\text{elec tot}}$ which is produced by using the selected solar cell energy.

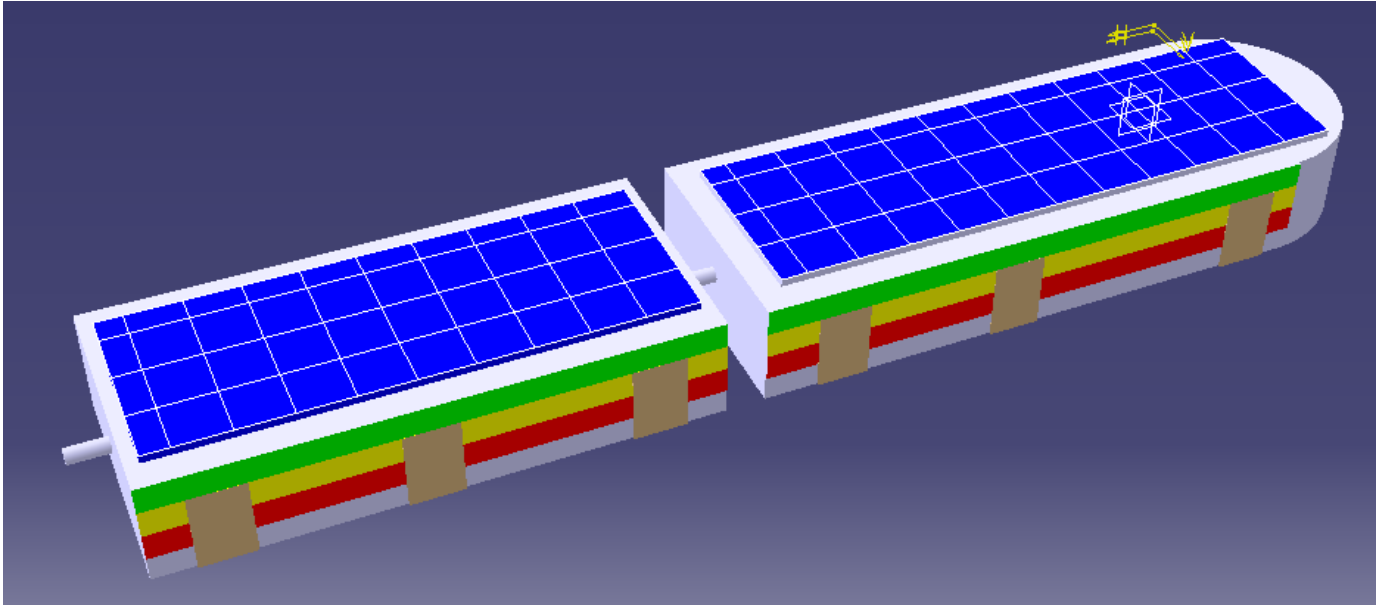


Fig.6.physical model of the train roof top area

Table.2. Physical characteristics of a solar cell and application

Company	Length (cm)	Width (cm)	Depth (cm)	Area of panel (m ²)	Weight (Kg)	No. of Cells per module	Applications area
Standard	1.651	0.9906	0.04572)	1.6354806	18.144-22.68	60-72	residential
Standard	1.9558	0.9906	0.04572)	1.9374155	18.144-22.68	60-72	commercial
Sun-power	1.5494	1.0414	0.04572)	1.6135452	18.144-22.68	96	residential

3.2.1. Model and Computation of Irradiation at the Surface of the Earth for Selected Stations.

To model the solar radiation Angstrom-type regression equation is related with the monthly average daily radiation to the clear day radiation at the location and the average fraction of possible sunshine hours which is collected from the National Meteorological Service Agency (NMSA).

In Ethiopia the National Meteorological Services Agency (NMSA) is responsible for installing, collecting, and archiving of meteorological and climatological data. It is also responsible for providing meteorological services including public weather forecast and conducting meteorological research.

Currently, the NMSA administers and runs about 630 meteorological stations of various classes nationwide. About 125 stations are in the first class category [33]. Most of these stations have Actinographies and Campbell stacks sunshine recorders. These first class stations are also equipped with anemometers and wind vanes, which measure wind speeds and wind directions respectively.

However, detailed and localized resource data on solar energy is not presently available. Consequently, lack of these data has remained one of the major constraints in the development of solar energy resources.

Before proceeding further with the results, it is desirable to give a brief account of the geographical and climatological conditions of Ethiopia. As mentioned above, Ethiopia is located in the tropics (horn of Africa). Thus, Ethiopia has an intense climate with typical seasonal rhythm strongly marked in respect of temperature, rainfall and weather generally. Cold, rainy summers from June to August and hot, dry winter from December to February are separated by autumn (September to November) and Spring (March to May) seasons of rapid change in weather conditions. The land surface of the country can be divided into the highlands of mountainous areas and low lying areas.

Regarding air temperature, Ethiopia has a cold summer and mild winter. Fog is infrequent and usually confined in summer in early mornings, but there are long periods in the mountainous areas. Visibility is generally very good; however, during the summer season the sky is not much clear. Finally, all parts of Ethiopia enjoy a very sunny climate compared with most countries. Due to lack of direct accurate measurements of solar energy reaching the ground physical and empirical models are to be used to estimate this resource.

In this research the railway routs from Sebeta to Meiso part of Addis Ababa to Djibouti and the Addis Ababa light rail transport system sample stations have been considered for the purpose of radiation model. Those stations are accepted to represent the different geophysical location of selected rout.

In the computation of the solar radiation on earth there are different types of models, among them the angstrom sunshine and temperature based models are most applicable therefore, here the sunshine hour model has been used and the result is tabulated in the following table.

The duration of the sunshine hour in a day can be calculated by using the well known Angstrom relation which is dependant the latitude of the station and the declination angle (δ) of the sun in turn dependant on the given day(n) starting from January first and the maximum tilting angle of the earth during the season as follows:

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

$$\text{Sunset} = 12 + \frac{1}{15^0} \cos^{-1} \left(\frac{-\sin(\phi) \sin(\delta)}{\cos(\phi) \cos(\delta)} \right) \quad (2)$$

Therefore, the duration of sunshine hour will be:

Sunshine hour duration = sunset- sunrise

In Sunshine-based models the most commonly used parameter for estimating global solar radiation is sunshine duration. Sunshine duration for a given period is defined as the sum of that sub-period for which the direct solar irradiance exceeds 120 Wm^{-2} . Solar radiation intensity is taken as incoming short-wave radiation measured in KW/m^2 /day. Then the monthly average daily global radiation intensity G on a horizontal surface ($\text{kwh.m}^{-2}.\text{day}^{-1}$). The global radiation at Addis Ababa for the first month, considering the number of days is 31 is calculated by using the following angstrom relations.

$$G = G_0 \left(a + b \left(\frac{S}{S_{Max}} \right) \right) \quad (3)$$

Where G = is the monthly average daily global radiation on a horizontal surface

G_0 =the monthly average daily extraterrestrial radiation on a horizontal surface ($\text{kwh.m}^{-2}.\text{day}^{-1}$)

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 they are empirical.

For given day the solar declination (δ) and the mean sunrise hour angle (w_s) can be calculated by the following equations

$$\delta = 23.45^0 \times \sin\left(\frac{360(284+n)}{365}\right) \quad (4)$$

$$\delta = 23.45 \sin\left(\frac{360(284+31)}{365}\right) = -17.78$$

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

$$w_s = \cos^{-1}(-\tan(9) \tan(-17.78)) = 87.09^0$$

The values of the monthly average daily extraterrestrial irradiation (G_0) can be calculated from the following equation

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

where I_{SC} is the solar constant ($=1367 \text{ W m}^{-2}$), ϕ the latitude of the site, δ the solar declination,

w_s is the mean sunrise hour angle for the given month, and n the number of days of the year starting from the first of January.

$$\begin{aligned} G_0 &= \left(\frac{24}{\pi}\right) \times 1367 \left[1 + 0.033 \cos\left(\frac{360 \times 31}{365}\right)\right] \times \left[\cos(9) \cos(-17.78) \sin(87.09) + \left(\frac{2\pi \times 87.09}{360}\right) \sin(9) \sin(-17.78)\right] \\ &= 9.348089 \text{ kwh/m}^2/\text{day} \end{aligned}$$

For a given month, the maximum possible day duration (monthly average day length (S_{Max})) which is related to W_s , the mean sunrise hour angle can be computed as.

$$S_{Max} = \frac{2w_s}{15} \quad (7)$$

$$S_{max}=S_{Max} = \frac{2W_s}{15} = 11.612 \text{ hrs}$$

The regression coefficient **a** and **b** has been calculated from the relationship given by

$$a = -0.11 + 0.235 \cos\phi + 0.323 \left(\frac{S}{S_{Max}}\right) \quad (8)$$

$$a = -0.11 + 0.235 \cos(9) + 0.323 \left(\frac{9.5}{11.612}\right) = 0.386$$

$$b = 1.449 - 0.553 \cos \phi - 0.694 \left(\frac{S}{S_{Max}} \right) \quad (9)$$

$$b = 1.449 - 0.553 \cos(9) - 0.694 \left(\frac{9.5}{11.612} \right) = 0.335$$

The average number of hours of sunshine were obtained from daily measurements covering a period of 3 to 5 years is calculated by using equation(1&2) and The values of the monthly average daily global radiation G reached to the earth surface at Addis Ababa is calculated using equation(3).

$$G = 9.348089(0.386 + 0.335 \left(\frac{9.5}{11.612} \right)) = 6.17 \text{ kwh/m}^2 \text{ day}$$

The other monthly average value and stations has been calculated with similar procedures and tabulated in the following tables for different stations and the value also subsequently graphically showed. The calculation for the next month includes the previous month duration plus the present month duration. That means for February n will be 59 days because we start to count the day from January first.

Table.3. Summarized yearly distribution of radiation at Addis Ababa

Months	No. of Day	$\phi(deg)$	S(hr)	$\delta(deg)$	w_s	S_{max} (hr)	a	b	G_o	G
Jan	31	9.01	9.5	-17.8	87.09	11.61	0.39	0.34	9.347	6.17
Feb	59	9.01	10	-8.67	88.62	11.82	0.4	0.32	10.13	6.713
Marc	90	9.01	8.6	3.62	90.57	12.08	0.35	0.41	10.8	6.946
April	120	9.01	6.8	14.6	92.36	12.32	0.3	0.52	10.99	6.455
May	151	9.01	6.8	21.9	93.65	12.49	0.3	0.52	10.9	6.362
Jun	181	9.01	5.2	23.2	93.89	12.52	0.26	0.61	10.86	5.557
Jul	212	9.01	5	18.2	92.98	12.4	0.25	0.62	10.97	5.523
Aug	243	9.01	3.25	8.1	91.29	12.17	0.21	0.72	10.93	4.37
Sept	273	9.01	4.8	-3.82	89.39	11.92	0.25	0.62	10.46	5.262
Oct	304	9.01	7.65	-15.1	87.56	11.67	0.33	0.45	9.609	6.028
Nov	334	9.01	9.3	-22	86.34	11.51	0.38	0.34	8.907	5.874
Dec	365	9.01	9.45	-23.1	86.13	11.48	0.39	0.33	8.782	5.804

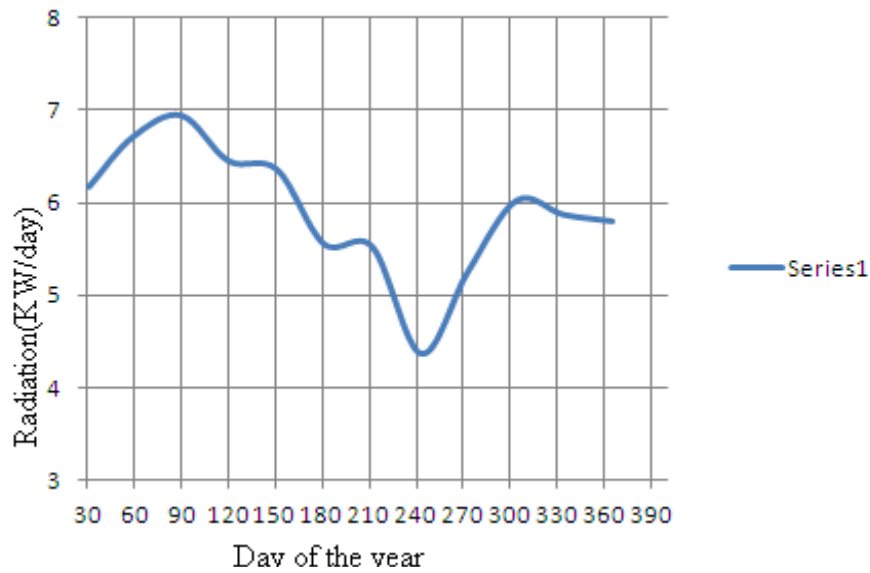


Figure.7. Radiation distribution throughout the year at Addis Ababa

Table. 4. Summarized yearly distribution of radiation Table at Debire Zeit

Months	No. of Day	$\phi(deg)$	S(hr)	$\delta(deg)$	w_s	S_{max} (hr)	a	B	G_o	G
Jan	31	8.44	9.2	-17.8	87.09	11.64	0.38	0.35	9.397	6.18
Feb	59	8.44	8.4	-8.67	88.62	11.83	0.35	0.41	10.16	6.531
Marc	90	8.44	8.4	3.619	90.57	12.07	0.35	0.42	10.79	6.895
Apri	120	8.44	7.4	14.59	92.36	12.3	0.32	0.49	10.95	6.656
May	151	8.44	7.7	21.9	93.65	12.46	0.32	0.47	10.83	6.652
Jun	181	8.44	6.3	23.18	93.89	12.49	0.28	0.55	10.79	6.08
Jul	212	8.44	5.2	18.17	92.98	12.37	0.26	0.61	10.91	5.611
Aug	243	8.44	5.1	8.105	91.29	12.16	0.26	0.61	10.9	5.603
Sept	273	8.44	6.4	-3.82	89.39	11.92	0.3	0.53	10.47	6.073
Oct	304	8.44	9.5	-15.1	87.56	11.69	0.38	0.34	9.65	6.369
Nov	334	8.44	9.1	-22	86.34	11.54	0.38	0.35	8.967	5.896
Dec	365	8.44	9.2	-23.1	86.13	11.52	0.38	0.35	8.845	5.826

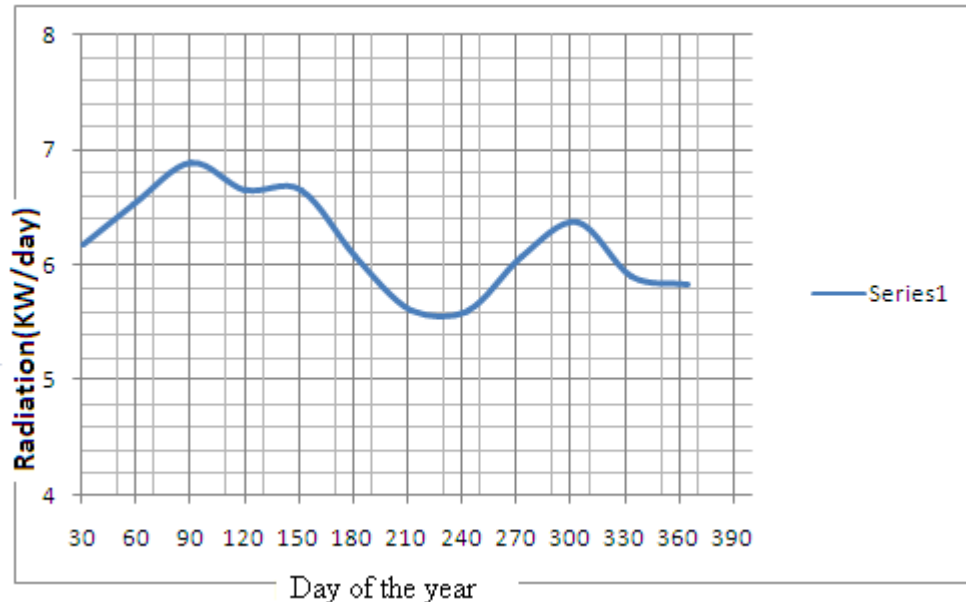


Figure.8. Radiation distribution throughout the year at Debire Zeit

Table.5. Summarized yearly distribution of radiation at Natherat

Months	No. of Day	$\phi(deg)$	S(hr)	$\delta(deg)$	w_s	S_{max} (hr)	a	B	G_o	G
Jan	31	8.33	9.4	-17.78	87.088	11.641	0.384	0.341	9.406	6.205
Feb	59	8.33	8.8	-8.67	88.616	11.829	0.363	0.386	10.16	6.608
Mar	90	8.33	8.2	3.6185	90.574	12.071	0.341	0.432	10.79	6.845
Apr	120	8.33	7.8	14.587	92.362	12.291	0.327	0.463	10.94	6.782
May	151	8.33	7.4	21.898	93.65	12.45	0.314	0.492	10.82	6.544
Jun	181	8.33	8.1	23.184	93.89	12.479	0.331	0.454	10.78	6.734
Jul	212	8.33	7	18.171	92.98	12.367	0.304	0.511	10.9	6.464
Aug	243	8.33	6.2	8.1046	91.292	12.159	0.287	0.549	10.9	6.173
Sept	273	8.33	7.6	-3.818	89.394	11.925	0.328	0.46	10.47	6.507
Oct	304	8.33	10.2	-15.06	87.558	11.699	0.404	0.296	9.657	6.406
Nov	334	8.33	9.6	-21.97	86.337	11.548	0.391	0.324	8.979	5.941
Dec	365	8.33	9.1	-23.09	86.129	11.523	0.378	0.353	8.857	5.825

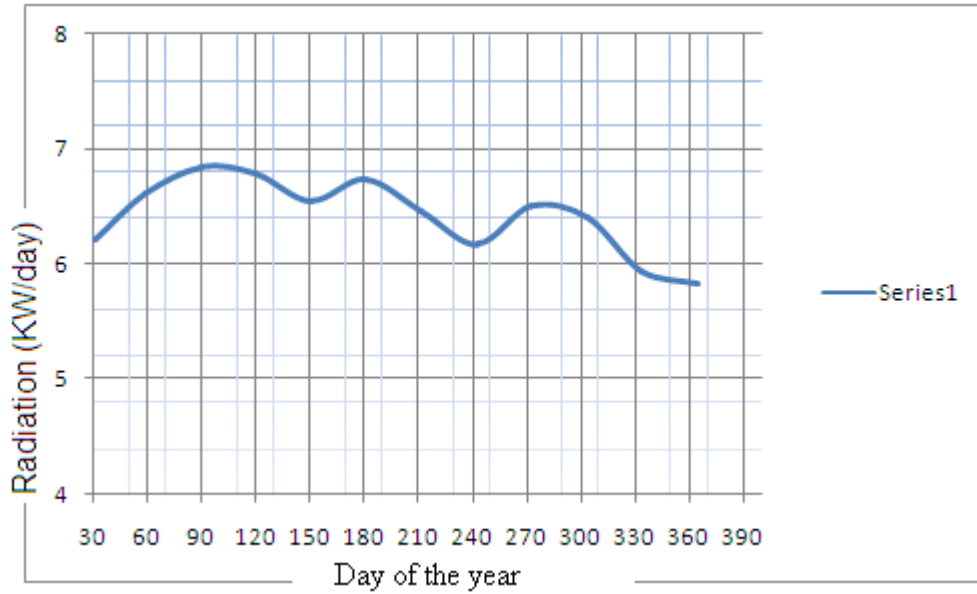


Figure.9. Radiation distribution throughout the year at Natherat

Table.6. Summarized yearly distribution of radiation at Metehara

Months	No. of Day	$\phi(deg)$	S(hr)	$\delta(deg)$	w_s	S_{max} (hr)	a	B	G_o	G
Jan	31	8.513	9.6	-17.78	87.09	11.63	0.39	0.33	9.39	6.209
Feb	59	8.513	8.7	-8.67	88.62	11.83	0.36	0.39	10.2	6.586
Mar	90	8.513	8.7	3.6185	90.57	12.07	0.35	0.4	10.8	6.961
Apr	120	8.513	8.2	14.587	92.36	12.3	0.34	0.44	11	6.906
May	151	8.513	8.6	21.898	93.65	12.46	0.34	0.42	10.8	6.906
Jun	181	8.513	7.6	23.184	93.89	12.49	0.32	0.48	10.8	6.595
Jul	212	8.513	6.9	18.171	92.98	12.38	0.3	0.52	10.9	6.435
Aug	243	8.513	6.8	8.1046	91.29	12.16	0.3	0.52	10.9	6.438
Sept	273	8.513	7.5	-3.818	89.39	11.92	0.33	0.47	10.5	6.474
Oct	304	8.513	9.4	-15.06	87.56	11.69	0.38	0.34	9.64	6.357
Nov	334	8.513	9.3	-21.97	86.34	11.54	0.38	0.34	8.96	5.909
Dec	365	8.513	9.5	-23.09	86.13	11.51	0.39	0.33	8.84	5.843

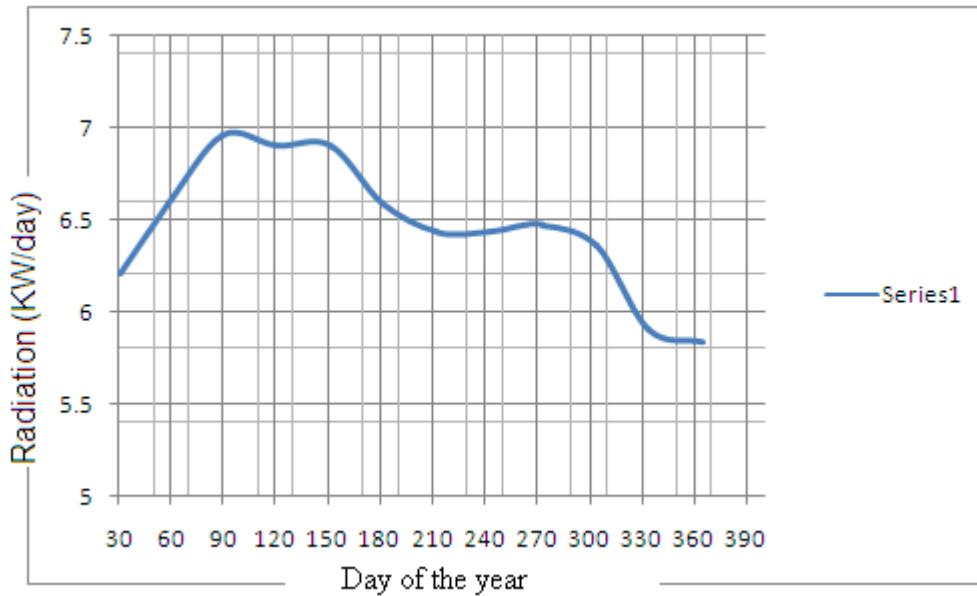


Figure.10. Radiation distribution throughout the year at Metehara

Table.7. Summarized yearly distribution of radiation at Dire Dawa

Months	No. of Day	$\phi(deg)$	S(hr)	$\delta(deg)$	w_s	S_{max} (hr)	a	B	G_o	G
Jan	31	9.58	9.3	-17.8	87.088	11.59	0.38	0.35	9.298	6.125
Feb	59	9.58	9.7	-8.67	88.616	11.8	0.39	0.33	10.11	6.68
Mar	90	9.58	9.3	3.619	90.574	12.08	0.37	0.37	10.81	7.076
Apr	120	9.58	7.2	14.59	92.362	12.34	0.31	0.5	11.03	6.636
May	151	9.58	8.8	21.9	93.65	12.52	0.35	0.41	10.96	7.028
Jun	181	9.58	7.7	23.18	93.89	12.55	0.32	0.48	10.93	6.706
Jul	212	9.58	7.5	18.17	92.98	12.42	0.32	0.48	11.02	6.718
Aug	243	9.58	7.5	8.105	91.292	12.18	0.32	0.48	10.95	6.722
Sept	273	9.58	6.6	-3.82	89.394	11.91	0.3	0.52	10.45	6.143
Oct	304	9.58	8.4	-15.1	87.558	11.65	0.35	0.4	9.567	6.169
Nov	334	9.58	9.7	-22	86.337	11.48	0.39	0.32	8.847	5.859
Dec	365	9.58	9.8	-23.1	86.129	11.45	0.4	0.31	8.72	5.779

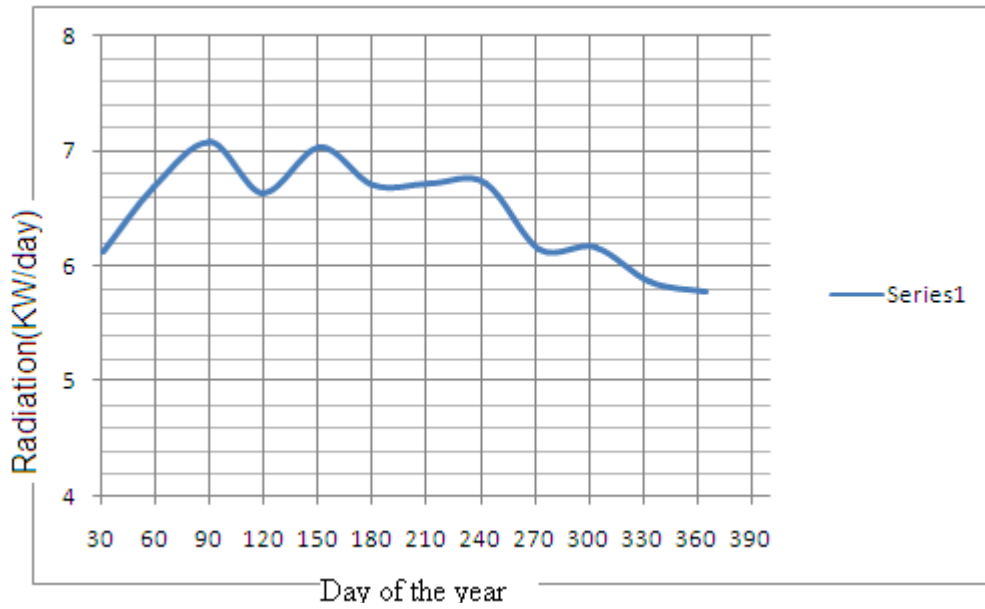


Figure. 11. Radiation distribution throughout the year at Dire Dawa

Table.8. Summarized yearly distribution of radiation at Meiso

Months	No. of Day	$\phi(deg)$	S(hr)	$\delta(deg)$	w_s	S_{max} (hr)	a	B	G_o	G
Jan	31	9.08	9.1	-17.78	87.088	11.61	0.38	0.36	9.342	6.133
Feb	59	9.08	5.8	-8.67	88.616	11.81	0.28	0.56	10.13	5.641
Marc	90	9.08	6.3	3.619	90.574	12.08	0.29	0.54	10.8	6.188
April	120	9.08	7.8	14.59	92.362	12.32	0.33	0.46	10.99	6.817
May	151	9.08	7.8	21.9	93.65	12.49	0.32	0.47	10.9	6.728
Jun	181	9.08	7.7	23.18	93.89	12.52	0.32	0.48	10.87	6.669
Jul	212	9.08	7.2	18.17	92.98	12.4	0.31	0.5	10.97	6.582
Aug	243	9.08	6.7	8.105	91.292	12.17	0.3	0.52	10.93	6.411
Sept	273	9.08	6.5	-3.818	89.394	11.92	0.3	0.52	10.45	6.108
Oct	304	9.08	9.1	-15.06	87.558	11.67	0.37	0.36	9.603	6.299
Nov	334	9.08	8.1	-21.97	86.337	11.51	0.35	0.41	8.901	5.706
Dec	365	9.08	9.1	-23.09	86.129	11.48	0.38	0.35	8.775	5.771

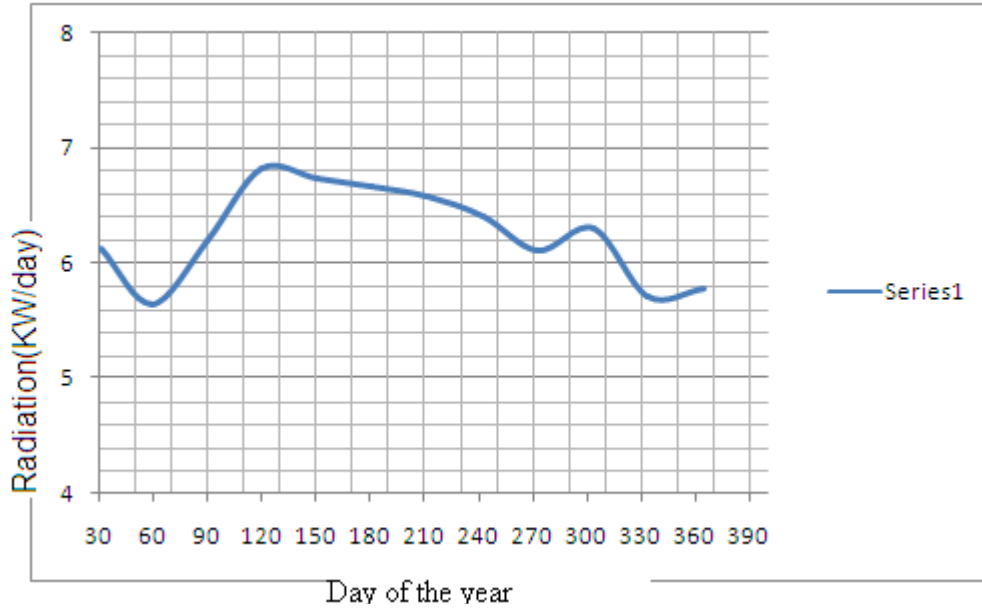


Figure.12. Radiation distribution throughout the year at Mieso

3.3. Daily Solar Energy Obtained

3.3.1. Daily Irradiance Model

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. Some researcher develop a polynomial model, but it is not logical at all because adapting the profile of irradiance to a different date or geographic location, a completely new polynomial has to be interpolated it is the drawback of the model. Here we will use a simple trigonometric model with only two parameters, the maximum irradiance G_{max} and the duration of the day T_{day} , that can be easily interpreted. The daily solar energy per square meter is the surface below the curve and can be easily calculated in equation (9). In order to take into account cloudy days, a constant η_{wthr} is added with a value between 1 (clear sky) and 0 (dark). This constitutes a margin for the calculation.

$$E_{day \text{ density}} = \frac{G_{max} T_{day}}{\pi/2} \eta_{wthr} \quad (10)$$

The two parameters I_{max} and T_{day} are depending on the location and the date.

It is observe that in winter (Ethiopian summer), the maximum irradiance decrease due to the very low sun elevation and cloudy and rainy day. Concerning the influence of the location on Earth, of course near the equator, the sun elevation becomes more favorable, but the night and day duration are then almost equivalent. Anyway the total amount of energy along the day is higher than on the equator.

3.3.2. Calculation of the Daily Solar Energy

The total electric energy is obtained by multiplying the result of equation (4) with the surface area of solar cells, their efficiency, the day condition coefficient, the efficiency of the MPPT and the number of car in a train set. Additionally, we have to take into account the fact that the cells are not disposed on a horizontal surface but follow the cambered shape of the roof top for this thesis we assume that the cell is on horizontal surface. In a series of interconnected cells, the one with the lowest irradiance limits the current for all the others. This problem occurs mainly at sunrise or sunset, when the sun elevation is low, and depends also on the train orientation, this effect is included under the calculation of the inclination angle.

This situation is represented in figure.3 where the first cell, near the border of attack, has the smallest elevation angle θ_1 and will then penalize the other cells.

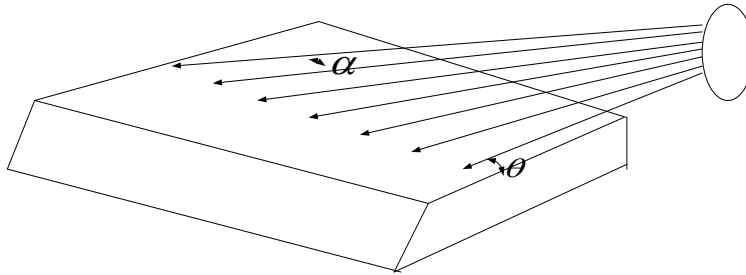


Figure.13. Variation of incidence angle on the solar cells for a roof top surface of the train at sunrise and sunset.

For this reason it is important to take care about the wiring configuration and preferably dispose the cells connected in series along the roof top, so that they have the same orientation. The camber of the top roof is neglected that means the roof top of the train in which the solar panel installed is considered almost flat.

$$P_{elec\ tot} = GA_{sc}\eta_{sc}\eta_{wt\ hr}\eta_{mppt} \quad (11)$$

Where P = power generated from the solar /day

A_{sc} = effective area available on the top roof of the train car which is equal to the total area covered

by solar cell .

η_{sc} = solar cell efficiency, $G_{per\ day}$ = solar radiation (KW/m²/day)

n = number of cars in a train set, $\eta_{wt\ hr}$ = day condition factor

η_{mppt} = the maximum power point tracer coefficient

We can observe that in winter (Ethiopian summer), the maximum irradiance decrease due to the very low sun elevation and cloudy and rainy day. Concerning the influence of the location on Earth, of course near the equator, the sun elevation becomes more favorable, but the night and day duration are then almost equivalent. Anyway the total amount of energy along the day is higher than on the equator.

3.3.3. Maximum Power Point Tracker

As described above, a solar cell has a working point on its current to voltage curve where the power retrieved is maximal. In order to work at this point, which is continuously moving because of the constantly changing irradiance conditions, and thus get the highest amount of energy, a so called Maximum Power Point Tracker (MPPT) is required. A MPPT is basically a DC/DC converter with variable and adjustable gain between the input and the output voltage, the input being the solar panels and the output the battery, grid and direct supply. It contains electronics that monitor both the current and the voltage on each side, which allows a determination for how the gain has to be changed to ensure the best use of the solar panels.

There are different algorithms to track this maximum power point. One very well known is called the "Hill Climbing" method; considering a constant battery voltage, which is valid at short term, increasing/decreasing the voltage gain makes the working point, on the power curve of figure (6), move respectively to the left/right. The current and voltage are measured to compute the actual power. If it is higher than the previous power, the direction of movement is kept as one is getting more energy, if not, direction is changed.

A consequence is that the working point is never at the MPP, but oscillating around it, giving thus an average power slightly below the maximum power. With the growth of the photovoltaic market, there are a lot of commercially available MPPTs, but as they are used mainly for fixed applications (garden house, etc.), they are never optimized for low weight.

In order to be complete, it has to be mentioned that η_{mppt} is the product between the efficiency of the DC/DC converter alone and the efficiency of the tracking algorithm. In fact, the working point is never constantly on the maximum power point but oscillating around it.

$$\eta_{mppt} = \eta_{mppt\ dc} \eta_{mppt\ algo} \quad (12)$$

For a MPPT that is well designed for a specific application, we can consider $\eta_{mppt\ dc} > 97\%$ and for the algorithm $\eta_{mppt\ algo} > 98\%$, leading to a total efficiency that should always be higher than 95%.

This tracking function operates only during the first phase of the battery charge, when the voltage is below the maximal value that would destruct the battery cells. In the second phase, i.e. constant voltage, decreasing current, the power has to be reduced below MPP. That means that the tracking is still executed, but with an additional condition that if the voltage approaches the maximum, the direction is automatically changed, reducing the power.

As part of the energy chain, the MPPT has to be as efficient as possible. A well designed MPPT should have efficiency above 95%, but the best products reach 99%.

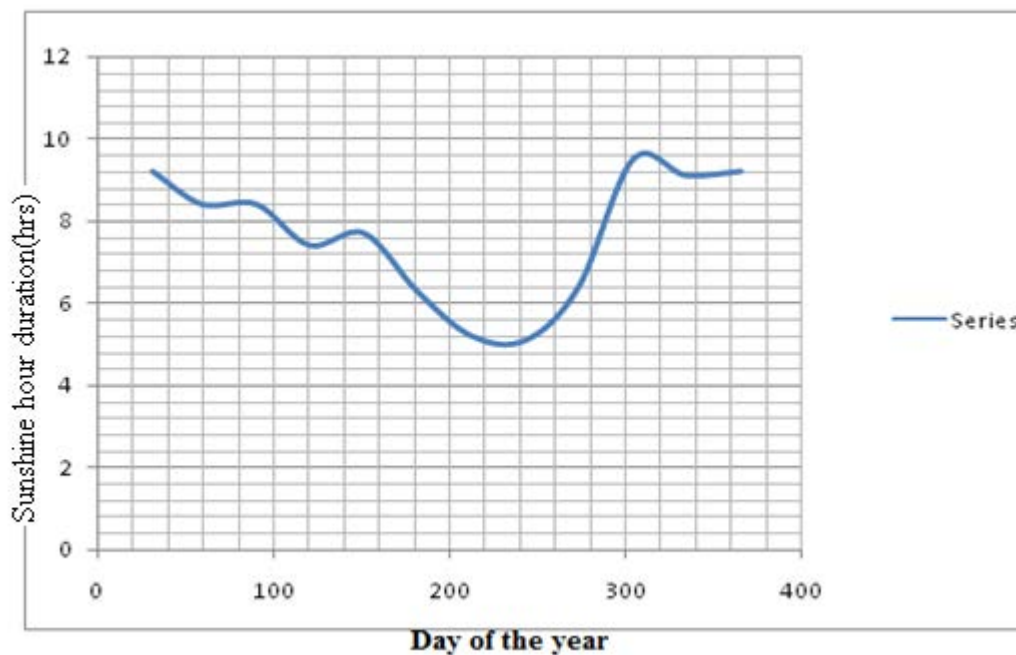


Figure.14. Sunshine hour variation in a year

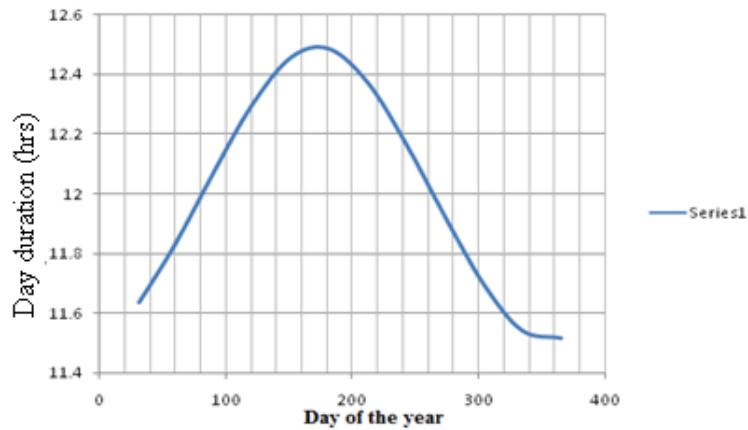


Figure.15. Day duration in a year

Table.9. The hourly distribution of radiation intensity

Hour	η_{wthr}	G_{max}	Irradiance dist.
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

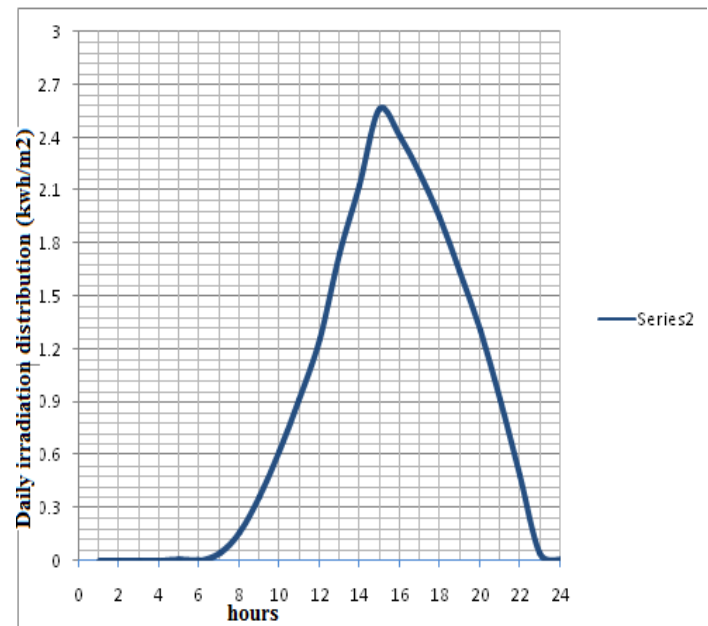


Figure.16. Approximation of irradiance as a sinusoid distribution in a day at Debire Zeit

3.4. Calculation of Solar Power That Can Be Harnessed By PV from the Top Roof of The Configured Train Car Set

In the computation of power generated from solar energy has to methods. First one, assume the amount of power want to generate then selecting the preferred panel potential finally we will calculate the required area to install the panel. The second is starting from the fixed area, computing the amount of power generated and number of panels then it is possible to suggest the preferred panel capacity.

In this research considering the second scenario is applicable, because even if we can set more cars in the configuration, the maximum number of cars and the top roof of the train car is limited.

Solar power that can be harnessed from the selected solar PV is determined by considering the effective available area, the type and efficiency of the PV cell, the radiation solar angle, sunshine hour, the location and the weather condition. To mount solar PV module on the roof tops, it is vital to consider the dimensions of the coach or locomotive and the effective area used. Because the entire area of roof surface cannot be used for installing solar PV modules, there have to be clearances that allow personnel to access the top easily for various purposes and associate auxiliary equipments on the roof top.

In this computation assume that the effect of aerodynamic effect , boundary condition near surface of the top, the camberness/ curvature of the roof, the property of the connected wire used in the power systems are negligible. And all the calculation is based on the clear sunshine hour duration.

In this research to calculation the power generated in a day, a monocrystalline silicon cell with an efficiency of 28% and the size of a cell is 195.59 X 99.06 mm ($A=1.9374155\text{m}^2$ approximately= 1.937m^2) and the maximum radiation energy per day is calculated based on the equation (4).

The number of car in a train set is different based on the purpose and driving condition. According to the Ethiopian railway corporation the maximum number of cars in a train set is 3 and 20 for AALRT and national purpose respectively. The dimension of the car is different based on their operation purpose and driving area (table .1.).

3.4.1. Computation of Solar Power from the Roof of AALRT

Area available on the roof of one coach $2.65\text{m} \times 28.4\text{m} = 75.26 \text{ m}^2$ but this area is the total area. it will reduced for walkway, fixing access, etc . Then consider an effective available area $= 71.669 \text{ m}^2$ and the maximum number configured car per train for AALRT is $= 3$

The energy produced from a set of train and the number of panels required is calculated by using the following formula

$$P = nG_{per\ day}A_{sc}\eta_{sc}\eta_{wt\ hr}\eta_{mppt}$$

$$\text{Number of panel required for sinle car} = \frac{\text{total active roof top area of car}}{\text{area of single panel}} = \frac{A_{EC}}{A_p} = \frac{71.669 \text{ m}^2}{1.937 \text{ m}^2} = 37$$

Where A_{EC} = effective area available on the top roof of the train car which is equal to the total area covered by solar cell equal to A_{sc}

η_{sc} = solar cell efficiency, $G_{per\ day}$ = solar radiation (KW/m²/day)

n = number of cars in a train set,

$\eta_{wt\ hr}$ = day condition factor = 1 because we consider the sunshine hour method

η_{mppt} = the maximum power point tracer coefficient assumes that is 0.98

Based on the above calculation the least amount of energy generated from a single car is 85.947KW/day in August which can be substitute 10.91% and the highest 136.6 KW/day in March and can be substitute 17.34% of the total power consumed by the car. Here as observed from the table the number of car set in the train is increased the amount of power generated also increase in turn in increases the substitution amount. From the technical proposal information the maximum train set for AALRT is 3 them the power generation will be the minimum 257.84kw/day in august and the maximum 409.8kw/day in March which substitutes 32.74% and 52.04% respectively.

According to the existing market assessment in Ethiopian suggested a panel with the specification of 300 watt 1.94m^2 costs around 35,000 ETB it includes all the accessories and man power cost for installation. But the price of a panel is around 9,800ETB. Here to produce an average power 37 panel/car is required which costs 1,295,000 ETB.

Table.10.The amount of power generation and percentile coverage for AALRT based on train set configuration.

Month	G (KW/m ² /day)	η_{mppt}	η_{SC}	Area (m ²)	Average power generated (kw/day)			power used from grid(kw)	% power substitute(per day)		
					No. of cars in train set				No. of cars in train set		
					1	2	3		1	2	3
Jan	6.17	0.98	0.28	71.669	121.41	242.81	364.22	787.8	15.42	30.83	46.25
Feb	6.71	0.98	0.28	71.669	132.03	264.05	396.08	787.8	16.77	33.53	50.3
Mar	6.95	0.98	0.28	71.669	136.6	273.2	409.8	787.8	17.35	34.69	52.04
Apr	6.45	0.98	0.28	71.669	126.94	253.88	380.82	787.8	16.12	32.24	48.36
May	6.36	0.98	0.28	71.669	125.11	250.23	375.34	787.8	15.89	31.77	47.66
Jun	5.56	0.98	0.28	71.669	109.29	218.57	327.86	787.8	13.88	27.76	41.63
Jul	5.52	0.98	0.28	71.669	108.61	217.23	325.84	787.8	13.79	27.58	41.38
Aug	4.37	0.98	0.28	71.669	85.947	171.89	257.84	787.8	10.91	21.83	32.74
Sep	5.26	0.98	0.28	71.669	103.48	206.97	310.45	787.8	13.14	26.28	39.42
Oct	6.03	0.98	0.28	71.669	118.55	237.11	355.66	787.8	15.05	30.11	45.16
Nov	5.87	0.98	0.28	71.669	115.52	231.04	346.56	787.8	14.67	29.34	44.01
Dec	5.8	0.98	0.28	71.669	114.14	228.28	342.42	787.8	14.49	28.99	43.48

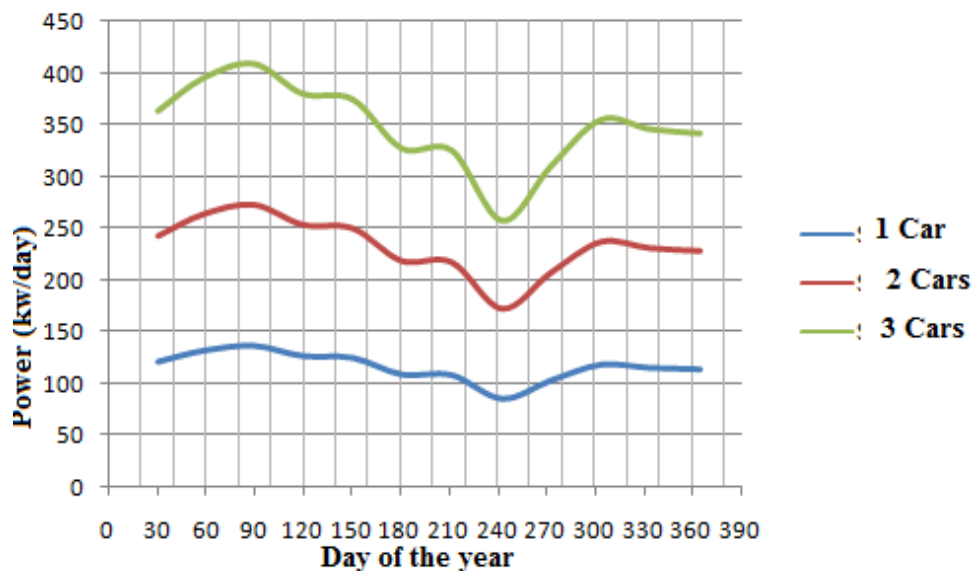


Figure.17. The power increment with the number of car configured for AALRT

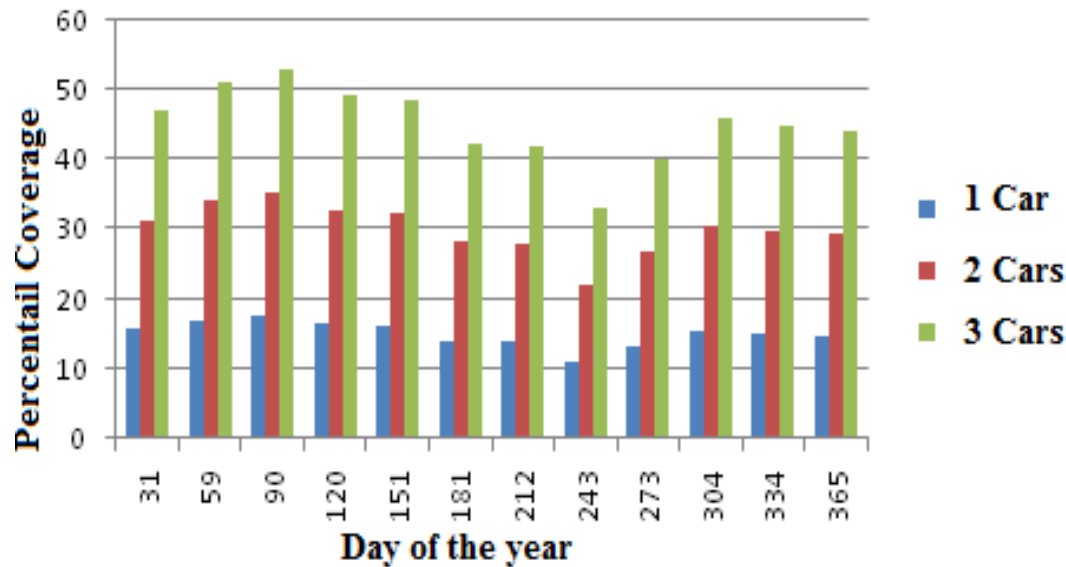


Fig.18. The percentage coverage of power based on the number of cars.

3.4.2. Computation of power from the roof top of configured Cross Country rail cars

According to the technical proposal of the ERC, Consider the maximum configuration of a car in a train for both transport and freight is 20car/train. Therefore, the available roof top area /car and the number of panels required to install on the available area for the selected types of cars are calculated as follows:

3.4.2.1. Box type Freight Car:

The available roof area/car is 54.027m² but the effective area is 50.362m² and the size of a panel is 1.937m² then the number of panels required for a single car is calculated as follows:

$$\text{Number of panels required/car} = \frac{50.362\text{m}^2}{1.937\text{m}^2} = 26$$

The total number of panels for the maximum configuration will be: 20x26= 520

The power generated from nth number of configured train cars also calculated as:

$$P = nG_{per\ ay}A_{sc}\eta_s\eta_{thr}\eta_{mppt}$$

But when the number of shunted train (trailer) is increased the power generated from the installed solar energy is increased

In the case of freight Box type train arrangement, the number of car configuration to cover the required amount of supply power at minimum and maximum solar radiation is 14 and 9 respectively.

Table.11. power generated from the solar source and possible percentile coverage of the main source

Box type freight car

Stations	Month		G (kw/m ² /day)	η_{sc}	η_{mppt}	A(m ²)	No. car	P (Kw/day)	P _{grid} (KW)	% covera ge	No. requir ed panel/ car	Sugge sted panel power (watt)
A.Aa	Aug	Min.	4.37	0.28	0.98	50.36	1	60.39	815.4	7.41	26	200
	Mar	Max.	6.95	0.28	0.98	50.36	20	1919.77	815.4	235.44		
D/Zeit	Aug	Min.	5.61	0.28	0.98	50.36	1	77.43	815.4	9.81		
	Mar	Max.	6.9	0.28	0.98	50.36	20	1944.55	815.4	238.48		
Natherat	Dec	Min.	5.73	0.28	0.98	50.36	1	80.75	815.4	9.87		
	Mar	Max.	6.86	0.28	0.98	50.36	20	1930.51	815.4	236.76		
Metehar	Dec	Min.	5.82	0.28	0.98	50.36	1	80.75	815.4	9.903		
	Mar	Max.	6.97	0.28	0.98	50.36	20	1923.87	815.4	235.94		
D/Dawa	Dec	Min.	6.11	0.28	0.98	50.36	1	79.86	815.4	9.79		
	Mar	Max.	7.02	0.28	0.98	50.36	20	1955.71	815.4	239.85		
Meiso	Feb	Min.	5.71	0.28	0.98	50.36	1	77.93	815.4	9.56		
	Apr	Max.	6.82	0.28	0.98	50.36	20	1884.98	815.4	231.17		

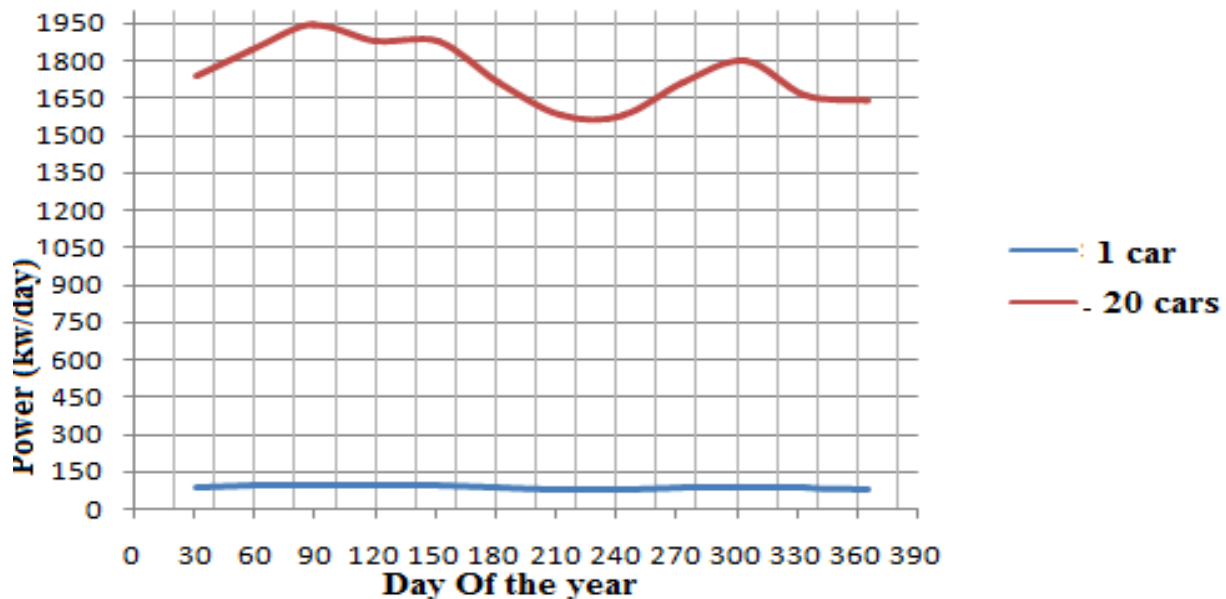


Figure. 19. The power increment with the number of car increase for Box type car

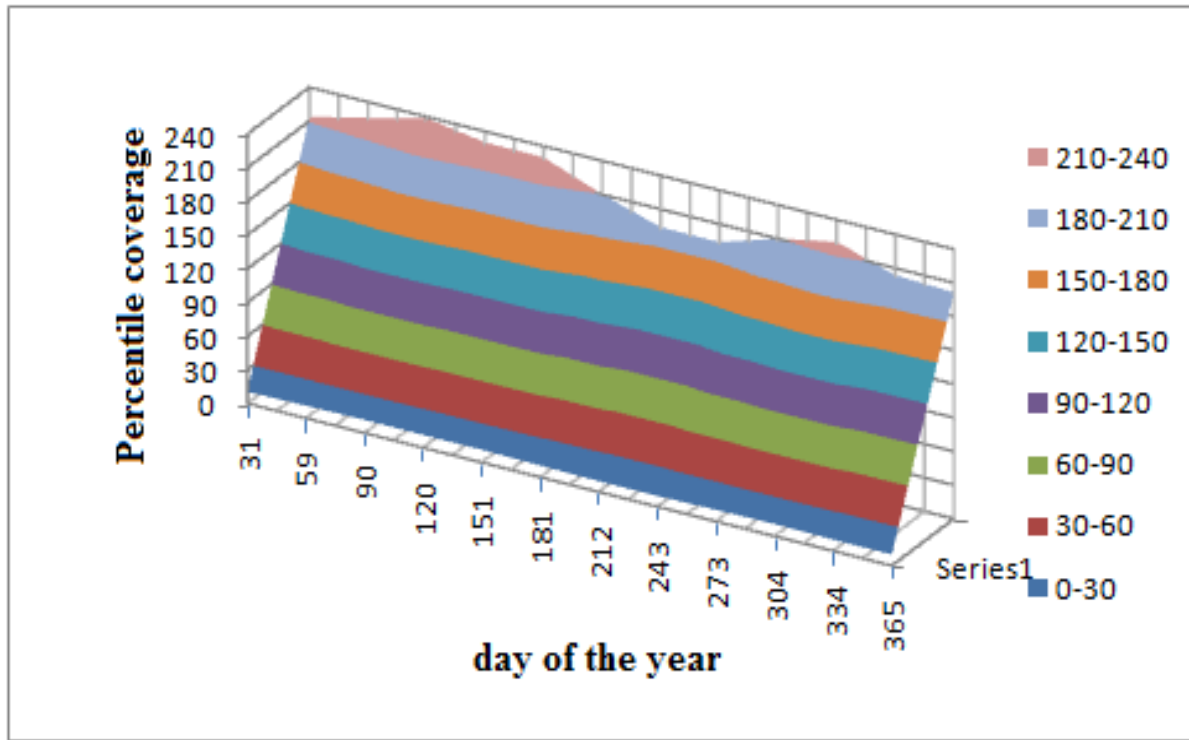


Figure.20. Percentile Coverage of power for box type car

3.4.2.2. YZ25G passenger car:

The total available roof area/car is 79.1775m^2 but the effective area is 75.543m^2 and the size of a panel is 1.937m^2 then the number of panels required for a single car is calculated as follows:

$$\text{Number of panels required/car} = \frac{75.543\text{m}^2}{1.937\text{m}^2} = 39$$

The total number of panels for the maximum configuration of train set is $20 \times 39 = 780$

The power generated from n^{th} number of configured train cars also calculated as:

$$P = nG_{\text{per day}}A_{sc}\eta_{sc}\eta_{wt hr}\eta_{mppt}$$

For these types of car configuration the number of cars required to generate the total required power at maximum and minimum solar radiation is 6 and 9 respectively.

Table.12. Power generated from the solar source and possible percentile substitution of the main source of YZ25G passenger car

Stations	Month		G (kwh/m ² /day)	η_{sc}	η_{mppt}	A (m ²)	No. car	P_{SC} (KW)	P_{con} (Kw)	%	No. of requir ed panel/ car	Sugge sted panel (watt)
AA	Aug	Min	4.37	0.28	0.98	75.54	1	90.59	815.4	11.11	39	275
	Mar	Max	6.95	0.28	0.98	75.54	20	2881	815.4	353.4		
D/Zeit	Aug	Min	5.61	0.28	0.98	75.54	1	116.3	815.4	14.26		
	Mar	Max	6.9	0.28	0.98	75.54	20	2861	815.4	350.8		
Natherat	Dec	Min	5.73	0.28	0.98	75.54	1	118.8	815.4	14.57		
	Mar	Max	6.86	0.28	0.98	75.54	20	2844	815.4	348.8		
Metehar	Dec	Min	5.82	0.28	0.98	75.54	1	120.6	815.4	14.8		
	Mar	Max	6.97	0.28	0.98	75.54	20	2890	815.4	354.4		
D/Dawa	Dec	Min	6.11	0.28	0.98	75.54	1	126.7	815.4	15.53		
	Mar	Max	7.02	0.28	0.98	75.54	20	2910	815.4	356.9		
Meiso	Feb	Min	5.71	0.28	0.98	75.54	1	118.4	815.4	14.52		
	Apr	Max	6.82	0.28	0.98	75.54	20	2827	815.4	346.8		

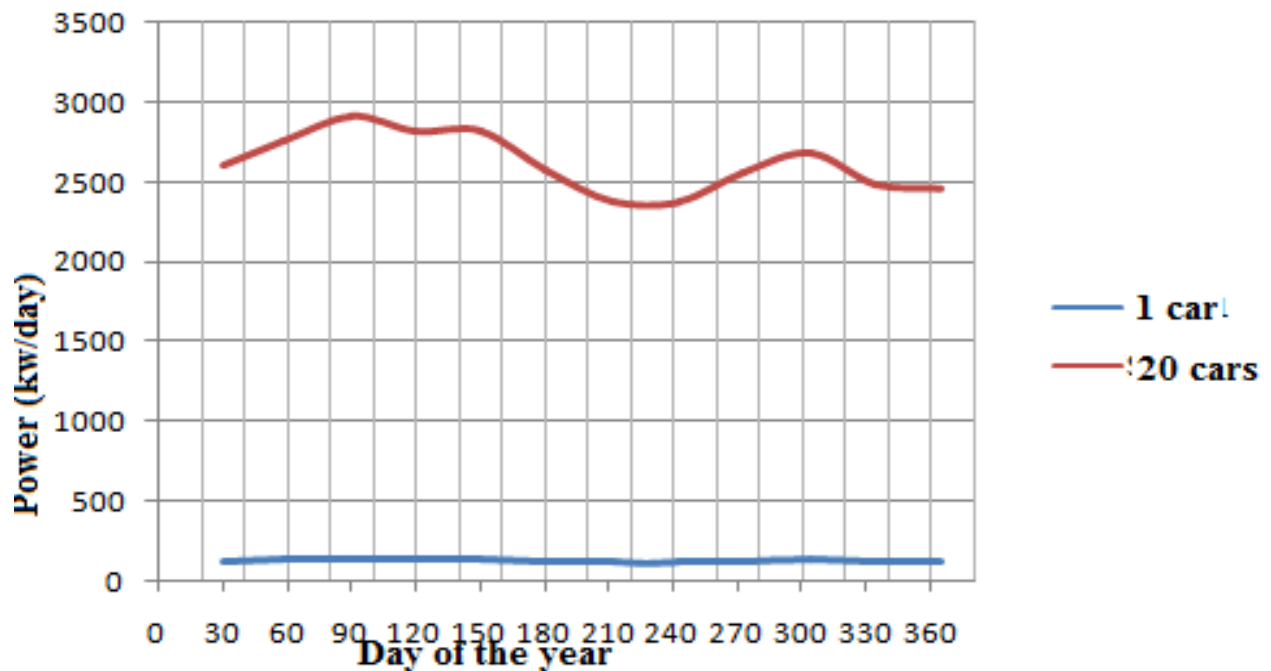


Figure. 21. The power increment with the number of car increase for YZ25G

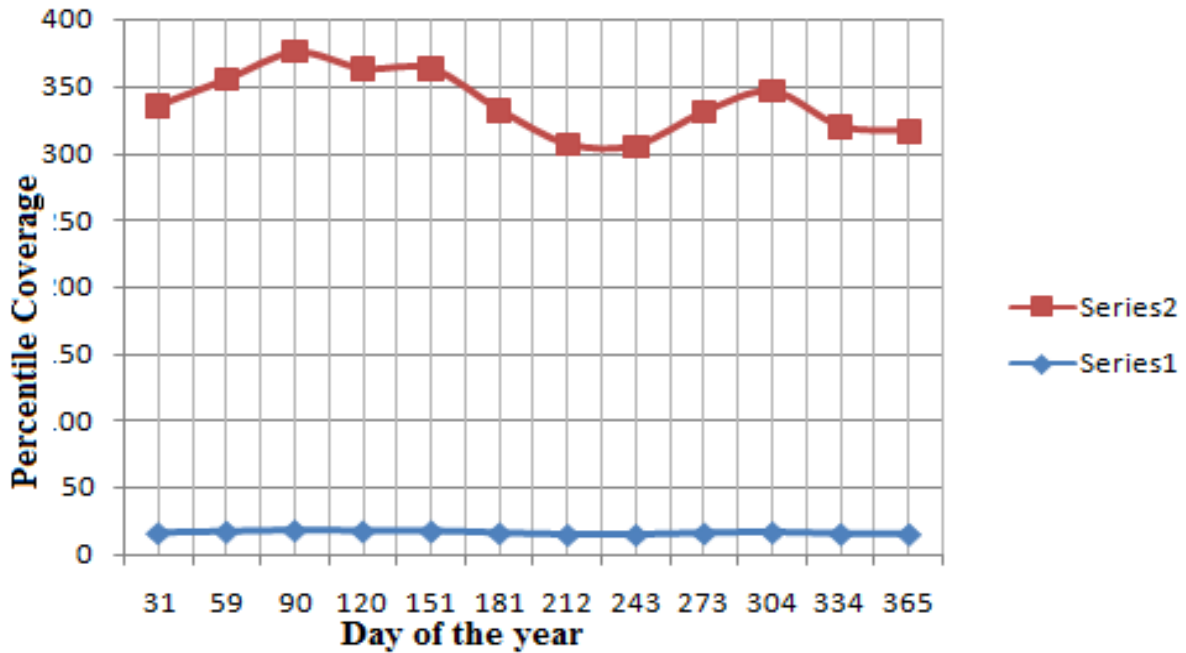


Figure.22. Percentile coverage of power for YZ25G car.

3.4.2.3 DFN7G multi-purpose car:

The total area of these types of car is $62m^2$ and the effective area is $58.11m^2$

$$Number\ of\ panels\ required/car = \frac{58.11m^2}{1.937m^2} = 30$$

$$P = nG_{per\ day}A_{sc}\eta_{sc}\eta_{wt\ hr}\eta_{mppt}$$

In the case of DFN7G multipurpose type train car the required number of car configuration to cover the required power for the train in a day at maximum and minimum extreme generation is 5 and 18 respectively. But the technical proposal shows the maximum configuration for the cross country railway train set is 20. Therefore for this type of car it is better to recommend increasing the configuration or use high efficient solar panel to operate effectively through the route unless in Addis Ababa the systems remain auxiliary power source rather to cover the required propulsion source because of its minimum production of energy at Addis Ababa.

Table.13. Power generated and percentage substitution for DFN7G multipurpose

Stations	Month		G (kwh/m ² /day)	η_{sc}	η_{mppt}	A (m ²)	No. car	P_{SC} (KW)	P_{con} (KW)	%	No. required panel/ car	Sugge sted panel(watt)
Aa	Aug	Min	4.37	0.28	0.98	58.11	1	69.68	1564	4.455	30	275
	Mar	Max	6.95	0.28	0.98	58.11	20	2216	1564	141.7		
D/Zeit	Aug	Min	5.61	0.28	0.98	58.11	1	89.45	1564	5.72		
	Mar	Max	6.9	0.28	0.98	58.11	20	2200	1564	140.7		
Natherat	Dec	Min	5.73	0.28	0.98	58.11	1	91.37	1564	5.842		
	Mar	Max	6.86	0.28	0.98	58.11	20	2188	1564	139.9		
Metehar	Dec	Min	5.82	0.28	0.98	58.11	1	92.8	1564	5.934		
	Mar	Max	6.97	0.28	0.98	58.11	20	2223	1564	142.1		
D/Dawa	Dec	Min	6.11	0.28	0.98	58.11	1	97.43	1564	6.229		
	Mar	Max	7.02	0.28	0.98	58.11	20	2239	1564	143.1		
Meiso	Feb	Min	5.71	0.28	0.98	58.11	1	91.05	1564	5.821		
	Apr	Max	6.82	0.28	0.98	58.11	20	2175	1564	139.1		

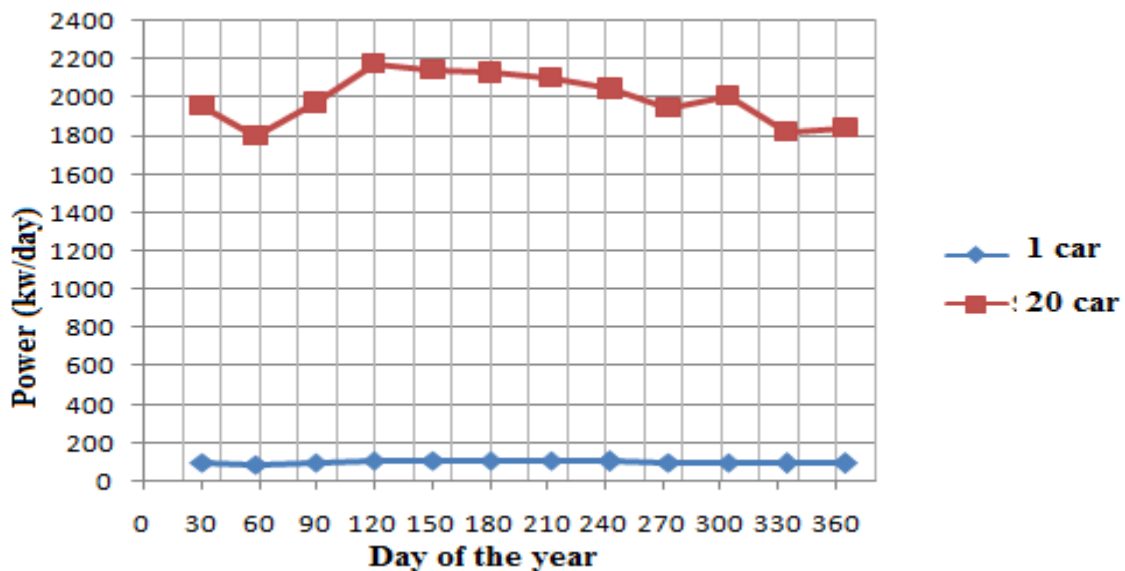


Figure. 23. Power increment of for DFN7G multipurpose train configuration.

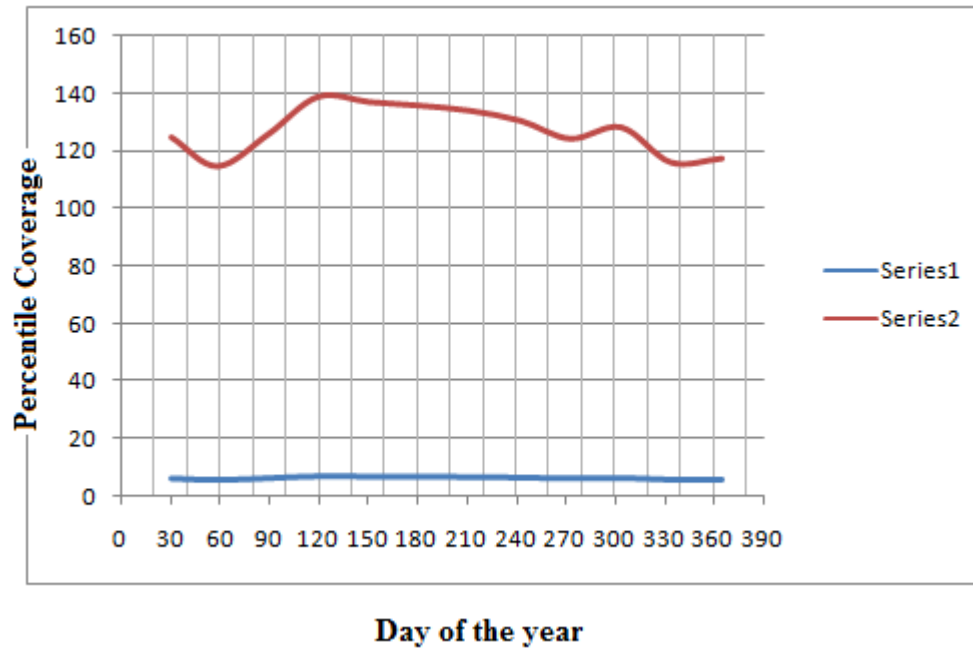


Figure.24. Percentile coverage of power of DFN7G train car

3.5. Computation and Analysis of the Diesel Power Generation

As we know one of the energy source of the train locomotive is a diesel fuel. From the technical specification of Ethiopian railway corporation (ERC) DFN7G multi uses a diesel generator to generate a driving energy.

The train consists of two power cars at either end and in turn with two power generator/motor which supply the required power for the entire rake. The proposed capacity of the train locomotive has a rated power of 1840KW with a power factor of 85%. That means the maximum service power will be 1564KW. Therefore from one engine we can get 782KW. But in the calculation it is necessary to consider the total required power generated from the two set of engines. According to the technical specification of the ERC information the diesel train uses 207+3%g/KWh of fuel with a speed of 120km/hr for freight and 160km/h for passenger and the journey duration with this speed from Addis Ababa to Djibouti 14hours and 7 hours respectively. For a safe operation of the train it also suggested that the train shall be operate with 80km/h with the same power generation

To calculate the power developed from the diesel engine, it is necessary to consider the fuel efficiency per unit and the amount of fuel used to develop the energy required to push or drive the train.

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

$$P = m_{diesel} \times LHV_{diesel}$$

Where m_{diesel} = is the kg of fuel consumed by the generator according to the ERC, it is 213.21 gm/KWh at rated power but here we consider the service power rather than the rated power.

LHV_{diesel} = is the lower heating value of diesel fuel, for this study taken to be 43MJ/Kg (11.979kwh/kg)

That mean from one kilogram of fuel it is obtain = 11.979kwh. Therefore the total amount of fuel used to generate this power will be calculated as follows and most of the times the efficiency of a diesel generator is ranging from 40- 80%. In this study assume that the efficiency is 75%.

Power rated = amount of fuel x fuel efficiency x power developed from one kg diesel

$$P = m \times \gamma \times P_{per/kg}$$

$$m = \frac{P}{\gamma \times LHV_{diesel}} = \frac{1564kw}{0.75 \times 11.979kwh/kg} = 174.08kg/h$$

Let assume the train is derived for one round trip; the total time will be 28 hours and 14 hours for the freight and passenger purposes respectively. Then we can calculate the amount of fuel consumed in a trip.

The total amount of fuel consumed in a single trip is dependent on the purpose used and it is calculated as follows:

$$a. \text{ If used as freight: } \frac{174.08kg}{h} \times 28h = 4874.31kg /trip,$$

It is known that the density of the diesel fuel used for train propulsion is 860kg/m³, therefore, the volume of the fuel could be:

$$V = \frac{M_{diesel}}{\rho_{diesel}} = \frac{4874.31}{860kg/m^3} = 5.67m^3 = 5667.8lit$$

For the freight it may require refuel the train because the fuel tank capacity for this type of car is 5000 lit

b. If used as a passenger: $\frac{174.08kg}{h} \times 14h = 2437.154kg/trip$

$$V = \frac{M_{diesel}}{\rho_{diesel}} = \frac{2437.154kg}{860kg/m^3} = 2.8339m^3 = 2833.9lit$$

As observed from the calculation of the total fuel consumption and based on the present Ethiopian energy minister information the price of the fuel per litter is around 18ETB (\$0.857). Therefore the cost of fuel consumed in a single trip \$4858.114 and \$2429.057 for freight and passenger respectively.

CHAPTER FOUR

4. ENERGY STORAGE, CONTROL UNITES AND JUNCTIONS

When the energy production is not constant and continuous, a good energy storage method is necessary. We can list many different ways to store energy [11]:

- Chemical (hydrogen, bio-fuels)
- Electrochemical (batteries, fuel cells)
- Electrical (capacitor, super capacitor, superconducting magnetic energy storage or SMES)
- Mechanical (compressed air, flywheel)
- Thermal

These different technologies coexist because their characteristics make them attractive to different applications. From a user point of view, the main selection criteria are the energy and power density, the response time, the lifetime, the efficiency and of course the costs.

In the case of a solar train and automobile, the gravimetric energy density in Wh/kg, also called specific energy, and the peak power are the most crucial parameters that determine the choice of the energy storage method. The volumetric energy density will of course also have an influence on the roof top size, but this volume plays a minor role on the power required compared to the weight. Therefore, in the present case, electrochemical batteries best candidates for the train. In fact, they have the highest gravimetric energy density from all the solutions that are reversible.

4.1. Electrochemical Batteries

4.1.1. Batteries

In the electrical and solar hybrid vehicle system a storage battery is used to store and supply power when needed. Concerning the battery design, it's necessary to consider its mass, the power consumption and autonomy night duration, and its gravimetric energy density. In this study we do not design the battery system rather we select the battery and analysis its storage capacity.

4.1.2. Design of Battery for hybrid System

4.1.2.1. Key Elements in Battery Selection

Selection of the proper battery for a solar photovoltaic system requires a complete analysis of the battery discharge requirements. In most cases the choice of battery is based on lowest price. Because of this, an inadequate and improper battery is selected, which reduces the system's reliability and durability. Many approaches can be followed for the selection of a PV battery.

Cycle life, performance at extreme temperature, effect of rate of discharge, self-discharge rate, battery voltage and maximum current drain capacity in ampere-hours, watt-hours per weight, maintenance requirements, and watt-hours per unit volume and cost per watt-hour are a few critical parameters which can be optimally combined to select the right battery for any particular PV installation. Conventionally, a lead-acid automotive battery has been used in most PV installations.

4.1.2.2. Batteries Commonly Used for PV Applications

The most commonly used storage battery for PV applications is the lead-acid type. Alkaline batteries, nickel cadmium, Automotive, traction, stationary and maintenance-free gelled electrolyte batteries are used.

Automotive batteries (also known as SLI; Starting, Lighting and Ignition batteries) have traditionally been used for daily shallow depth of-discharge (DOD) PV applications, e.g. street lighting, although they have only a 2 – 4 Years life span and a poor cycling ability. A stationary battery is frequently used for applications involving telecommunications, navigational aids, emergency lights, uninterrupted power supply systems, etc.

These are capable of occasional deep discharge. Rechargeable traction or motive power batteries are used in electric vehicles, which can also be powered by a photovoltaic array.

Maintenance-free batteries are increasingly required in automotive, traction or stationary applications which serve up to 15 years. Gelled electrolyte or sealed maintenance-free batteries are suitable for PV applications, which require completely unattended operations. Nominal voltage standards in the industry (such as 6, 12, 32, 36, 48, etc. volts) are preferred. In this research considering a sealed maintenance free 48 quantities with a total voltage of 96v and an individual current capacity of 500Ah which is compatible to the battery used in technical specification of ERC. So it is recommended to use this type of battery in the hybrid system which results in reduction of cost and weight of the system that satisfy the present engineering design principles.

In the design we will take depth of discharge to be 75% which is the minimum allowable one and the temperature correction 0.9, it needs because at low temperature battery efficiency decreases.

$$B_{rc} = \frac{E_{c(AH)} D_s}{(DOD)_{\max} \eta} \quad (14)$$

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 or load is given by ampere in hour

Assume the charging autonomy is 5 hours then the battery charging capacity will be

$$B_{rc} = \frac{500Ah \times 5}{0.75 \times 0.9} = 3703.704Ah$$

Now the possible total power can delivered from the battery can be

$$P_{b \text{ single}} = B_{rc} \times V_b = 3703.704 \times 2 = 7.407kwh$$

Therefore, the required number of battery to store the energy required for:-

1. AALRT :- $787.4/7.407 = 106.25 \approx 107$ batteries
2. Box type freight and YZ25G passenger:- $815.4/7.407 = 110.09 \approx 110$ batteries
3. DFN7G multi-purpose car : $1564/7.407 = 211.152 \approx 212$ batteries

Therefore the total number of batteries required for the four type of train set is 429.

4.2. Control Unit and Converters

The control unites and converter in the hybrid solar system is very essential. There for in this research the VVVF with a capacity of output power greater than 1000KW is selected it is similar to the proposed type for ERC. The maximum power tracker (MPPT) of the system, a Voltronic solar power inverter was selected with the power output of greater than 1000kw is used and for each train car it is required one MPPT. The junction box used in the system, a three way 1C2M type with a capacity of DC 850v is used to distribute the system power. The other unit in the system is a battery charge and discharge controller therefore; we

chose a capacity of 280VAC output voltage. It has a charging span of 10,000 times and the system requires 4 charger controllers for each locomotive batteries

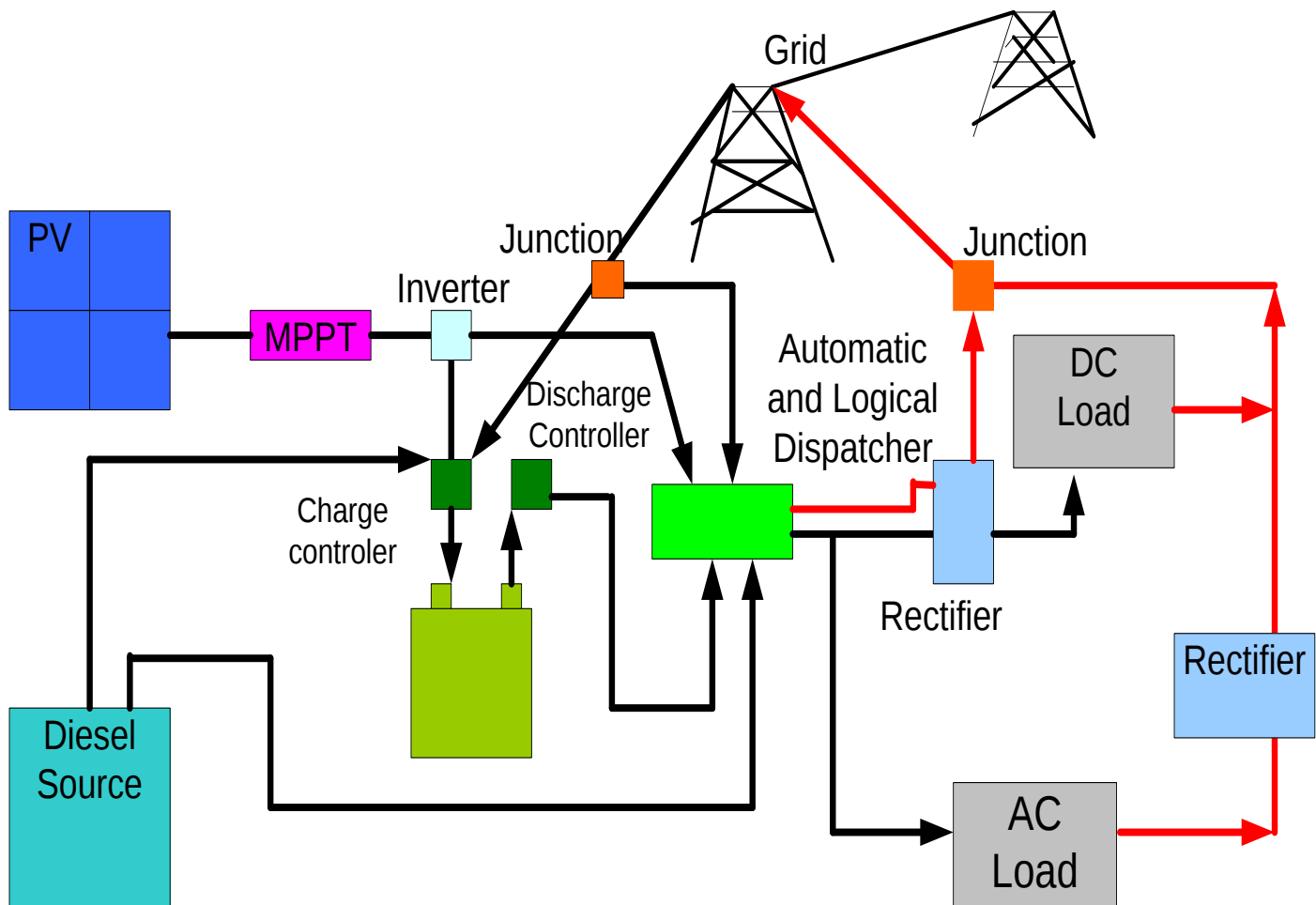


Figure. 25.PV, Diesel and Grid Connected hybrid system circuit diagram

CHAPTER FIVE

5. COST LEVELIZATION AND COST COMPARISON OF THE ELECTRIC, DIESEL AND HYBRID SYSTEM

5.1. Cost Comparison of Electrical, Diesel And Solar

According to the world battery market the price of the single battery is \$350, therefore the total price of the battery is:

Total price of battery = total number of battery X price/ battery = (107+110+110+212) x350= \$188,650
which is equivalent of 3,886,190 ETB

The price of electricity consumed by the train is calculated based on the present selling price of the Ethiopian electrical power corporation which is 1.75 ETB per KWh. Then the total price for one trip from Addis Ababa to Djibouti will be :

$$C_{total} = P \times H \times C_{per\ KWH}$$

Where C_{total} = total price of consumed power; P=power consumed; H= number of driving hours and

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

1. For ALLRT assume that the train is operating 12 hours per day then

$$C_{total} = 787.8\text{kw} \times 12\text{h} \times 1.75\text{ETB/KWh} = 16,543.8\text{ ETB}$$

2. For Box type : $C_{total} = 815.4\text{kw} \times 28\text{h} \times 1.75\text{ETB/KWh} = 39954.6\text{ ETB}$

3. For YZ25G car: $C_{total} = 815.4\text{kw} \times 14\text{h} \times 1.75\text{ETB/KWh} = 19903.8\text{ ETB}$

4. For DFN7G multi-purpose diesel: as calculated above the cost of fuel \$4858.114(99,809.35Birr) and \$2429.057(50,038.57Birr)/trip for freight and passenger respectively.

In addition to the above the total price of the battery and solar panel used for both types of train the different accessories and components of the system cost had been assumed and included in the computation of the system price and it is tabulated in the following table. The selected inverter, MPPT, junction, and charge and discharge controller \$525, \$600, \$87 and \$52. The prices of all the necessary components are included in total cost of a panel.

Price of Energy generated from solar/year = no.car x 1.75 x energy/day x365

Consumed energy price/year = power used x price/KWh x driving hour x number of trip/year.

Table. 14. Energy production from PV and Cost computation

Type	Max. No. of cars	No. panel /car	Total No. of panel	panel capacity (watt)	Total cost/ panel	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

5.2. Cost Levelization Of The Hybrid System

Most of the present manufacture solar cell has service life of 20 to 30 years and the battery should replace within 15 years. Based on the manufacturer information a monocrystal silicon solar cell panel has a potential of 27 to 30 years based on the operation and environmental factor. Therefore let assume the life span of the PV for our case it could be 30 years. According to the technical specification of Ethiopian Railway Corporation the service life of the train car will be 30 years so the battery is replaced once in its life. Then for the replacement of batteries it costs \$188,650 (3,867,325Birr) in life. Assume that the maintenance cost of the system is negligible, and then the total cost of the solar system could be the summation of the battery replacing cost and the first investment cost which is 56,764,325 Birr. It is known that one of the feasibility of any investment is the duration of it cost return. Therefore the cost return time based on the minimum average energy production from the top roof surface of the maximum allowable configuration will be 12 years. It shows that the project can run with a profit of 18 years. But this duration may decrease if the train operates with the maximum average energy production and the system shares system components.

CHAPTER SIX

6. Carbon Dioxide Emission

6.1. Computing The Carbon Emission Reduced By Using The Solar Hybrid Energy Source

Environmental pollution is a series problem in ore planet. The most source of this pollution is a carbon emission from different mobile and fixed machineries. A diesel train is the one in which have a great contribution for this problem. Therefore, to reduce the carbon emission, using a solar hybrid energy source is a solution. As seen in the literature the effect of solar energy emission is insignificant, therefore, the computation of carbon emission from electric source and solar system is negligible and considered only the diesel source because in any aspect of diesel fuel application have a great emission gas released to the environment.

6.1.1. Emission from the diesel source

In the calculation of carbon dioxide emission, United States, the code of federal regulations provides value for carbon content per gallon of diesel fuel which environmental protection agency uses in calculating the fuel economy and emission of a vehicle. According to this code diesel fuel carbon content per gallon is 2778gm. The estimation of average carbon content of conventional diesel fuel does not specifically address the impact of fuel additives that may depend on the feedstock.

6.1.2. Calculating CO₂ Emission Reduction.

The intergovernmental panel on climate change (IPCC) guidelines for calculating emission inventories requires an oxidation factor be applied to the carbon content to account for a small portion of the fuel that is not oxidized into CO₂. For oil and oil products, the oxidation factor used is 0.99(99%) of the carbon in the fuel is eventually oxidized, while 1% remain un-oxidized. Based on this information the railway locomotives emission of carbon is 0.85kg/lit. And as we discuss in the literature review the train locomotive using solar system can be reduce 750gm/KWh. Here to calculate the carbon dioxide emission from the locomotive used the first scenario.

As observed from table.12 production of electrical energy from solar for DFN7G multi-purpose diesel train set produces a minimum 69.68kw/day at Addis Ababa and a maximum of 335.8kw/day at Dire Dawa. Therefore the amount of carbon emission reduction is proportional to the amount of percentile coverage of the consumed power. Then the amount of reduction can be calculated for the following cases:

1. If For the freight purpose:

Carbon emission = $0.85\text{kg/lit} \times 5667.8\text{lit} = 4817.63\text{kg/trip}$ can be emitted

The amount of reduction of carbon dioxide with due to the production of solar energy from the top roof surface area of the configured train sets

a. At the minimum solar energy = $4817.63 \times 4.455\% = 214.63 \text{ kg/trip}$

b. At the maximum solar energy = $4817.63\text{kg/trip} \times 143.1\% = 6845.85\text{kg/trip}$

2. If it uses for passenger transportation purpose: the amount of carbon dioxide emission

$2833.9\text{lit} \times 0.85\text{kg/lit} = 2408.82\text{kg}$,

a. At the minimum solar energy = $2408.82\text{kg} \times 4.455\% = 107.313 \text{ kg/trip}$

b. At the maximum solar energy = $2408.82\text{kg} \times 143.1\% = 3447.02\text{kg/trip}$

Generally the reduction of carbon emission which is calculated based on the amount of fuel consumed ranging from 214.63kg to 6845.85kg per trip and 107.313kg to 3447.02kg per trip for freight and passenger transportation respectively.

CHAPTER SEVEN

7. Result Discussion, Conclusion And Recommendations

7.1. Result Discussion

This thesis describes the assessment of solar energy for the application of train traction system as a supplemental (hybrid) form. To generate a solar power it is necessary to compute the irradiation intensity of the selected area. The amount of energy produced is dependent on the irradiation of the sun, the surface area of the solar panel, sunshine hour duration, the seasonal inclination of the sun, the altitude of the selected region, the efficiency and type of solar cells. Here a monocrystalline silicon solar cell with the efficiency of 28% and the area of 1.937m^2 which is available in Ethiopia had been used for the computation and the required number of panels for a selected train configuration with the recommended wattage was found. In this thesis the known angstrom correlation model had been used for the computation of solar radiation. The radiation distribution for the selected station at Addis Ababa and along the rout of Ethio-Djibouti railway system is computed and the result was tabulated from table 3 to 8. It is observed that the minimum radiation was $4.37\text{KW}/\text{m}^2/\text{day}$ obtained at Addis Ababa in august and the maximum was obtained at Dire Dawa which was $7.2\text{ KW}/\text{m}^2/\text{day}$. Based on the radiation distribution during a year, the possible amount of energy was computed and the result had been tabulated from table 10 to 13. The result shows that the minimum daily energy was found at Addis Ababa and the maximum was at Dire Dawa with the respective amount of radiation intensity.

It is known that the production of electric energy is highly proportional with the size of the installed solar panel surface area. But the roof top of the train car is limited then the computation had been started from the calculation of the selected rail cars roof top area which are proposed and expected to will used in Ethiopia. As observed from the tabulated value of energy computation the minimum percentile energy coverage is found 4.455% on the DFN7G multipurpose rail car if we use a single car but the number of train car increases in the configuration the power generated increases and at some number of configuration there is a possibility produce the whole energy required for the specific train set power and then the excess energy will send to the grid. In the technical proposal of ERC the power interred to the system can be return to the main grid through the return wire. The other work included in this thesis was the selection of battery to store and the inverter, rectifier and junctions; the cost of the conventional and renewable energy sources had been computed.

7.2. Conclusion

As we know Ethiopia is a country which found at the equatorial region and has high solar intensity almost throughout the year and has a potential to generate abundant energy from the sun. The purpose of this work has been to compute the possible amount of solar energy produced from the roof top of the train car, percentage reduction of both energy consumption and carbon emission. As we observed the value tabulated from table 10 to 13, for AALRT, Box type, YZ25G and DFN7G with the coverage percentile value of 10.91-52.04%, 7.41- 239.85%, 11.11 -356.9% and 4.455-143.1% and the required number of car configuration to totally cover the energy for the train locomotive with the minimum energy production is 10,14,9 and 18 respectively. This value is based on the number of configured train car and operating area and condition. But for AALRT the maximum allowable configuration of car is three therefore it is remain as a supplemental system by using logical efficient dispatching system.

The other observation from this research the cost of the solar system is high but the operating and maintenance cost is too low and it requires a turn back time of 12 years. Based on the possible expected life span of the solar panel 30 year, the train can be operates with a profit of 18 years. Regarding the carbon dioxide emission reduction considered that the DFN7G multipurpose train cars and the value reduction was calculated based on the production of solar energy from the roof of the train which is varying from 214.63kg to 6845.85kg per trip and 107.313kg to 3447.02kg per trip for freight and passenger transportation application respectively. Therefore it is possible to conclude that the energy generated from the top roof surface area of the train car shows a promising result for future generation. Since the efficiency of the solar panel and the roof top area is fixed, the required energy for the train can be increased by increasing the number of trains' car configuration. The energy extracted from the solar can produced more than the required energy for the train consumption, and then it shall send back it to the main grid for other purposes

In general it is possible to conclude that the energy generation from the top roof of the train can cover a significant amount of required energy for the locomotive and reduces a carbon emission to safe our planet. In turn it helps to reduce the cost investing on fuel and increase the growth of the country usage of renewable energy efficiency.

7.3. Recommendation And Suggestion of Future Work

This research, the design of a hybrid solar energy for train locomotive power supply by installing the solar panel at the top roof the train shows that there is possibility to generate high amount of electrical energy, therefore it is recommend to the Ethiopian power suppliers and railroad industry, a series of measures that shall be adopted in order to achieve energy security, sustainable development & minimize environment damages.

Since this research was done under many constraints subsequently it requires further and deep study. Therefore, the following future works has been recommended:

1. The aerodynamic and boundary condition effect of the moving air at the top surface.
2. Developing the efficient dispatching system algorithm to use efficiently the produced energy.
3. The environmental effect on the solar panel in a country.
4. Analysis of movable and fixed solar panel installation related to its efficiency and sun motion tracking.

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