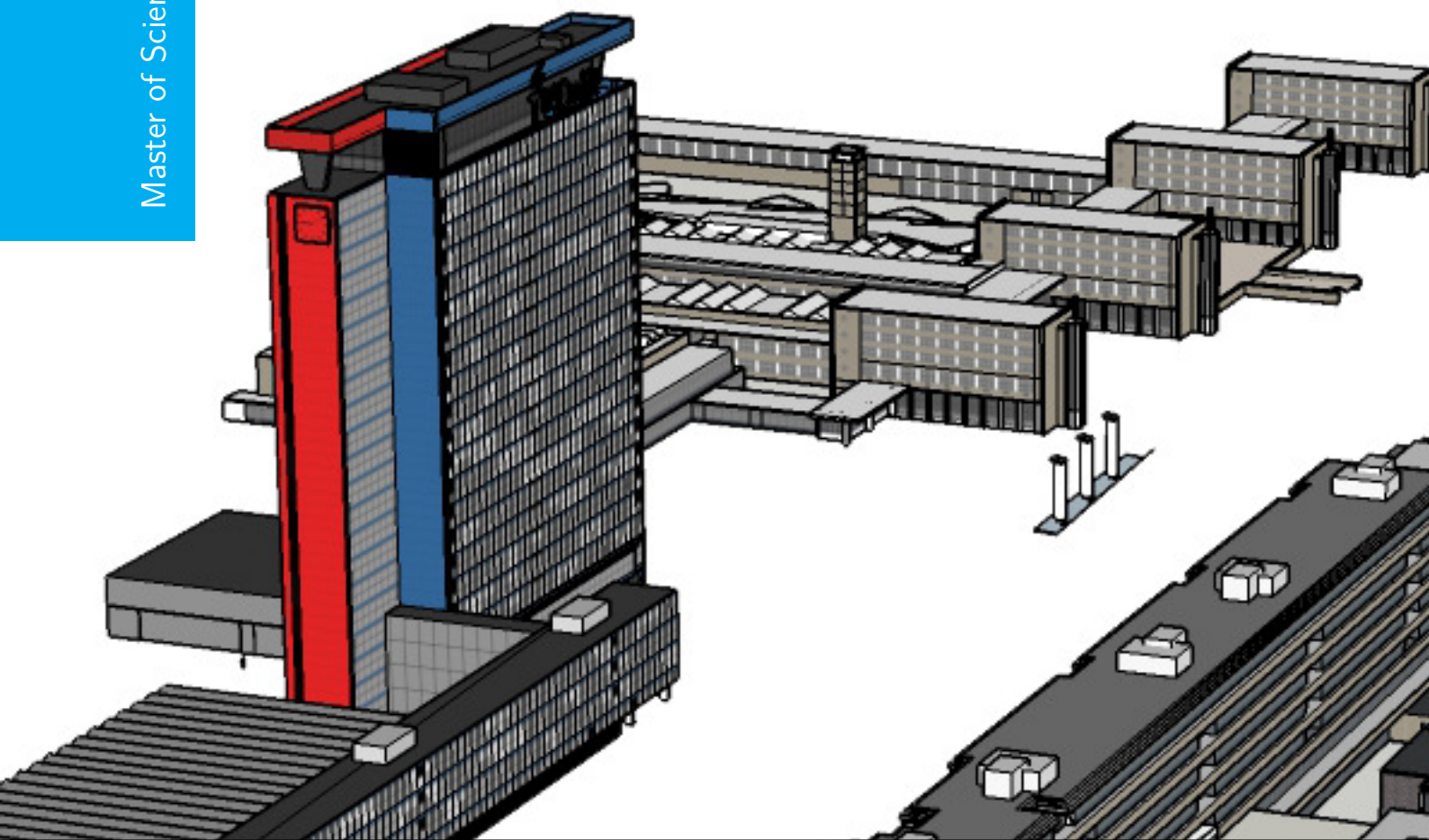


Designing and Energy Yield Analysis of Roadside PV System

Bheeshma Chatrath

Master of Science Thesis



Designing and Energy Yield Analysis of Roadside PV System

by

Bheeshma Chatrath

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Abstract

Low powered electric vehicles and electricity generation with the help of renewable energy technology are two kind of technological advancements which are taking place to meet growing global energy demand while reducing greenhouse gas emissions together at the same time. Achieving these objectives indicate shift from energy demand followed by fossil fuels to renewables. Renewable energy technology and plug-in vehicle electrification adoption have substantial problems associated with it, however there are ways to exploit their potential in order to develop sustainability in the field of electricity and transportation.

This thesis aims at designing the Roadside Photovoltaic (PV) system that act as a major supply of electrical power to charge Electric Bikes (E-bikes). The expansion and rapid growth in E-bikes is tremendous in the Netherlands, therefore the charging of E-bikes is chosen as an application to build the roadside PV system for campus located at Mekelweg, Delft. The E-bike dynamic consumption is modelled to calculate the driving efficiency of an E-bike, and thus this model is used to compute the state of charge of incoming E-bikes in order to determine the daily consumption of charging station. Furthermore, for maximizing the energy yield of the PV system, the optimal orientation of module is analysed. The mounting and placement of these optimally oriented modules beside the road is decided such that the overall effect of shading is minimal. Moreover, as it is a Roadside PV, the system is compared with the solar road technology to see the difference of how the system behaves when placed optimally beside the roads on poles instead horizontally on roads. Finally, performance of entire grid-tied Roadside PV system with storage is determined according to chosen application.

Keywords: *Roadside PV, E-bike, Solar road*

Glossary

List of Acronyms

TU Delft	Delft University of Technology
EU	European Union
PV	Photovoltaic
SVF	Sky View Factor
E-bikes	Electric Bikes
KNMI	Koninklijk Nederlands Meteorologisch Instituut
CESAR	Cabauw Experimental Site for Atmospheric Research
DNI	Direct Normal Irradiance
DHI	Diffuse Horizontal Irradiance
GHI	Global Horizontal Irradiance
ESH	Equivalent Sun Hours
STC	Standard Test Conditions
MATLAB	Matrix Laboratory
AC	Alternating Current
LIDAR	Light Detection and Ranging
TNO	Toegepast Natuurwetenschappelijk Onderzoek
SOC	State of Charge
DOD	Depth of Discharge
Li-Ion	Lithium Ion

Pb-acid	Lead acid
NiCd	Nickel cadmium
NiMH	Nickel metal hydride
NaNiCl	Sodium nickel chloride
HWFET	Highway Fuel Economy Test
EEMCS	Faculty of Electrical Engineering, Mathematics and Computer Science
EV	Electric Vehicle
MPPT	Maximum Power Point Tracker

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Delft, University of Technology
September 18, 2017

Bheeshma Chatrath

Chapter 1

Introduction

The world has witnessed rapid growth in many fields including population rise, it is indeed one of the major concerns. Since, it has led to unprecedented increase in the utilization of natural resources. There has been rising demands for energy resources which have been fulfilled by fossil fuels. However, these are non-renewable sources and are going to be depleted in near future. Therefore, an utmost requirement of generating energy resources through an alternative way is necessary to meet demands of the users.

From the past few years, the new trend has been set up, i.e., non-conventional energy resources to fulfil these energy demands. It is evident from Figure 1-1 which compares the increase in growth of clean energy with other primary resources from the year 2005 till 2015 and depicts that this transition is taking place, but it has still not reached the stage where all of renewable resources can be sole provider of energy. Therefore, there is a need to expand its generation with the help of green energy.

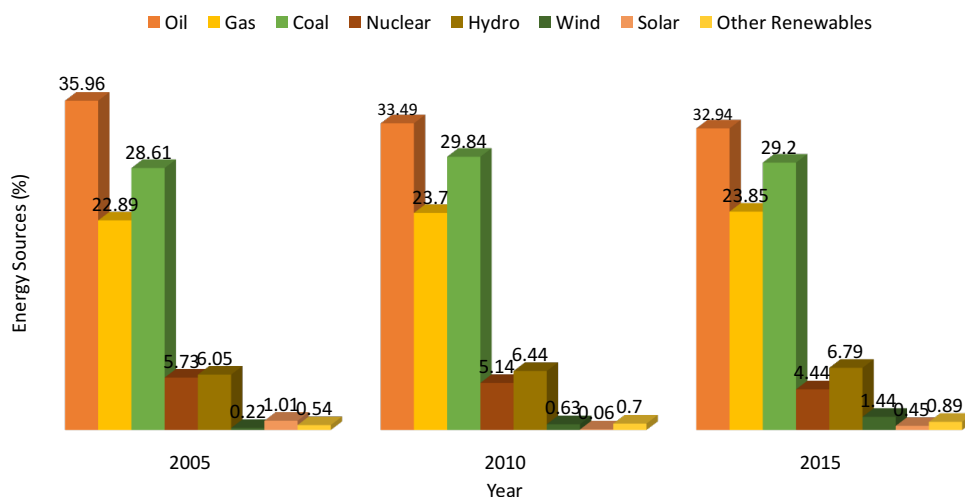


Figure 1-1: Energy consumption comparison [1].

As it is illustrated in Figure 1-1, there is a rise in renewable energy from past and it is expected to rise in near future. The reason behind this is the development in technical knowledge and skills that has a convincing influence on renewable energy technology. Due to this, there are more innovative ideas to produce and store renewable energy so that it can meet world energy demands. Moreover, there are more investment in producing renewable energy [16] which has led to decrement of prices than conventional source of energy. In addition, adopting the renewable energy technology is also a clean way to meet user demands since it is abundant.

1-1 Electricity scenario

According to World Energy Council [2], electricity demand will double in 2060. This is due to the advancement in standards of living, developing technology for urban and rural lifestyles and rapid changes in economy which leads to high demand of electricity. In addition, [2] describes that by the year 2030, taking into account the current scenario, final consumption of electricity will increase up to 20%, from 18% in 2014. The rise in demand of electricity will average around 1.9% till 2030. After 2030, need for electricity will continue to grow at a rate of 1.4% per annum till 2060. By then, electricity generation will be doubled since 2014 and the electrification of final energy consumption will reach at 28%. Moreover, considering these scenarios investment in electricity generation till 2060, ranges from US \$ 35-43trillion (based on 2010 market exchange rate). And, to meet this demand, there will be increase in demand of new energy resources, which indeed requires significant amount of capital and system integration so that it could be advantageous to every consumer. Therefore, Figure 1-2 classifies the role of renewables especially wind, solar and geothermal for generation of electricity, for the year 2014, 2030 and 2060.

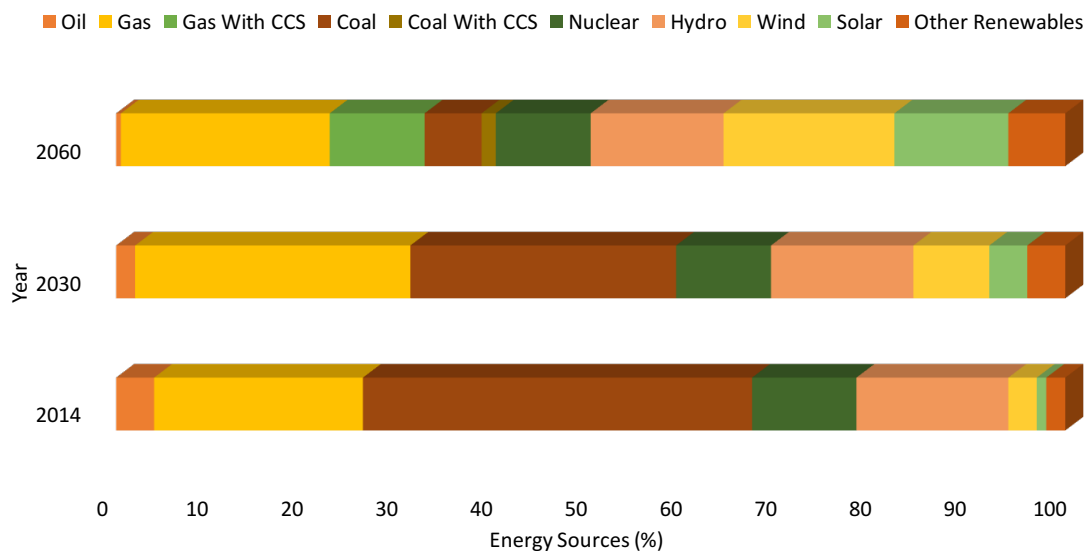


Figure 1-2: Electricity consumption comparison [2].

According to [17], producing renewable energy resources with the help of solar, wind, hydro, geothermal energy sources is of utter importance for generation of power due to the following reasons:

- Reduction in carbon emissions : Utilizing sustainable energy resources provides benefits to the environment;
- Abundance availability: Renewable energy resources are infinite sources of power which means it has long-term certainty;
- Energy security : Fulfilling energy needs with locally produced clean and reliable electricity which enhances local economic growth as well.

1-2 Motivation of the thesis

One of the main objectives of the thesis was to learn more about renewable energy resources that help in generating clean energy for the society. As it was not possible to explore each and every renewable energy resources, the main focus particularly in this thesis is in the area of solar energy. Moreover, the research is limited to this because of interest in the field of Photovoltaic (PV) and to its related system.

The development of Toegepast Natuurwetenschappelijk Onderzoek (TNO) solaroad generates interest due to its unique & innovative idea of generating electricity with PV system which can also be seen in Figure 1-3. In this technology, solar modules are placed on the road surface for supplying energy to meet desired load demands.

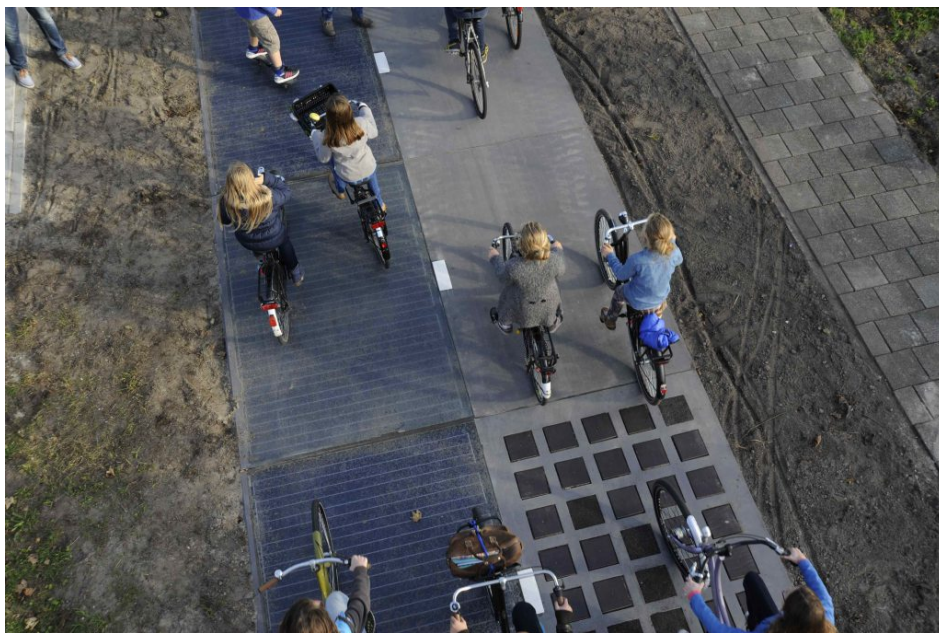


Figure 1-3: TNO Solaroad.
Image Source: [3]

However, it is believed that if these solar modules are placed beside the road instead on it, then it might be more advantageous in producing more energy. Therefore, the author is motivated to work on Roadside PV system and then compare it with solar road.

1-3 Research questions

The following problem statement is addressed in this thesis:

"Designing of a Roadside PV system that supplies power to appropriate application which is further compared with solar road"

Possible research questions are as follows:

1. What application should be chosen for designing the grid connected Roadside PV system?

An application is needed for implementing Roadside PV system and determining its operational requirements. Moreover, an load consumption pattern will also be decided based on the chosen application.

2. What should be the design of Roadside PV system at relevant location to meet specific load demands?

The sizing of the system depends on the total power and energy consumption of the loads that need to be supplied by the PV system. And, for the system designing, it is necessary to know about the system configuration and the area required by the solar modules. Furthermore, following sub research question are also necessary for designing Roadside PV system:

- 2.1. What should be the optimal orientation of Roadside PV system for specific location?

To determine optimal azimuth and tilt of solar modules for specific location as it plays a vital role when designing the PV system to maximize the energy production.

- 2.2. What is the annual energy yield output that can be expected from the Roadside PV system?

To find out how much solar energy is available throughout the year with solar and how much of electrical power can be generated throughout the year with the same.

- 2.3. What factors effects the energy yield of the Roadside PV System?

To analyse the possible factors that can have an impact on power production such as irradiation, temperature and shading.

3. How is PV system design besides the road different from solar road?

Roadside PV system design which has optimum orientation will be compared with solar road on the basis of variation with irradiation and temperature, module efficiency, energy yield analysis, number of required modules, area covered, maintenance and installation.

4. How architecture of Roadside PV system will be designed?

System architecture will be designed for Roadside PV system according to selected application.

1-4 Thesis structure

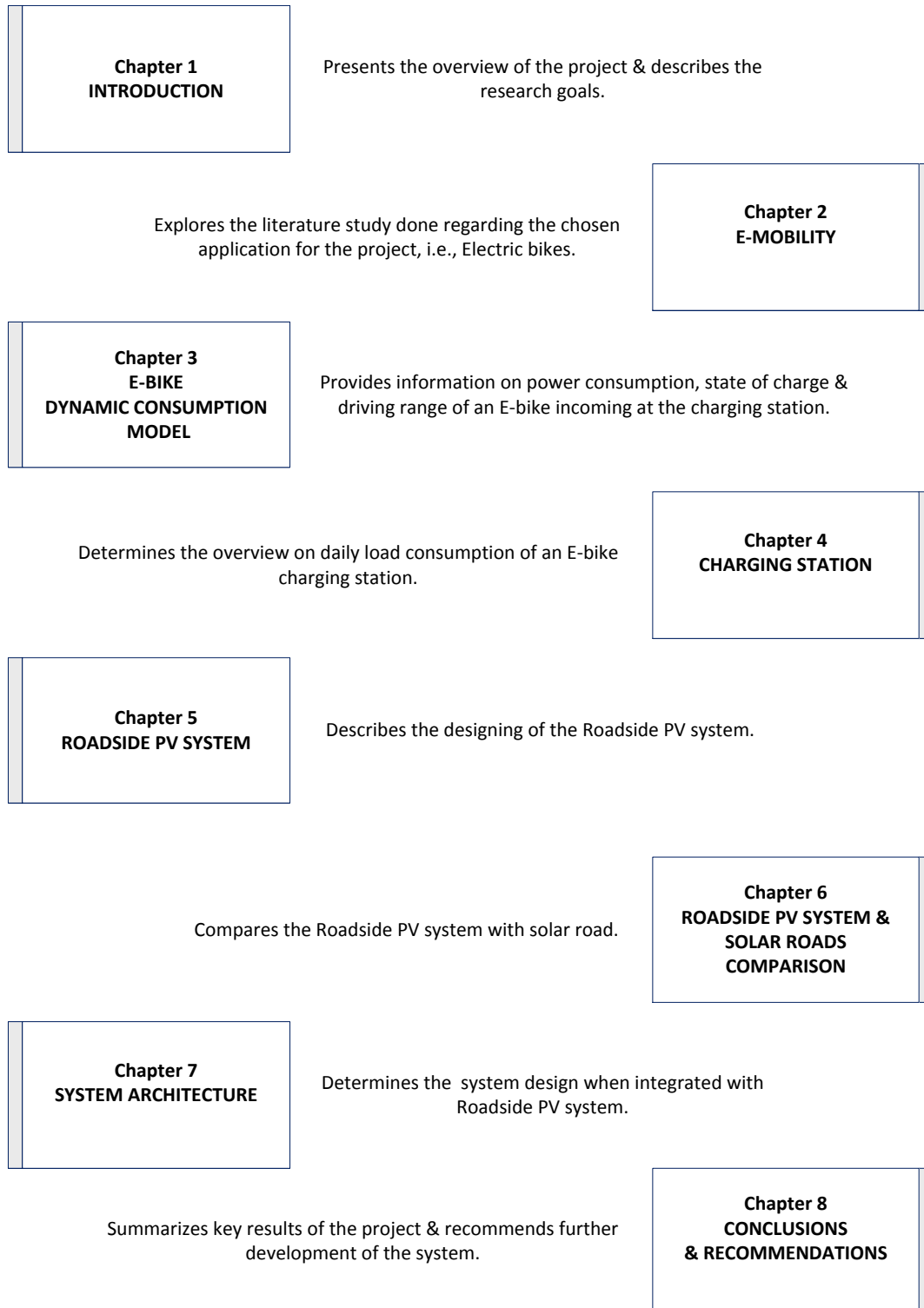


Figure 1-4: Thesis structure.

Chapter 2

E-Mobility

Chapter Overview:

This chapter discusses the application chosen, i.e., Electric Bikes or E-bikes for implementation of Roadside PV system, which has shown rapid growth all around the world especially in The Netherlands. Therefore, this section explores the literature on E-bikes for which Roadside PV system would be designed.

Currently, oil prices are increasing, and commuters are searching for transport which are less costly. Electric Bikes (E-bikes) seem to be an alternative to cars and it is great for the cities where traffic is increasing as well [9]. The growth in this field is evident from Figure 2-1 which shows the rise in E-bike Sales 2012-2018 of different regions in the world. It also showcases that maximum E-bike sales is in the Western Europe [4]. The predicted rise in sales of E-bikes in EU has streamlined the ideas about integration of the development in PV system and E-bike charging stations.

Furthermore, there are problems associated with the growth in electrification of bikes, especially when it is utilized for personal use. One of the major issues that an E-biker faces is range anxiety, i.e., risk of losing energy in the E-bike battery and fear of travelling long distances due to lack of charging infrastructures [18]. This can also lead to delays in their journey due to the long recharging time. Therefore, it is a requirement to have these charging stations in the public and working places.

However, charging these E-bikes can affect environment through CO_2 emissions, and thus these need to be charged sustainably, and not with the help of conventional sources. Low powered electric vehicles and electricity generation with the help of renewable energy technology are the two kinds of technological advancements which are taking place to meet growing global energy demand while reducing greenhouse gas emissions at the same time. Achieving these objectives indicate a shift from energy demands from fossil fuels to renewables [18].

Renewable energy technology and plug-in vehicle electrification adoption have substantial problems associated with it, however there are ways to exploit their potential in order to

develop sustainability in the field of electricity and transportation. These two technologies have natural synergies amongst them, which can be beneficial when integrated together with the existing grid as it can gain environment benefits as well [18]. Moreover, low powered electric vehicles are also flexible in terms of charging profile, as it can even help to shift the peak load demand.

Therefore, further in this research, charging infrastructure integrating with renewable will be discussed.

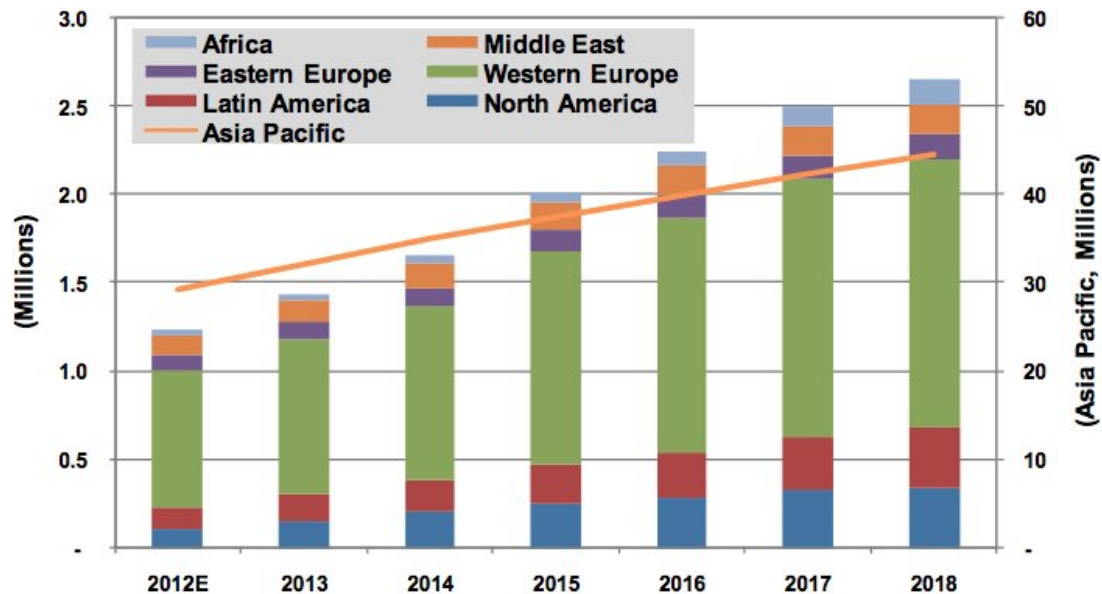


Figure 2-1: E-bike sales of different regions in world (Year 2012-2018).

Image Source: Pike Research [4]

2-1 Rise of E-bikes in the Netherlands

Figure 2-2, depicts that most sales for E-bikes in European Union (EU) has happened in The Netherlands. After analysing that the E-bike market which is wide in The Netherlands, it was then decided to choose this location for building up the Roadside PV system to charge E-bikes.

From [19], it is known fact that biking is prevalent in the Netherlands with 35000 km total length of Dutch cycle paths which also one of the reason why E-bike is on a rise in this country. According to [20], there are around 19 million conventional bikes on Dutch roads among which 1 million are E-bikes. They also report that growth from 2007 to 2011 is around 6 to 20%, which is predicted to increase in near future.

Therefore, when the rise in sales of E-bikes is growing, it is also important to see how these E-bikes are being charged. One of the ways is to charge it sustainably, which can be done with the help Roadside PV E-bike charging station.

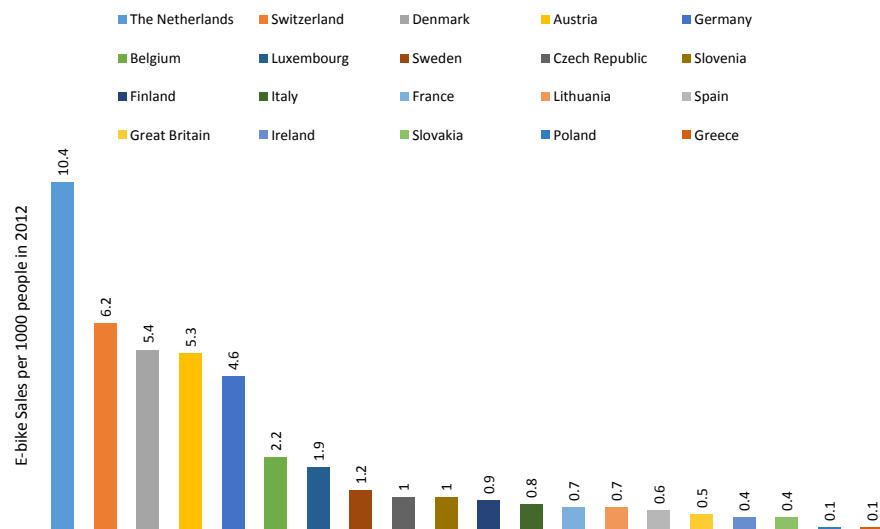


Figure 2-2: E-bike sales of different regions in EU.
Source: Fishman and Cherry, 2015 [5]

2-2 Electricity in road transport

It has been observed during the literature study that electricity consumption will increase in road transport sector in future as a result of vehicle electrification, and according to [21], it predicts that in The Netherlands there will be increment of around 2.61% from 2015 to 2050 which is also shown in Figure 2-3.

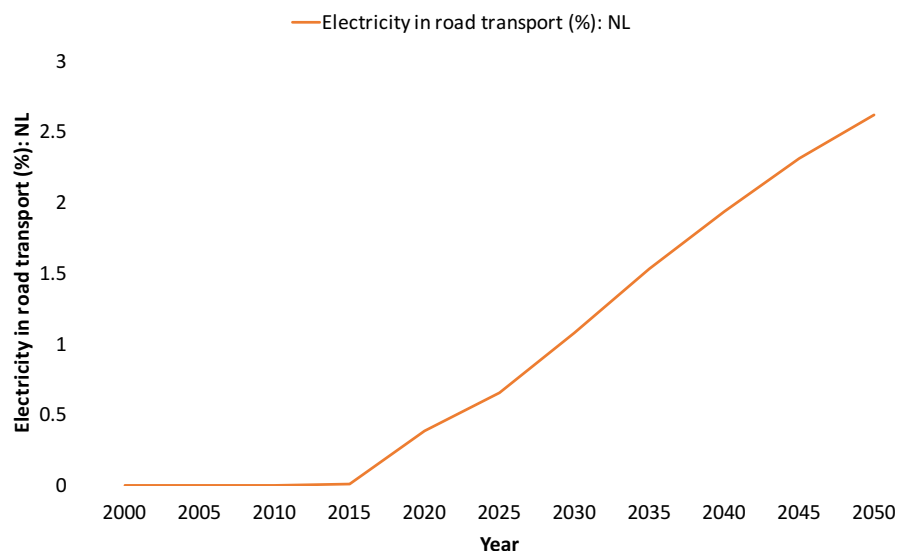


Figure 2-3: Electricity in road transport (%): NL (Year 2000-2050).
Source: EU Reference Scenario 2016 based on PRIMES, GAINS

2-3 In-depth mobility analysis

In this section, an in-depth mobility analysis is done in which it is described that why people in the Netherlands decide to buy E-bikes and what are its effect on its users.

According to [6], around two thirds of all E-bike users stated that since they bought an E-bike, it became possible to ride faster, more frequently, and for longer distances. Furthermore, E-bike user also reported that they tend to take longer journeys, thus covering greater distances, rather than to ride faster as it is convenient and comfortable, which was also useful during the time of strong winds [6], [20].

Moreover, around 60% of E-bike users thought that E-bikes had a positive impact but around 36%, thought that having an E-bike suited their social and personal image. The scenario of E-bikes is subject to change, as these have been sold in large numbers for diverse segments like folding, racing and mountain bikes for different age groups. Lastly, all the impacts of using E-bike such as variation in cycling more faster, for longer routes and what is impact of E-bike on the users, are shown in Figure 2-4.

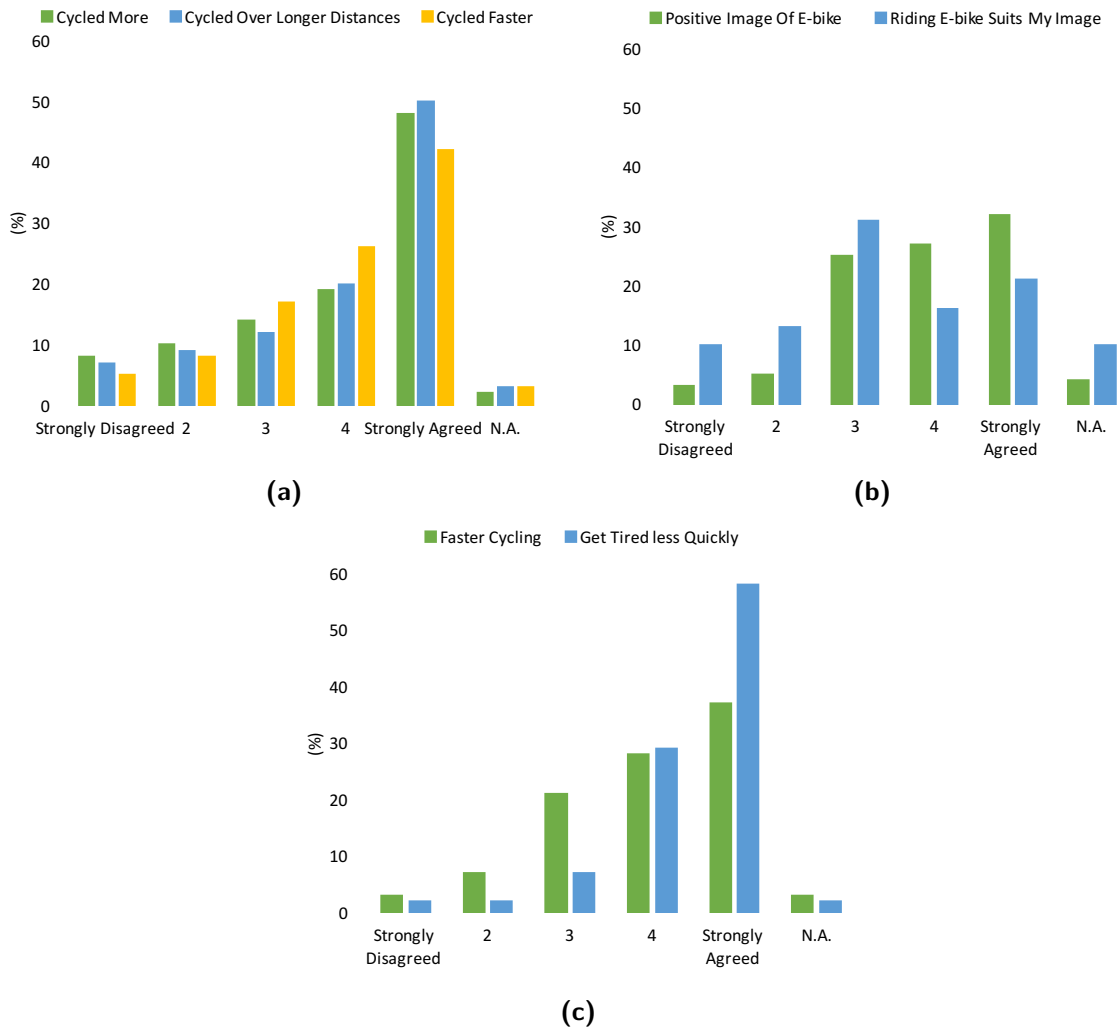


Figure 2-4: Impacts of E-bike usage.

Source: Beleving en beeldvorming van mobiliteit (2016); calculation by KiM [6].

2-4 Introduction to E-bikes

E-bikes can be defined as a bicycle integrated with a small electric motor which are connected to rechargeable batteries. In E-bikes, basic method of propulsion is throttle and pedal assist, in which the rider can get power from both pedalling and motor. This mode of transport is cheaper and more energy efficient than other modes of transport. Furthermore, rider can cover long routes with less or no efforts when compared to normal bicycle. As an example Figure 2-5 shows one of the E-bike available in the market.



Figure 2-5: Gazelle E-bike.
Image Source: [7]

According to EU Regulation No 168/2013, these are categorised under L-category vehicles. In which powered cycles are sub categorised under L1e-A category which states the following [22]:

- The propulsion should be limited at a speed of 25 km/h [22];
- The maximum continuous rated power or net motor power should not exceed 250 W (Commuter E-bike)[22];
- It includes two, three and four-wheel vehicles, i.e., also electric cargo bikes with more than two wheels [22].

2-4-1 Basic configuration of an E-bike

Figure 2-6 shows the basic configuration for the electric bikes which consists of battery, motor, controller, throttle/pedal assist. These aforementioned components will be discussed briefly in the following subsections.

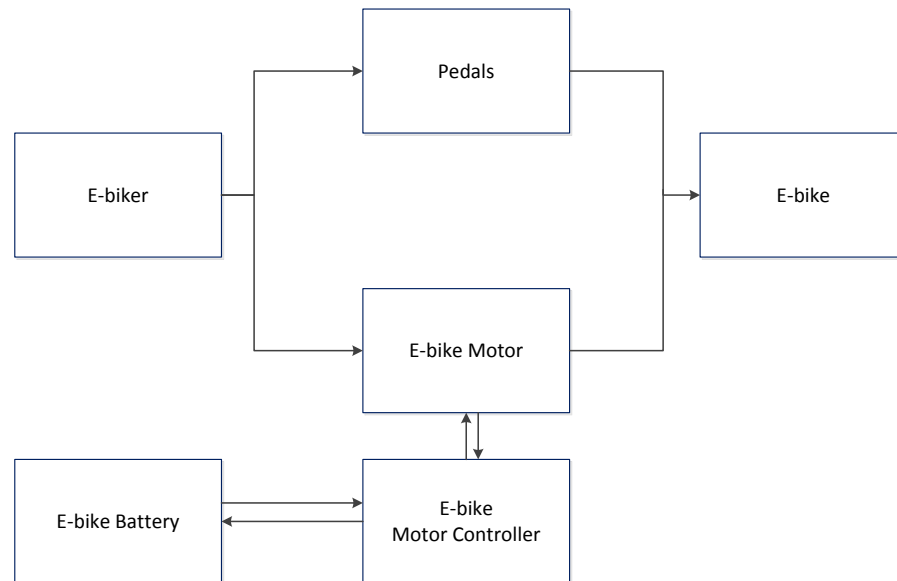


Figure 2-6: E-bike configuration [8].

2-4-2 E-bike battery

An E-bike battery is the component from which power is supplied to the motor, therefore it is necessary that the capacity of battery should be large enough so that it can match the demand of E-biker. However, it should also be kept in mind if the battery technology used meets the technical requirements and how safe it is for the E-bike [23]. Following subsections focuses on different types of technologies and specifications for the E-bike battery.

2-4-2-1 E-bike Battery Technology

There are mainly five types of E-bike battery technologies which are commonly used in E-bikes available in the market namely Lead acid (Pb-acid), Nickel cadmium (NiCd), Nickel metal hydride (NiMH), Sodium nickel chloride (NaNiCl) and Lithium Ion (Li-Ion) [20]. Out of the available battery technologies, according to [20], Pb-acid, NiCd, NiMH, are heavier, toxic and less efficient in terms of energy. And, among all batteries mentioned NaNiCl is the most efficient but due to its heavy weight, most of the E-bikes in Europe uses **Li-ion battery technology**.

Pros and cons of using Li-ion batteries are shown in Table 2-1 [24].

Table 2-1: Advantages and disadvantages of Li-ion battery.

E-Bike Battery Technology	Advantages	Disadvantages
Li-Ion	-Longer lifetime -Small Size -Light weight -Relatively low self-discharge -No problem of intermediate charging -Safe to use	-Protection required for maintaining voltage and current within safe limits -Expensive to manufacture -Ageing Effect

2-4-2-2 E-bike battery specifications:

Most of the E-bikes used in the Netherlands have basic specification of batteries used in E-bikes. Among which, it is observed that typical battery voltages which have being used are 24, 36 and 48 V. Out of which, it is seen that most commonly used E-battery voltage is 36 V.

According to the E-bike battery data sheet [24], it is determined that the most commonly used battery specification in term of energy, ranges from 240-504 Wh battery capacity. Moreover, [24] shows few common configurations such as 24V 10Ah, 36V 9Ah, 36V 10Ah, 36V 11Ah, 36V 12Ah, 36V 14Ah. It is also observed that, Li-ion battery type is mostly used in E-bikes with 36V 11Ah which is equivalent to 400Wh battery energy capacity which needs a basic time to charge E-bikes fully is approximately around 3 hours [25].

2-4-3 E-bike motor

According to [8], commonly used electric motors in an E-bike are of two kinds, i.e., brushed and brushless DC motor. Furthermore, Table 2-2, showcases about the different advantages and disadvantages for these two types of E-bike motor.

Table 2-2: E-bike motor types [8].

E-Bike Motor Technology	Brushed DC Motor	Brushless DC Motor
Advantages	- Controller is simple	- More efficient than brushed DC motor - Smaller motor size
Disadvantages	- Efficiency is low - Larger motor size - Difficult to mount the motor in bikes	- Complex Controller

The aforementioned electric motor can be mounted in three possible location in an E-bike which are at the front wheel, rear wheel or in the middle of the E-bike frame which can also be seen in Figure 2-7.

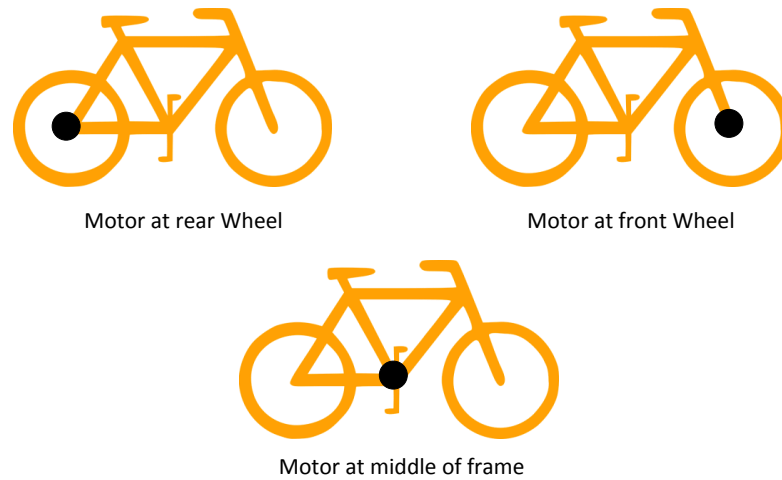


Figure 2-7: E-bike motor location [9].

Chapter summary

For our analysis of E-bikes, dynamic consumption model is discussed in Chapter 3, the Li-ion battery type will be used which consists of 10 Li-ion battery cells. The nominal voltage of each cell is 3.6V which in total is 36V and its nominal capacity is 11Ah which take around 3 hours to get charged from 0 to 100% [25]. Li-ion battery is an ideal battery type used in electric bikes due to its high energy and power ratio [26]

E-bike Dynamic Consumption Model

Chapter Overview:

In this chapter, dynamic consumption model for an electric bike has been proposed which focuses on estimating total energy consumed, state of charge and maximum driving range of E-bikes. In this model, total power consumption is calculated from which total energy consumed by battery is determined. This model is necessary to achieve the outputs which will be used further in the analysis of load consumption explained in Chapter 4.

Dynamic consumption model evaluates the battery State of Charge (SOC) and driving range of an E-bike considering power consumed when a rider is propelling it. This model is a mathematical modelling that will determine the performance of an E-bike. A basic construction of the model has been depicted in Figure 3-1.

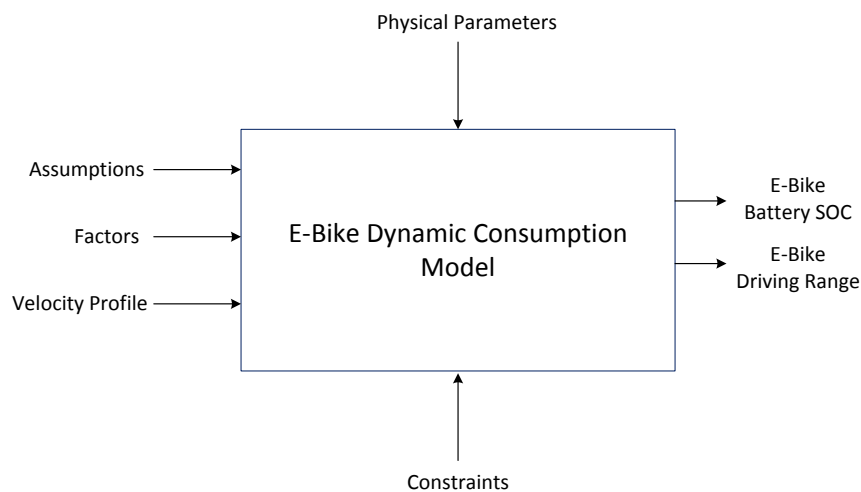


Figure 3-1: E-bike Dynamic Consumption Model.

In further sections, assumptions and inputs which are required to build up the mathematical model are explained in detail.

3-1 Model assumptions

The model involves the following assumptions:

- Firstly, it is assumed that the E-bike will have overnight charging and therefore, initial SOC, SOC_0 of battery will be 100%;
- Secondly, it is assumed that angle of inclination, i.e., $\theta = 0^\circ$, as most of the land in the Netherlands is flat;
- Lastly, it is also assumed that only 60% of energy is recovered during regenerative braking.

3-2 Inputs

3-2-1 Factors

To start with the model, firstly it is required to provide with the factors namely, total Mass, M_{total} in which mass of E-bike, battery and rider is included and frontal Area, A_f . Furthermore, values used in the model according to European commuter are mentioned in Table 3-1.

3-2-2 Physical parameters

The model involves the following physical parameters:

- Acceleration due to gravity, g , i.e., the acceleration which is gained by an object because of gravitational force, (m/s^2) .
- Coefficient of rolling resistance of bicycle tire, C_r .
- Coefficient of aerodynamic drag for road bicycle plus rider, touring position, C_d .
- Density of air, ρ , kg/m^3 .
- Speed of wind, m/s which is taken as average according to the chosen location.
- Efficiency of E-bike Motor, η_M .
- Efficiency of Gear system, η_G .
- System Efficiency, η_S which includes motor, gear, electronic efficiency of an E-bike.
- Current Losses Coefficient, $\delta(I)$.

Table 3-1 shows the input values that are used in the E-bike dynamic consumption model.

Table 3-1: Input parameters.

Inputs		
Factors		
M_{total}	kg	100
M_{rider}	kg	75
$M_{bike+battery}$	kg	25
A_f (Bike+Rider)	m^2	0.557[27]
Physical Parameters		
g	$(m/s)^2$	9.81
C_r		0.006[27]
C_d (Bike+Rider)		1.1[27]
ρ (At Sea Level)	(kg/m^3)	1.225[28]
η_S	%	87.5
η_M	%	95[29]
η_G	%	98[29]
η_E	%	94[23]
$\delta(I)$		0.98[30]
Average wind speed (NL)	m/s	3.5
Constraints		
Battery Capacity	Ah	11
Energy Capacity	Wh	400
$V_{battery}$	V	36
DOD	%	80[31]

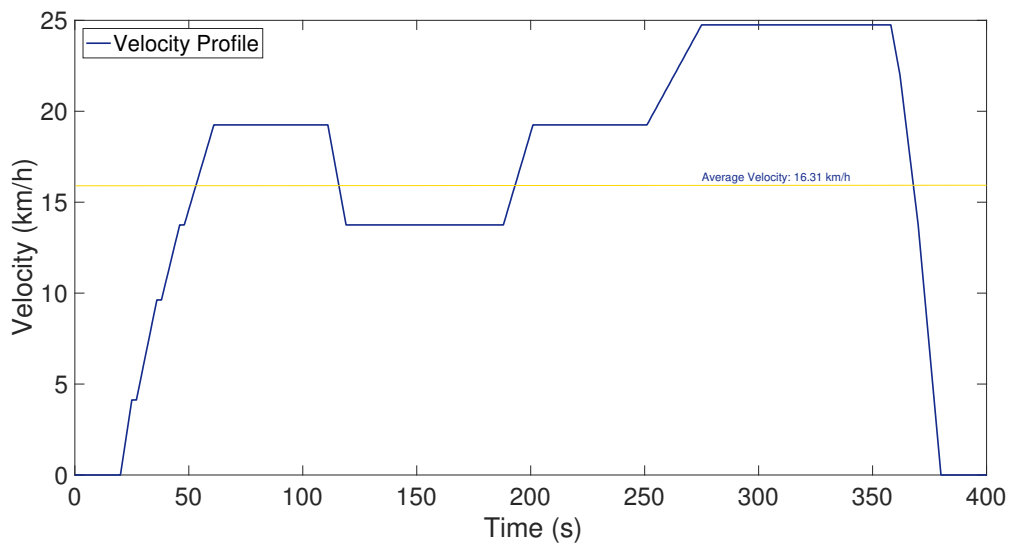
3-2-3 Velocity profile

Speed of E-bike determines the energy consumed by an E-bike in moving conditions [32]. Therefore, it is required to perform the testing with drive cycle. For our analysis, *UN/ECE Extra-Urban Driving Cycle (Low Powered Vehicles)* velocity profile of electric vehicles is used [33].

The factor of 0.275 is multiplied with all the given values in velocity profile. The transformed velocity profile values for the drive cycle is shown in Figure 3-2. This factor was chosen as it is known that the maximum speed for E-bikes is limited to 25km/h and by multiplying with factor of 0.275 will result in valid values. Main features of drive cycles are given in Table 3-2.

Table 3-2: Main features of velocity profile.

UN/ECE Drive Cycle		
Average Speed	<i>km/h</i>	16.31
Time	<i>sec</i>	400
Total Distance Travelled	<i>m</i>	1817.5
Maximum Speed	<i>km/h</i>	24.75
Maximum Acceleration	<i>m/s²</i>	0.22

**Figure 3-2:** Velocity profile for E-bike.

3-2-4 Model constraints

The model involves the following constraints:

- Battery capacity;
- Voltage of battery;
- Energy capacity;
- Depth of Discharge (DOD).

The aforementioned model constraints reflects the total amount of energy capacity (i.e. 400Wh) and battery depth of discharge (i.e. 80%) is used while calculating the total driving range of an E-bike.

3-2-5 Outputs

After applying the above shown assumptions, inputs, and constraints in the model, the final SOC and the driving range of the E-bike arriving at the charging station.

However, before calculating the SOC of E-bike, it is required to calculate the total power consumption of the same.

3-2-5-1 Power consumption

The power consumed by an E-bike can vary according to conditions of the traffic, characteristics of the E-bike itself, speed, and various forces such as rolling resistance, aerodynamic drag, gravitational and inertial forces which are explained further in this section [32].

The power consumption of E-bike can be computed with the help of forces shown in Figure 3-3.

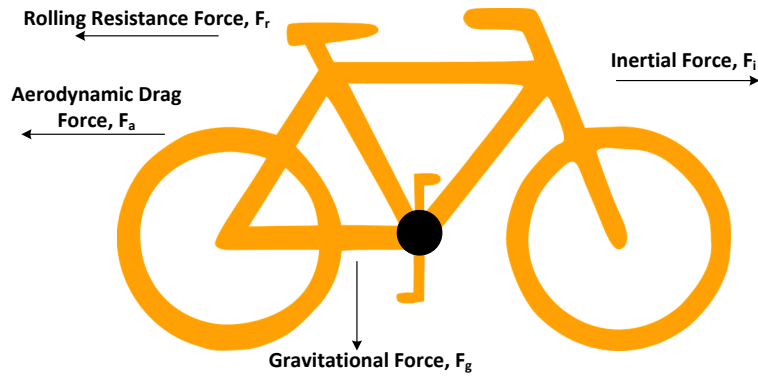


Figure 3-3: Various forces on E-bike.

Rolling resistance is the force required to overcome the tyre friction. Equation 3-1 shows the force needed to surpass rolling resistance which is dependent on coefficient of rolling resistance, acceleration due to gravity, total mass of E-bike rider and surface inclination where the E-bike is used [34]. The value of coefficient of rolling resistance has been taken as 1.1 which is equivalent for European upright commuter [27]. Furthermore, the values used in the Equation 3-1 are provided in Table 3-1.

$$F_r = C_r * g * M_{total} * \cos(\theta), \quad (3-1)$$

where, F_r is the rolling resistance in (Newton), C_r is the coefficient of rolling friction, g is the acceleration due to gravity in (m/s^2), M_{total} is the total mass of bike plus rider in (kg), and θ is the angle of inclination in (degrees).

Aerodynamic drag is the force of wind pushing in the opposite direction of the motion of the object. The expression for estimating aerodynamic drag is given in Equation 3-2 which is further dependent on coefficient of drag, density of air, speed of the wind, E-bike velocity and frontal Area [34]. Moreover, the values used in the Equation 3-2 are mentioned in table 3-1.

$$F_a = 0.5 * \rho * C_d * (v + w)^2 * A_f, \quad (3-2)$$

where, F_a is the aerodynamic drag in (Newton), ρ is the density of air in (kg/m^3), C_d is the coefficient of drag, v is the velocity in (m/s), w is the average wind speed in (m/s), and A_f is the frontal Area in (m^2).

Gravitational force are the forces acting on the object due to gravity when moving on an inclined surface. It can be calculated with the help of Equation 3-3 which is dependent on total mass of bike plus rider, surface inclination and acceleration due to gravity [34]. The values used in the Equation 3-3 are provided in Table 3-1.

$$F_g = M_{total} * g * \sin(\theta), \quad (3-3)$$

where, F_g is the gravitational force in (Newton), M_{total} is the total mass of bike plus rider in (kg), g is the acceleration due to gravity in (m/s^2), and θ is the angle of inclination in (degrees).

Inertial forces are forces due to dynamic changes in the vehicle due to acceleration and deceleration [15]. It can be computed with Equation 3-4:

$$F_i = M_{total} * \frac{dv}{dt} = M_{total} * a, \quad (3-4)$$

where, F_i is the inertial forces in (Newton), $a = \frac{dv}{dt}$ is the acceleration(+)/deceleration(-) in (m/s^2), M_{total} is the total mass of bike plus rider in (kg).

Total E-bike forces

Total bike forces can be calculated with the help of Equation 3-5, which is summation of all aforementioned forces.

$$F_T = F_M + F_H = F_r + F_a + F_g + F_i. \quad (3-5)$$

where, F_T is the total bike forces in (Newton), F_M is the motor force, F_H is the human force.

Human power

As E-bike propels together with human plus motor power, and the power provided by E-bike rider vary person to person. However, according to [34], [27], a healthy non-athletic human being can provide 75W of body power for 8 hours while normal biking. Furthermore, according to [23], an E-bike rider can deliver power around 50W.

Total power consumption at the wheels

Total power consumption at the wheels can be computed with the help of Equation 3-6:

$$P_W = F_T * v, \quad (3-6)$$

where, P_W is the power consumption wheels in (W), v is the velocity in (m/s).

Power supplied by the motor

Power deliver by the E-bike motor can be determined with Equation 3-7:

$$P_M = P_W - P_H, \quad (3-7)$$

where, P_M is the power supplied by motor in (W), P_H is the power supplied by human in (W).

3-2-5-2 Battery power

Power supplied by the battery

Power supplied by the battery can be computed with Equation 3-8 [31]:

$$P_B = \frac{P_M}{\eta}, \quad (3-8)$$

where, P_B is the power supplied by battery in (W), P_M is the power supplied by motor in (W) [$(P_M > 0)$], η is the system efficiency.

Power recovered by the battery

Power recovered to recharge the battery during braking can be calculated by Equation 3-9 [31] by assuming that only 60% [34] of power will be recovered:

$$P_R = P_M * \eta * 0.60, \quad (3-9)$$

where :

P_R is the power recovered by the battery in (W), P_M is the power Supplied by motor in (W) [$(P_M < 0)$], η is the system Efficiency.

Total battery power

Total battery power can be calculated by Equation 3-10:

$$P_T = P_B + P_R \quad (3-10)$$

where, P_T is the total battery power in (W), P_B is the power supplied by battery in (W), and P_R is the power recovered by the battery in (W).

3-2-5-3 Energy consumption

Energy consumed per km by E-bike can be calculated by following Equation 3-11 [31]:

$$E_p = \frac{\int_0^t P_T dt}{D_T} \quad (3-11)$$

where, E_p is the average energy consumption in (Wh/km), P_T is the total battery power in (W), and D_T is the total distance travelled in (km).

3-2-5-4 E-bike SOC

SOC of battery is defined as the the ratio of the differences between nominal capacity and the net amount of charge discharged from the battery since the maximum battery SOC [35]. Estimating SOC is an important parameter for determining performance of an E-bike battery. It basically provides us the knowledge about remaining battery capacity or knowing that how long the battery of E-bike will last. Moreover, it is of utmost importance for the battery management system. Therefore, this section presents the theory about the method used for determining the SOC of the E-bike battery.

For our analysis, SOC of E-bike battery is calculated with the help of Ah counting method. According to this method, while battery is charging, current is supplied to the battery and while the battery is discharging the current is withdrawn from the battery [36]. This shows the direct relationship between SOC and current, therefore battery current balancing is applied. SOC can be computed with Equation 3-12 [30]. The results are shown in Table 3-3.

$$SOC_i = SOC_0 - \left(\frac{1}{C} \int_0^t \delta(I) I_b dt \right) * 100 \quad (3-12)$$

where, SOC_i is the State of charge for E-bike arriving at charging station (%), SOC_0 is the initial state of charge of E-bike (%), C is the nominal capacity of battery (Ah), $I(b)$ is the discharge current of battery (A), and $\delta(I)$ is the current loss coefficient (typically 0.98 - 1).

3-2-5-5 Driving range of E-bike

After calculating the SOC of the E-bike arriving at the charging station, it is now possible to calculate the driving range.

Driving range of E-bike can be calculated by Equation 3-13 [15]:

$$D_r = \frac{D_T * DOD}{SOC_0 - SOC_i} \quad (3-13)$$

where, D_r is the driving range in (km), D_T is the total distance travelled in (km), DOD is the depth of discharge in (%), SOC_0 is the initial state of charge(%), and SOC_b is the state of charge at the end of distance travelled(%).

3-3 Simulation results

Furthermore, with the help of mathematical equations & assumptions given in Section 3-2 and input values provided in Table 3-1, following results are computed in Matrix Laboratory (MATLAB).

For every second total wheel power plot can be computed with the help of Equation 3-6, which is shown in Figure 3-4. This compares the different types of loads, i.e., rolling resistance load, aerodynamic drag, inertial load, and gravitational load acting on E-bike. Total wheel power is computed by doing summation of all these loads.

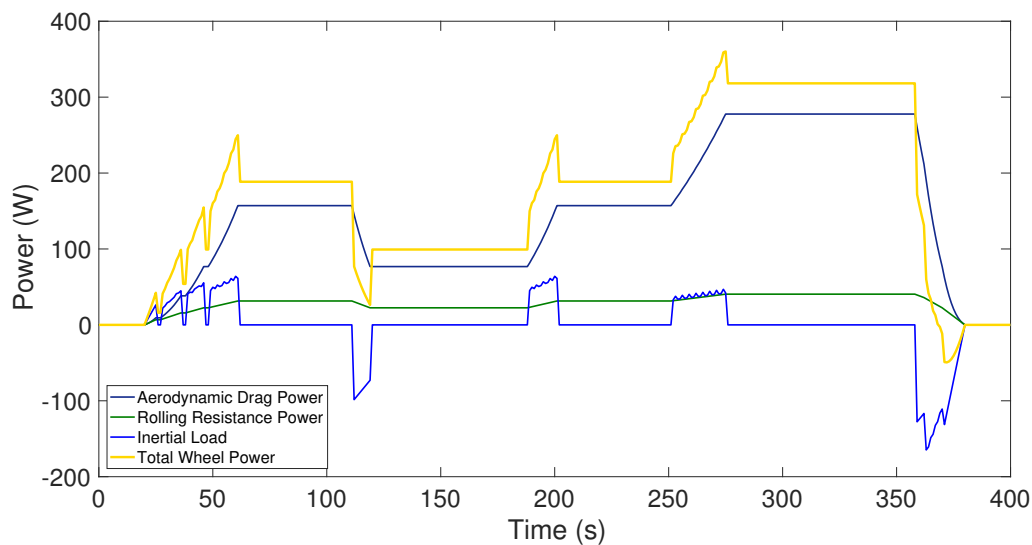


Figure 3-4: Power required for propelling E-bike.

Total battery power which is calculated with Equation 3-10 can be depicted in Figure 3-5, which shows that maximum power needed with UN/ECE Extra-Urban Drive Cycle is 289W. After calculating the total power consumption by the battery, total energy consumed per km can be computed with Equation 3-11 which comes out to be around 8.4 Wh/km. Furthermore, Figure A-4 shows the energy plot for entire distance travelled. SOC of E-bike battery for various distance travelled for the provided velocity profile is shown in Table 3-3, which has been calculated with the help of Equation 3-12 and SOC for entire distance travelled by an E-bike until reaches its Depth of Discharge (DOD), is shown in Figure A-5.

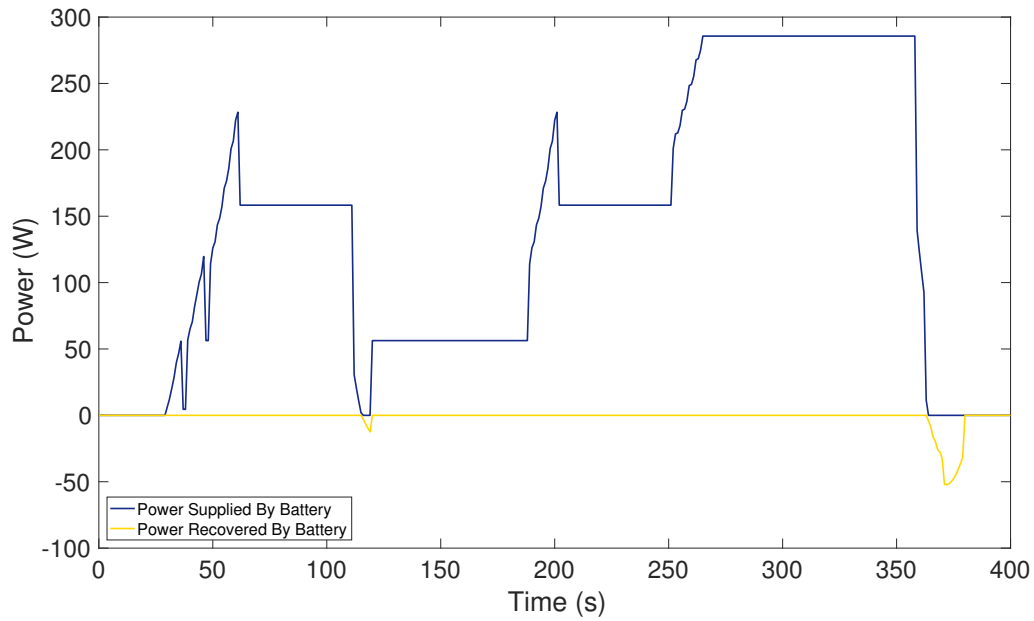


Figure 3-5: Total E-bike battery power.

Table 3-3: State of charge of incoming E-bikes.

Total distance travelled (km)	SOC_i (%)
10	79.73
15	69.18
20	58.72
25	48.48
30	38.43
35	27.89
38.6	20

Total driving range of an E-bike for the given velocity profile is calculated with the help of Equation 3-13 and it is determined that the range is around 38.6km.

3-4 Validation of E-bike dynamic consumption model

The model was simulated for the parameters values which are adopted from literature [15]. The results for the same are computed in Table 3-5. According to the literature [15], SOC and driving range was determined using Equation 3-14 and 3-15 respectively, and the results for the same are mentioned the Table 3-5.

$$SOC_b = SOC_0 - \left(\frac{K_m}{K_b} M_{total} + \frac{K_a}{K_b} a_f C_d \right) D_T, \quad (3-14)$$

where, SOC_b is the state of charge for E-bike arriving at charging station (%), SOC_0 is the initial state of charge of E-bike (%), K_m is the mass constant of drive cycle = $1.3371 * 10^{-7} kg^{-1} km^{-1} (HWFET)$, K_b is the capacity factor=1, K_a is the area constant of drive cycle = $2.2176 * 10^{-4} km^{-1} (HWFET)$, M_{total} is the total mass (kg), a_f is the frontal area (m^2), C_d is the coefficient of drag, D_T is the total distance travelled (km).

In Equation 3-14, K_m is the slope of slope of SOC vs distance and different E-bike mass (keeping front area = 0) and K_a is the slope of slope of SOC versus different frontal areas (keeping total mass =0).

$$D_r = \frac{D_T * DOD}{SOC_0 - SOC_b} \quad (3-15)$$

where, D_r is the driving range in (km), D_T is the total distance travelled in (km), DOD is the depth of discharge in (%), SOC_0 is the initial state of charge(%), SOC_b is the state of charge at the end of distance travelled(%).

Table 3-4: Specifications used in the model [15].

Parameters		
Total Mass, M_{total}	Kg	19000
Frontal Area, a_f	m^2	8.568
Coefficient of Drag, C_d		0.7
Coefficient of Resitance, C_r		0.01
ρ	kg/m^3	1.225
g	m/s^2	9.80665
θ	$^\circ$	0
Battery Specifications		
Battery Capacity	Ah	600
Voltage	V	540
Energy Capacity	kWh	324
DOD	%	80
Energy converted during regenerative braking	%	60
System Efficiency	%	80
Initial SOC	%	95

Table 3-5: Results.

Results	HWFET Drive Cycle	
	Total Distance Travelled (Km)	SOC (%)
With Literature[15]	16.50	88.61
With Dynamic Consumption Model	16.50	86.80
With Dynamic Consumption Model (without wind speed)	16.50	87.83

From Table 3-5, it can be seen that values for SOC, which is also compared in Figure 3-7 for Highway Fuel Economy Test (HWFET) drive cycle, SOC came around to be similar with the literature when it is travelled for same distance. The difference dynamic consumption model is little different from literature as it also takes into account the average speed of the wind due to which more battery power is consumed by the electric vehicle.

Moreover, the total wheel power and the total battery power (i.e supplied power and regenerated power), for HWFET drive cycle using model parameters mentioned in Table 3-4 are shown in Figure 3-6. Furthermore, Figure 3-7 also depicts the battery SOC when dynamic consumption model (with and without taking account wind speed) compared with model from literature.

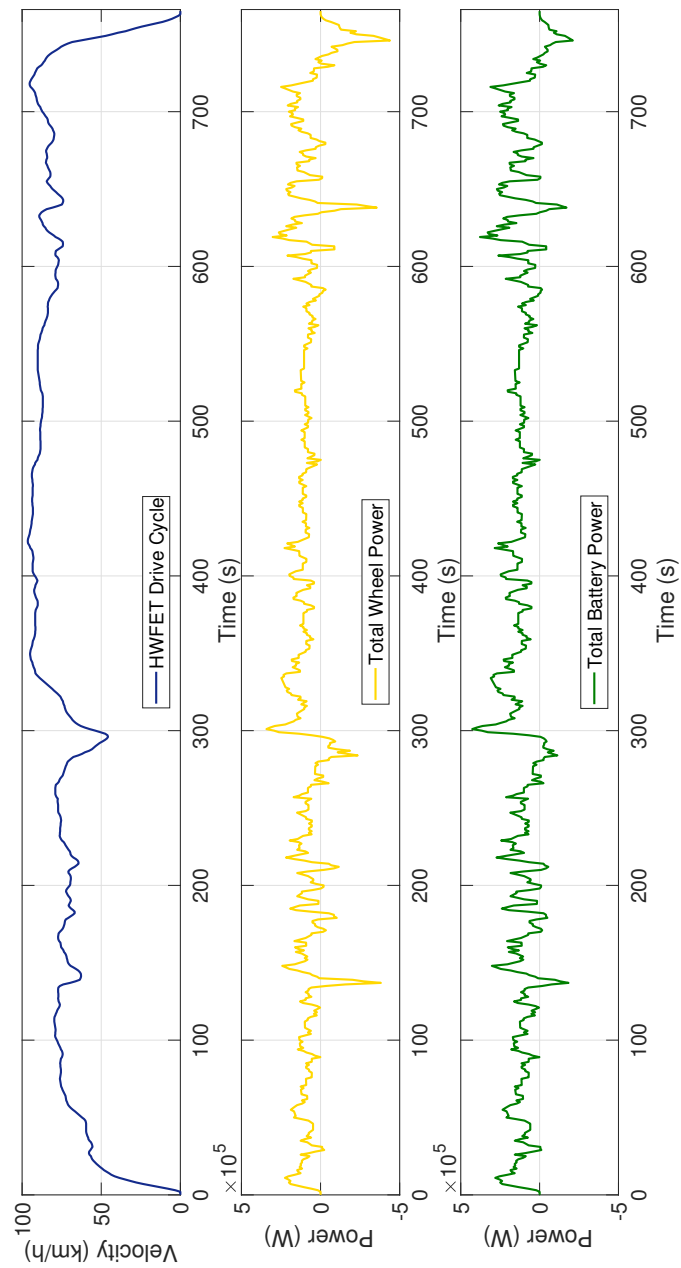


Figure 3-6: Plots for HWFET drive cycle.

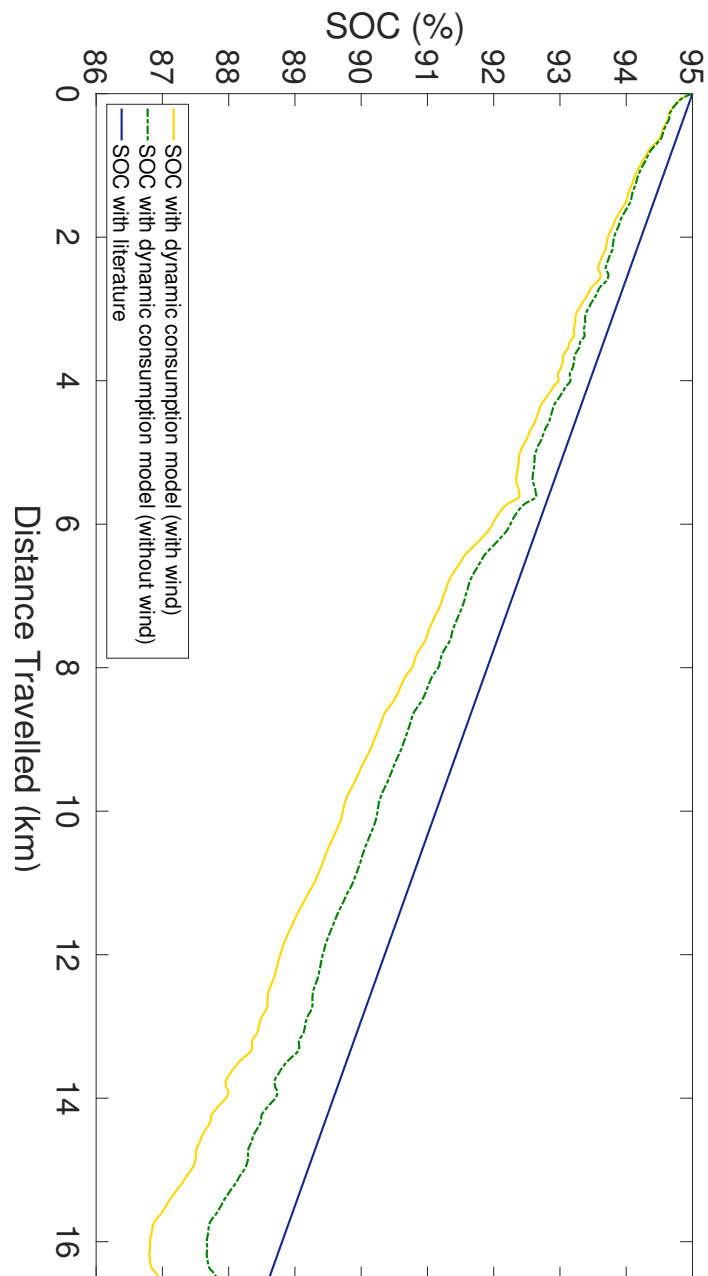


Figure 3-7: Comparison of SOC of reference battery from model and literature for HWFET drive cycle.

Chapter summary

In this chapter, E-bike used by an average European commuter was discussed. According to E-bike dynamic consumption model taking aforementioned parameters into account efficiency of an E-bike is around 8.4 Wh/km. Moreover, with the help of this model battery SOC is determined which will be used in Chapter 4 to compute daily load consumption of the E-bike charging station.

Chapter 4

Charging Station

Chapter Overview:

The goal of this chapter is to discuss insight about the E-bike charging station which is powered through grid connected roadside PV system with storage. This chapter will determine the daily load consumption of E-bikes at the charging station. Daily load profile depends on SOC of incoming E-bikes which in our case has been determined by E-bike dynamic consumption model from Chapter 3, number of incoming E-bikes, E-bike charging strategies and constraints which are explained further in this chapter.

Development of charging station for daily use of E-bikes with the help of renewable energy resources is an important concern. Therefore, it is extremely necessary for this charging station to be proficient in the following:

- Charging the E-bike;
- Detecting the SOC of incoming E-bike;
- Integrate with renewable energy resources (i.e. solar energy).

The E-bike charging station takes into account the SOC of incoming E-bikes which is calculated previously with the help of E-bike dynamic consumption model in Chapter 3, total number of E-bikes going to be charged in a day, and other factors such as constraints and charging strategies of the station. And, the electrical supply to the charging station that would done with the help of grid connected roadside PV system with storage (explained in further chapter of this thesis).

To analyse the total daily load consumption it is necessary to know about the overview of E-bike charging station. An outline of how the charging station will calculate the same is shown in Figure 4-1.

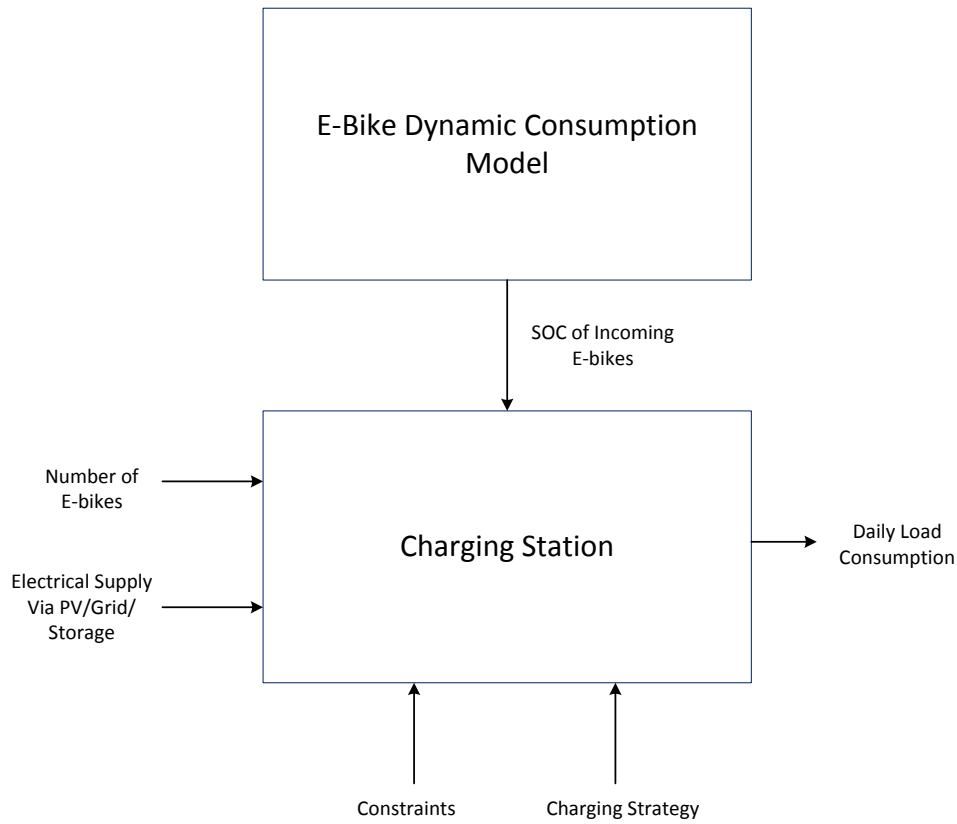


Figure 4-1: Charging station model.

4-1 Background

The charging station have following parts namely *electricity supply device*, i.e., (Roadside PV, grid or storage), *power cord*, i.e., required for connecting all devices, *charger* for E-bike charging.

4-1-1 Charging station specifications

Roadside PV Integrated station has following specifications that is used in for charging E-bikes:

- Charging current: 6A or 0.54C [25];
- Charging voltage: 42V [25];
- Power level of charging, P_{max} : 252W [25].

4-1-2 Assumptions

The charging station involves the following assumptions:

- Total bike charging in a day : 30
According to the literature [19], there are around 21% E-bikes in entire Netherlands (2014), and according to [37] there are 6% rider use E-bike for working purposes. And, if the E-bike charging station is installed at the TU Delft campus near Faculty of Electrical Engineering, Mathematics and Computer Science (EEMCS) building which has bike capacity of approximately 500 bikes, there could be possibly 30 E-bikes that needs to be charged.
- It has been assumed that E-bike battery has depth of discharge as 80%.
- Maximum charging limit = 100%
By default the maximum charging limit has been set to 100% SOC to ensure that E-bike gets maximum driving range after departing the charging station.

4-1-3 Inputs

SOC of incoming E-bikes

The SOC of incoming E-bikes are already calculated in Section 3-2-5-4 with the help of dynamic consumption model, which can be depicted in Figure 4-2.

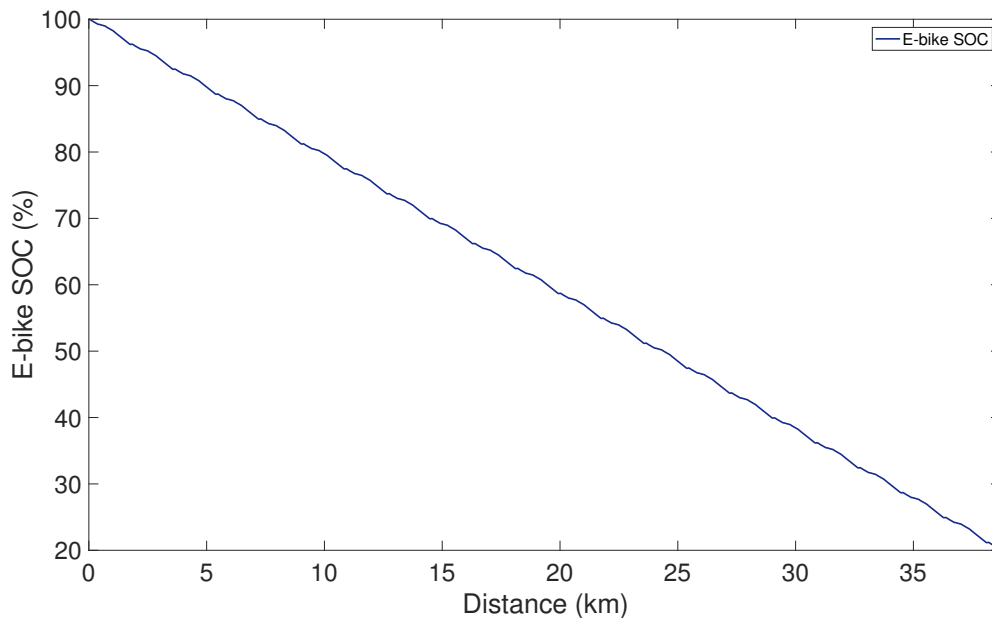


Figure 4-2: SOC plot for E-bike.

4-1-4 Constraints

- E-bike charging power constraint

- Power level of charging, P_{max} : 252W [25]
- Charging efficiency, $\eta=95\%$

$$\text{Charging Power, } P_c = \begin{cases} \eta * P_{max} \\ 0 \text{ i.e no E - bike Available} \end{cases}$$

- Maximum available energy of charging station
- Maximum number of E-bikes charging at a time

4-1-5 Charging strategy

This section discusses the strategy for charging E-bikes. [25] describes two method of charging Electric Vehicle (EV) which are namely : power scaling (constant time) strategy and time scaling (constant power) strategy. This literature uses a combination of the mentioned approaches.

However, in our charging method, more precisely when a E-bike arrives at the charging station, it has 20% SOC which is around 80Wh and is charged with nominal charging power i.e., 252W. And, the charging time can be calculated with Equation 4-1 [38].

$$T_c = \frac{(SOC_f - SOC_i) * E_{max}}{\eta * P_{max}} \quad (4-1)$$

where, E_{max} is the energy capacity of E-bike battery, η is the charging efficiency, SOC_f is the final SOC on leaving charging station, SOC_i is the SOC of E-bike when it arrives at charging station, P_{max} is the maximum charging power.

The E-bikes will get charged with charging power P_{max} and as soon as it reaches the required E-bike battery energy content, it will get disconnected.

4-2 Load analysis

This section explains the load profile required to simulate the expected load behaviour for charging of the electric bikes. A load profile is determined by the daily load consumption provided by the charging station which are described in further sections. Each E-bike battery has a capacity of 400 Wh and a total of 30 such E-bikes, assuming that they arrive with 20% SOC that would translate to a daily load of 12.84 kWh/day.

4-2-1 Daily load consumption

For the initial sizing and further system modelling, it is required to have a load profile that is similar with the expected load behaviour at the charging station. Figure 4-3 shows the area within the radius of 16km from the location of charging station, i.e., Mekelweg, Delft.



Figure 4-3: Locations within radius of 16 km from Mekelweg, Delft
Map source: [10]

Furthermore, number of incoming E-bikes at the charging station are shown in Figure 4-4. It shows arrival of E-bikes at the station between 8:00 to 16:00 which is a bar graph plotted with the help of random number generator in MATLAB.

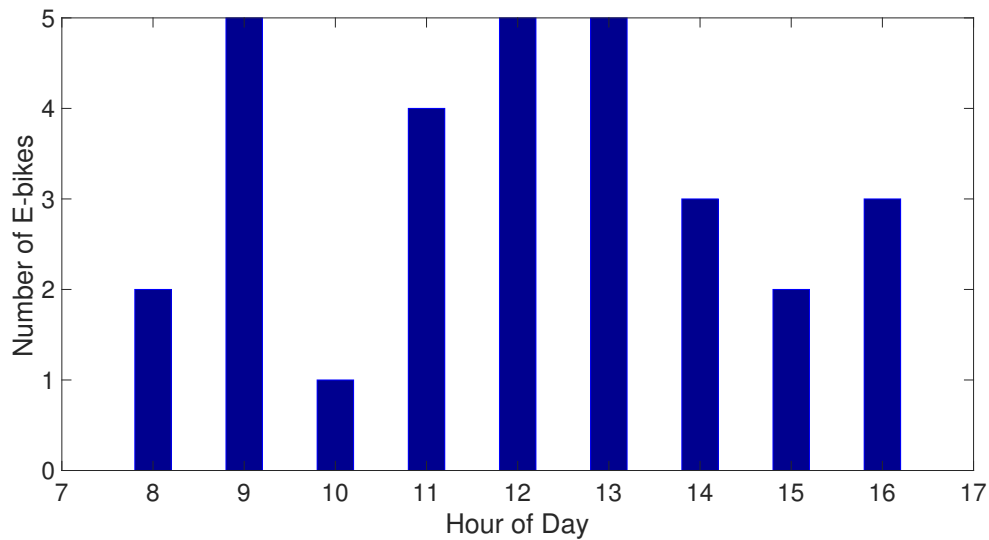


Figure 4-4: Incoming E-bikes at charging station.

With the help of E-bike dynamic consumption model SOC of battery is computed assuming that most of the incoming E-bikes has used around 67% of battery power after travelling 16km on E-bike having 400Wh energy capacity. Taking this into account daily load consumption for 30 E-bikes annually have been plotted. Figure 4-5 shows SOC for incoming E-bikes at

charging station in a year. It is a histogram created with the help of MATLAB random generator using 67% as mean.

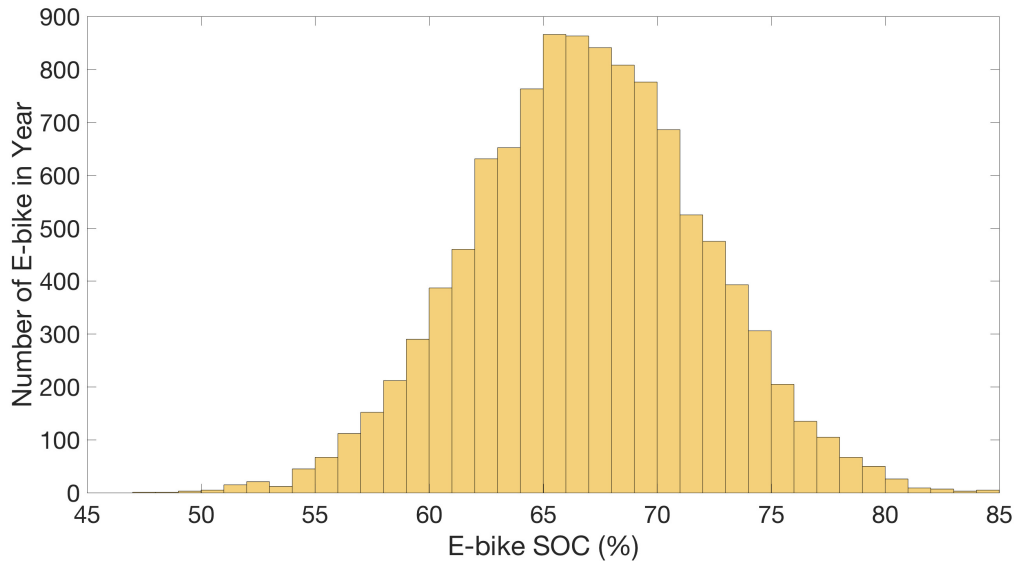


Figure 4-5: SOC for E-bikes over the year.

Figure 4-6 shows the daily load consumption for 30 E-bikes which is based on aforementioned E-bike SOC. According to this, the average daily load consumption is approximately around 4KWh/day. Figure 4-6 illustrates the daily load required by all together 30 E-bikes when incoming to station on the weekdays, as the location of this particular charging station is at the university campus, i.e., a work place and which is usually closed during the weekends.

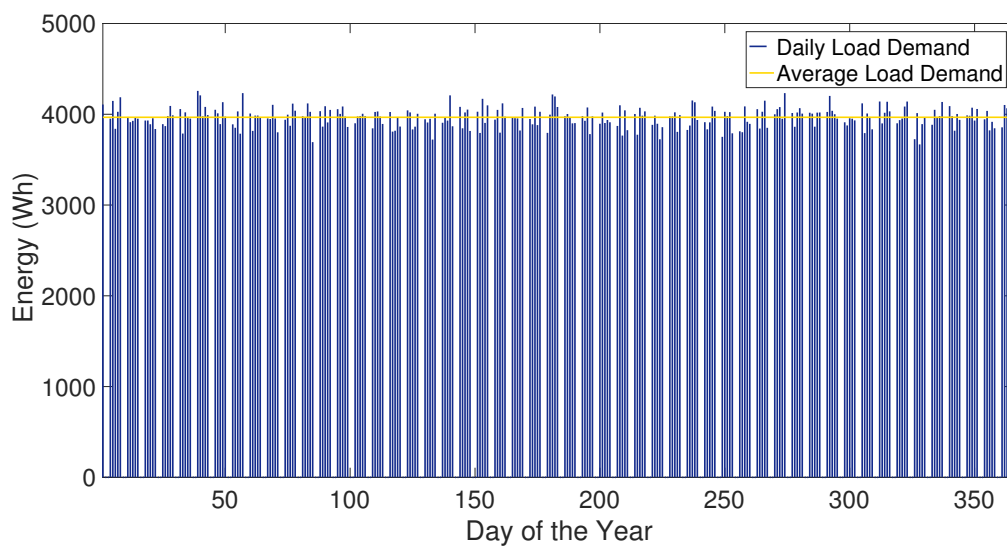


Figure 4-6: Daily load consumption over the year.

Load profile for charging 30 incoming bikes on the day of maximum load is shown in Figure 4-8. This figure is in correspondence to number of E-bikes incoming and their respective SOC as shown in Figure 4-4 and 4-7.

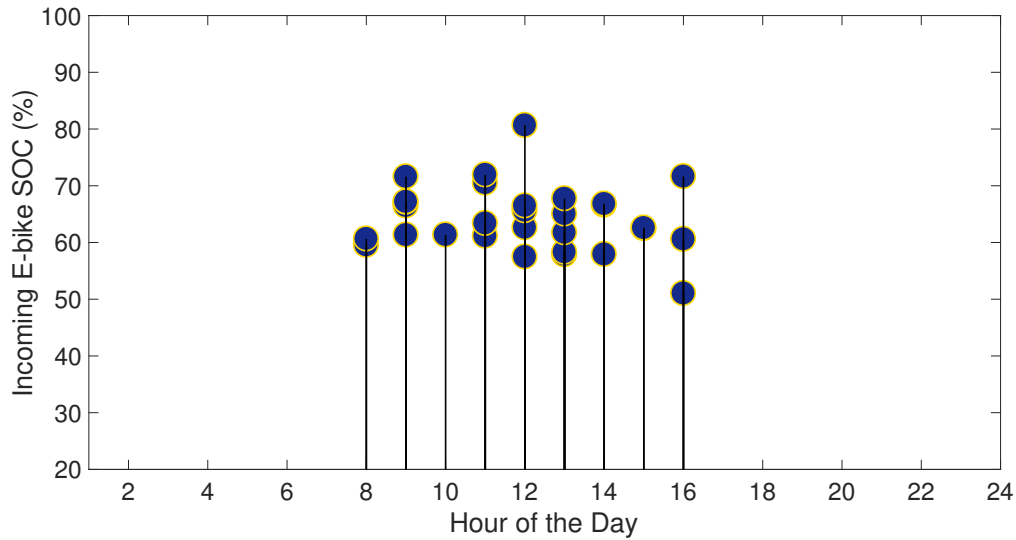


Figure 4-7: Load Profile.

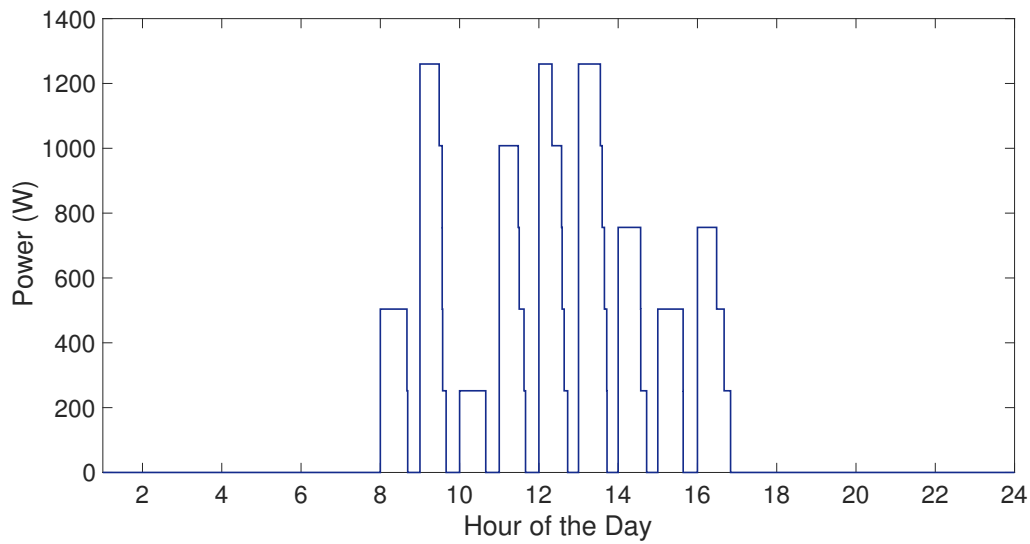


Figure 4-8: Load Profile.

The maximum number of chargers required for incoming E-bikes considered to be 5, for assuring the balance operation by serving maximum number of E-bikes. However, taking into account the contingencies up to N-1, it is decided to have 6 chargers [39] .

4-3 Charging station locations in Netherlands

As determined in Chapter 3, the driving range of E-bike is around 39km and if similar charging station of Roadside PV E-bike charging Station needs to be placed all around the Netherlands, then it is analysed that, to possibly cover every part of the country around 27 stations are necessary, which is also displayed in Figure 4-9.



Figure 4-9: Charging station location around the Netherlands.
Map source: [10]

This thesis focuses on charging station which is located in Delft specifically at Mekelweg, TU Delft Campus and not all around the Netherlands. Therefore, the charging station and Roadside PV system (which will be explained briefly in Chapter 5) size might vary according to the location where it is placed.

Chapter summary

In this chapter, load analysis of E-bike charging station is determined by taking into account the incoming E-bikes at the station having a mean of 67% of E-bike battery SOC around the year. Now, this daily load consumption will be used in Chapter 5 to model the Roadside PV system which will become the major electrical supply of the entire charging station.

Chapter 5

Roadside PV System

Chapter Overview:

This chapter aims at modelling of Roadside PV system in which analysis about location, meteorological data, irradiation model, temperature model, effect of irradiation and temperature on PV module, shading factor analysis, optimum module orientation, and PV output analysis will be done.

PV technology for production of power is becoming progressively fascinating for many different applications. This is mostly due to the decrement in the PV technology prices in recent times. Furthermore, which is also illustrated in Figure 5-1 that depicts the sudden change in power production cost of PV in \$/Watt over the years in relation with the PV system installation.

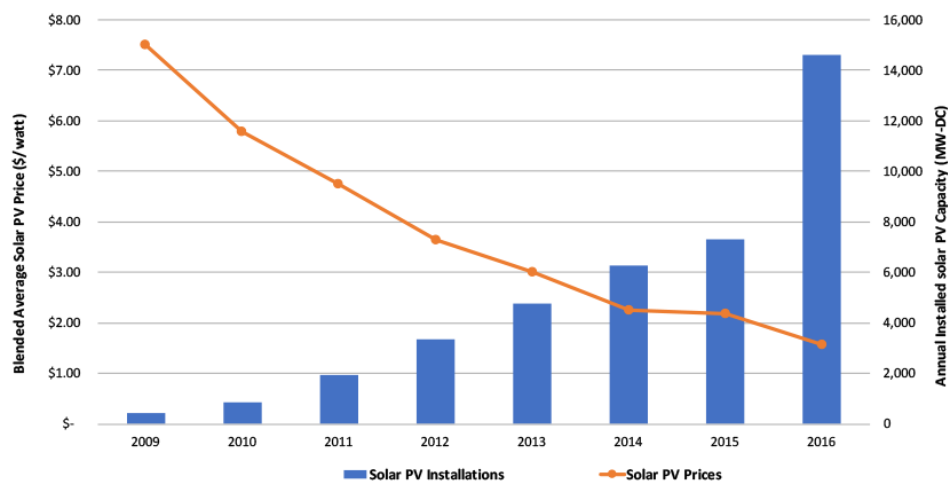


Figure 5-1: Photovoltaic market prices over the years.
Source: Solar energy industries association [11]

5-1 Solar in Netherlands

According to [40], there will be improvements in the solar PV industry as the net electricity generation is on a rise and will increase in near future in EU. Furthermore, if Netherlands is taken specifically with respect to net electricity generation in the field of solar, it has shown rise from the year 2000 till present and is expected to show more growth in the coming years. Moreover, it has been predicted to give a rise around 6000 MW net generation capacity in the Netherlands. Figure, 5-2 depicts the rise of solar net electricity generation in the Netherlands when compared to other European countries. In the year 2020, as compared with other EU nations, the Netherlands going to contribute around 4.1% of total electricity generated by solar which is also shown in Figure 5-3.

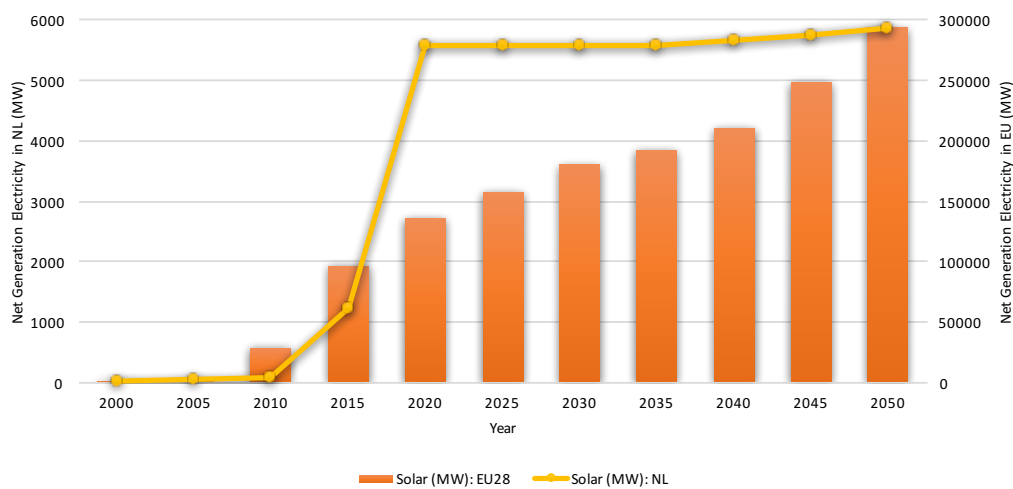


Figure 5-2: Net generation of electricity in NL & EU28 (Year 2000 - 2050).

Source: EU reference scenario 2016 based on PRIMES, GAINS

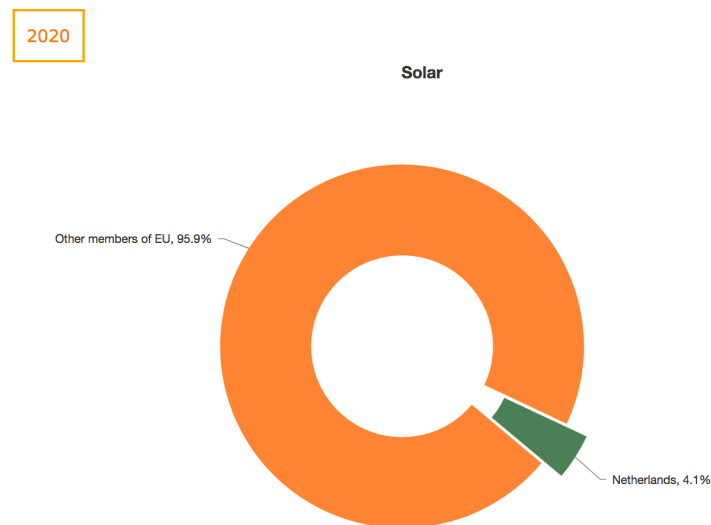


Figure 5-3: Net generation of electricity in NL & EU28 (Year 2020).

Source: EU reference scenario 2016 based on PRIMES, GAINS

ROADSIDE PV SYSTEM MODELLING

5-2 Location analysis

As briefly introduced in the beginning, the purpose of this thesis is to design a Roadside PV system would be able to supply power to E-bike charging stations. Considering the objective of project, location for the system has been taken as the Netherlands. As it is described in Chapter 2, that according to [5], the Netherlands has the maximum sale for E-bikes which is also shown in Figure 2-2. Therefore TU Delft, Delft has been chosen to design this PV system.

Figure 5-4 shows a sketch up model of Roadside PV system located in TU Delft campus at Mekelweg.

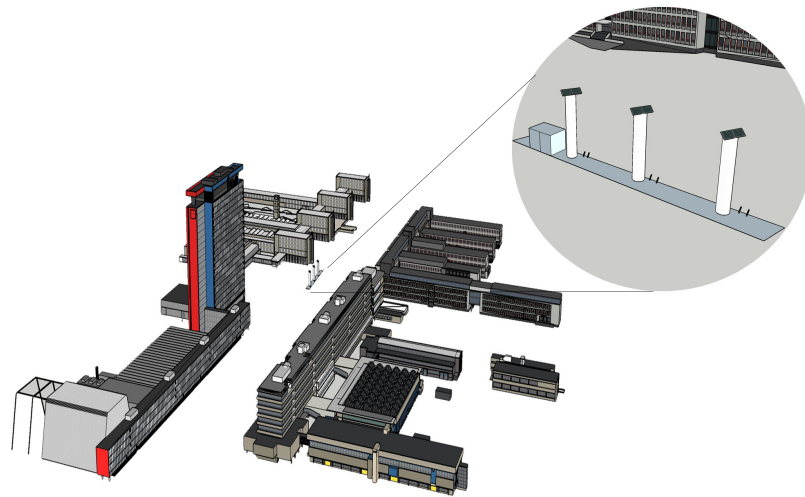


Figure 5-4: Roadside PV system model in TU Delft campus using Sketch Up.

In further sections, the analysis of this location for designing the Roadside PV system, as well as the meteorological data related to required for this system will be presented.

5-2-1 Meteorological data

The incident sunlight on a PV module is not only function of the module's orientation itself, but also position of the sun over time which have been computed with help of Matrix Laboratory (MATLAB). First of all, the sun position over the year of the chosen location has been determined. In Figure 5-5, path diagram of the sun for Delft is shown, which displays the winter and summer solstice & equinox respectively, it also shows the significant variation between summer and winter period.

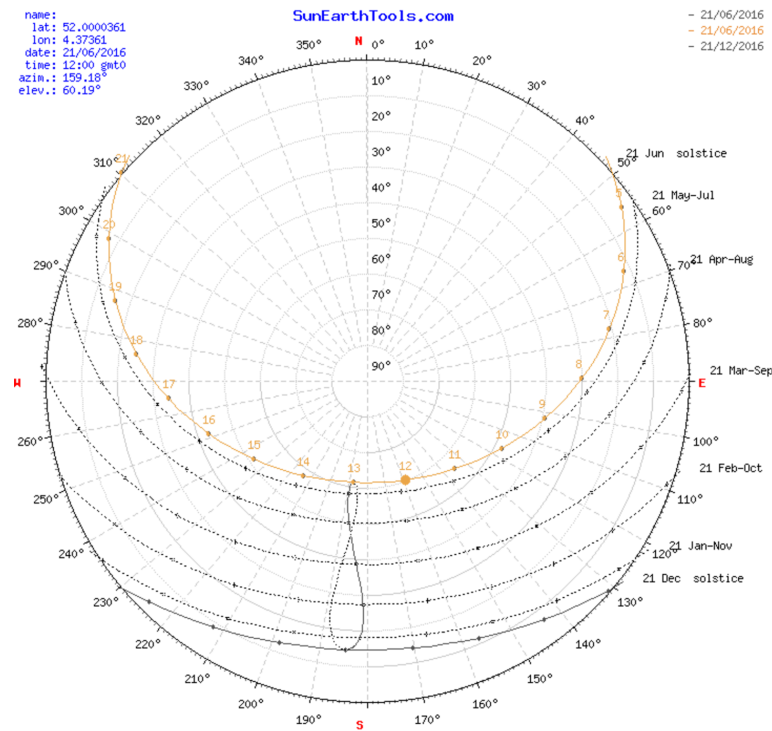


Figure 5-5: Sun path for Delft.
Image Source: [12]

However, a more precise evaluation of the sun position over the year is essential for determining the altitude and azimuth. Therefore, Figure 5-6 shows the sun position for Delft with 52.00° N, 4.37° E coordinates for the year 2016 that has been computed in MATLAB with the help of sun position calculator, explained in Appendix B.

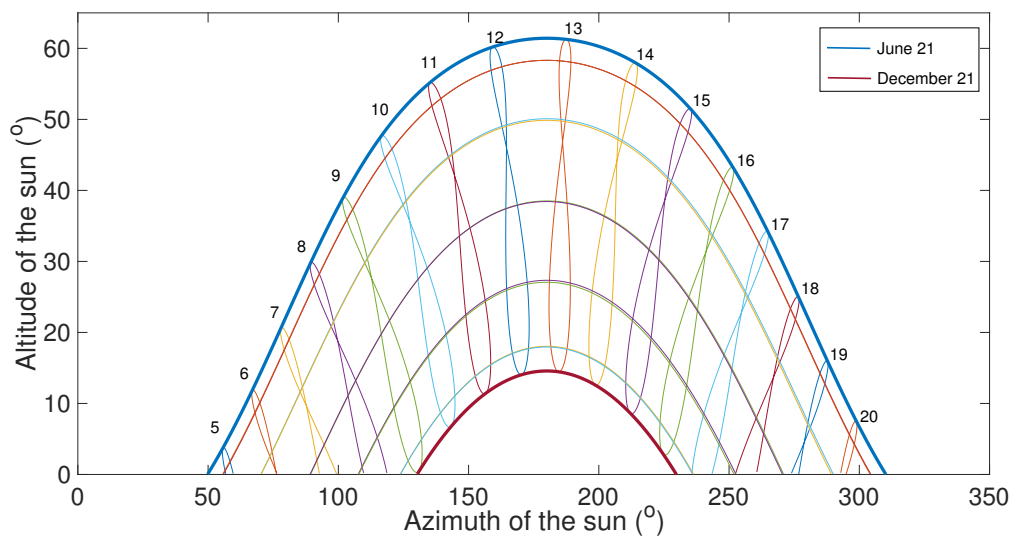


Figure 5-6: Analemma.

5-2-2 Global irradiance

In order to determine the global irradiation reaching the module located at specific latitude and longitude, direct and diffuse component are required which has been taken from Koninklijk Nederlands Meteorologisch Instituut (KNMI), Cabauw Experimental Site for Atmospheric Research (CESAR) database for the year 2016 as shown in Appendix C. With the help of sun position calculator explained in Appendix B, it is possible to evaluate sun altitude and azimuth for every hour of the year which is applied in the following calculations.

Global horizontal irradiance, (W/m^2) consists of two components namely;

- Direct Normal Irradiance (DNI), I_{dir} ;
- Diffuse Horizontal Irradiance (DHI), I_{dif} .

Direct irradiance on a module can be calculated with Equation 5-1 where $\cos \gamma$ is calculated as per Equation 5-2.

$$G_m^{dir} = I_{dir} * \cos \gamma, \quad (5-1)$$

$$\cos \gamma = \cos a_M \cdot \cos a_s \cdot \cos(A_M - A_S) + \sin a_M \cdot \sin a_s, \quad (5-2)$$

Diffuse irradiance on a module can be calculated with the help Hay and Davies diffuse model [41]. This model divides the sky diffuse irradiance into isotropic and circumsolar components as shown in Equation 5-3 where Sky View Factor (SVF) is calculated using Equation 5-4 [42] further in which β is the module tilt angle, A_i is the anisotropy index which is calculated using Equation 5-5 where E_a is the extraterrestrial radiation.

$$G_m^{dif} = I_{dif} * [A_i \cdot \cos(\gamma) + (1 - A_i) \cdot SVF], \quad (5-3)$$

$$SVF = \frac{1 + \cos(\beta)}{2}, \quad (5-4)$$

$$A_i = \frac{I_{dir}}{E_a}, \quad (5-5)$$

Irradiance reflected from ground can be calculated with Equation 5-6 [42] where GHI is global horizontal irradiation, SVF i.e. sky view factor, α is the ground surface reflectivity which is taken as 0.2 according to [43].

$$G_m^{gnd} = GHI * (1 - SVF) * \alpha, \quad (5-6)$$

Therefore global irradiance falling on a surface is the addition of direct and diffuse components which is given by Equation 5-7 [42].

$$G_M = G_m^{dir} + G_m^{dif} + G_m^{gnd} \quad (5-7)$$

Figure 5-7 shows the Global Horizontal Irradiance (GHI) with the help of aforementioned Equations and data from KNMI. The maximum calculated irradiance placed horizontally is 871 W/m^2 for the year 2016. Integration of this for the whole year gives the irradiation of 1047 kWh/m^2 which give an Equivalent Sun Hours (ESH) of 2.86 hours/day.

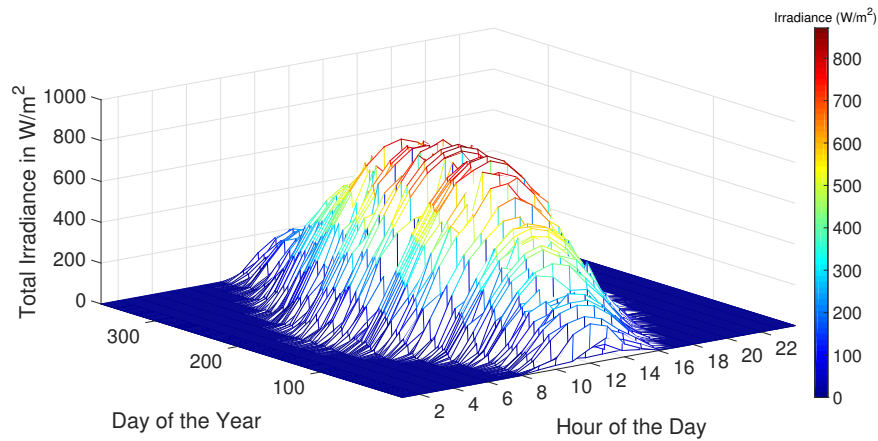


Figure 5-7: Module irradiance.

5-2-3 Module orientation

Proper orientation is a very important part for maximizing the energy yield from the solar module. Therefore, in this section optimal Module Tilt & Azimuth is being determined for surrounded free area. Furthermore, for a surrounded free area, it was found that when the solar module is tilted at angle of 36° and towards south for the chosen location, i.e., Delft, the incident energy over a year was maximum when optimized for a year, that can be further seen in the contour plot in Figure 5-8. The contour plots takes into account yearly global module irradiation and then evaluates on which tilt angle and azimuth it would be maximum.

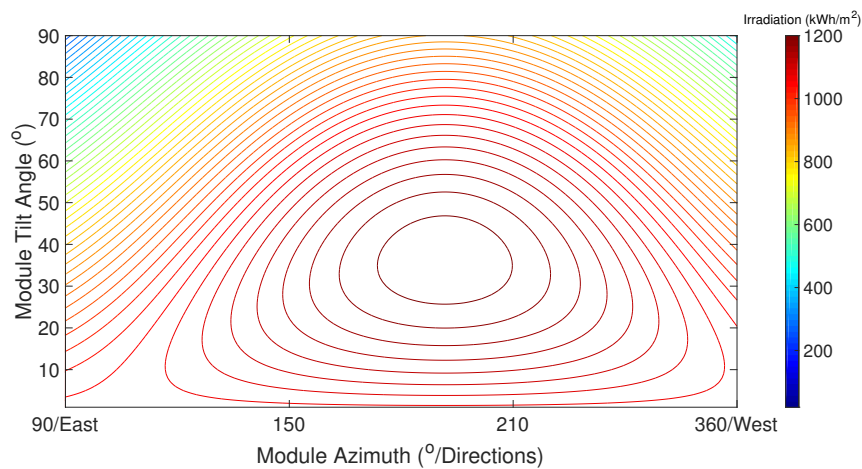


Figure 5-8: Contour Plot: Various Tilt Angle & Azimuth (optimized for a year).

5-2-4 Shading analysis

This section discusses the shading analysis done for the chosen location. Furthermore, the analysis can be done with various tools. But, for this project Horicatcher, Light Detection and Ranging (LIDAR) data images and Meteonorm is used to predict the effect of shading on the system which is discussed further in the thesis.

5-2-4-1 Using Horicatcher & Meteonorm

Horicatcher is one of the on site device for performing survey of the location. In this tool, a fish eye camera is installed above the horizon mirror which is further mounted on the tripod of height around 1.7 meters. This device also has a compass which make sure that it is placed on the right direction, for instance in this case it is placed perfectly north. With the help of Horicatcher, 360° image of chosen location can be visualized. Furthermore, Figure 5-9 depicts such image which is taken for the chosen location on a sunny day to visualise the surrounded buildings and structures that can cause shading to the system due to movement of the sun. Therefore, this device is a useful tool for depicting the horizon of a location to analyse the effect of shading.



Figure 5-9: Horicature device.

As shown in Figure 5-9 that is taken with the help of Horicatcher is a 360° image of the location. To process this image in Meteonorm, this image has to be transformed into panoramic

view which shows horizon of the location. Therefore, transformed image that is used in Meteonorm is shown in Figure 5-10.

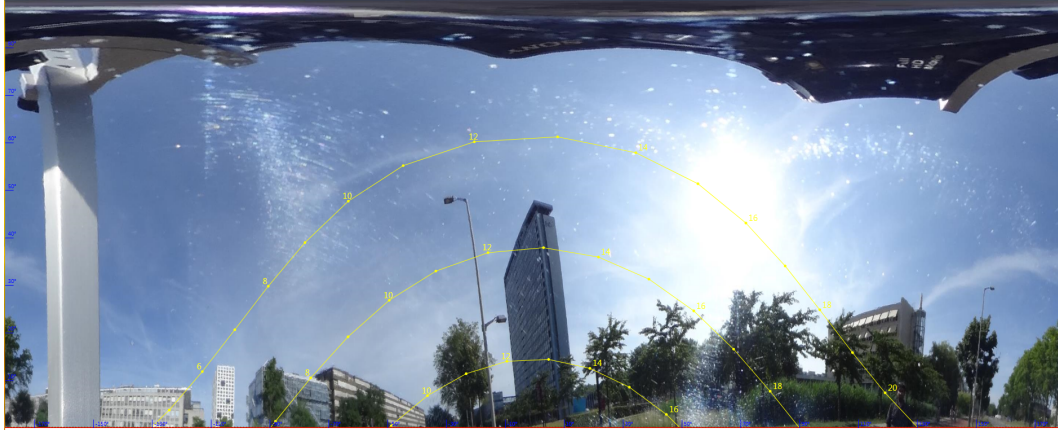


Figure 5-10: Horizon Free Horicature image.

After getting the panoramic view of the location, horizon has to be customized with the help of Meteonorm, which covers all the surrounded building and objects for the shading analysis.

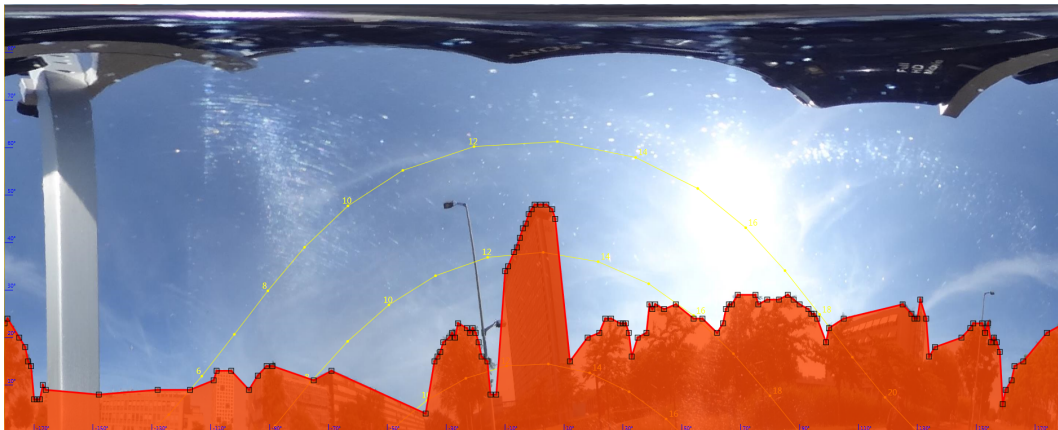


Figure 5-11: Customized horizon Horicature image.

However, as it was mentioned earlier that this device is mounted on a tripod and the height of the apparatus is 1.7 meters from ground. And, this is one of the drawback of using Horicature, that, it is very difficult to vary the image with different heights. As the focus of Roadside PV system is to have PV panels besides the roads, the height of the pole on which PV modules is mounted can vary, so the horizon will vary according to the placement of modules on different heights, which is not possible to gain with the help of Horicature images.

Therefore, another way of obtaining images at different horizons is using LIDAR data, which is further described in the thesis.

5-2-4-2 Using LIDAR data & Meteonorm

LIDAR is a survey tool, which uses laser light to determine distances to the Earth. This data is usually gathered with help of air using LIDAR instrument with aeroplanes and helicopters [44].

LIDAR data allows to inspect natural & human made environments which is accurate, precise and flexible [44]. Therefore, by using LIDAR data images at various horizon can be obtained. Figure 5-12 shows LIDAR data image, i.e., used for shading analysis. LIDAR images with 2.5 meters, 5 meters, 7.5 meters and 10 meters can be seen in Appendix E with their respective heights.

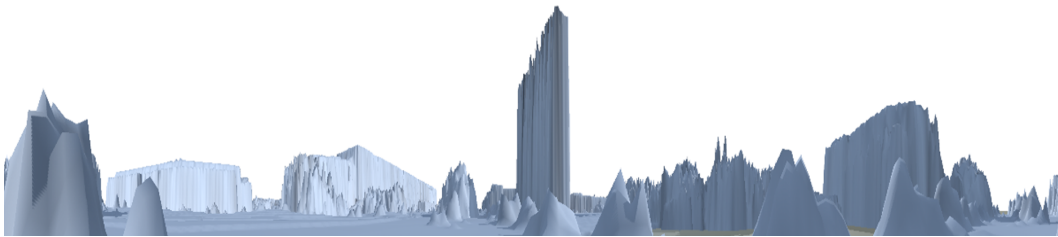


Figure 5-12: LIDAR data image.

This image is now inputted into Meteonorm for analysing the effect of shading. Figure 5-13 shows the customised horizon which is done on Meteonorm.

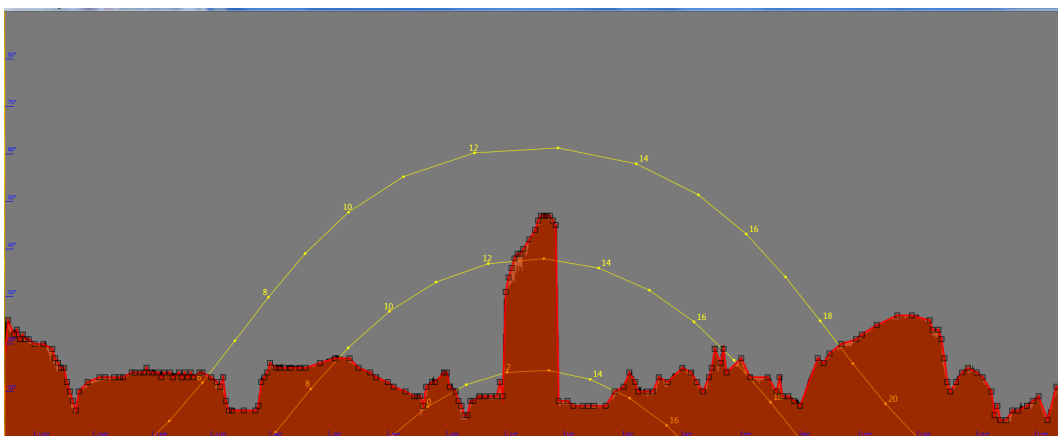


Figure 5-13: LIDAR data image (with customized horizon).

5-2-4-3 Shading factor

After inputting this customized horizon shown in Figure 5-11, irradiance due to shading can be determined. Now, shading factor of the location can be computed with the help of following formula 5-8 which is the ratio of irradiance receiving on module at shaded area and non shaded area. If a shading factor is 1, it means the surface is shaded free and if it is 0 which means surface is totally shaded [45].

$$SF = \frac{I_{CH}}{I_{HF}} \quad (5-8)$$

where, SF is the shading factor I_{CH} is the irradiance with customized horizon (W/m^2), I_{HF} is the horizon free irradiance (W/m^2).

Shading factor is computed using LIDAR data and Meteonorm for various module heights i.e ground reference, Horticature reference, 2.5 m, 5 m, 7.5 m and 10m. The images of LIDAR data at different heights and with customized horizon as shown in Appendix E.

Furthermore, shading factor for 21 June 2016 (shortest shadow) and 21 December 2016 (longest shadow) is compared with each other for various module heights in Figure 5-14 and 5-15. It can be easily depicted that the height of module placement and shading has inverse relationship which means with increase of height of module placement, there is reduction of shading due to surrounding structures and trees.

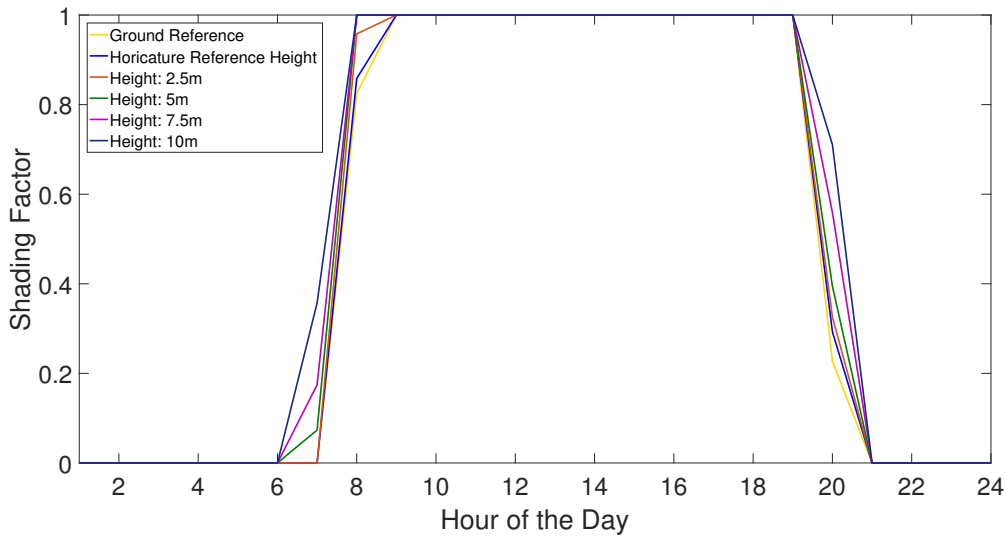


Figure 5-14: Comparison of shading factor on 21 June 2016 with various module heights.

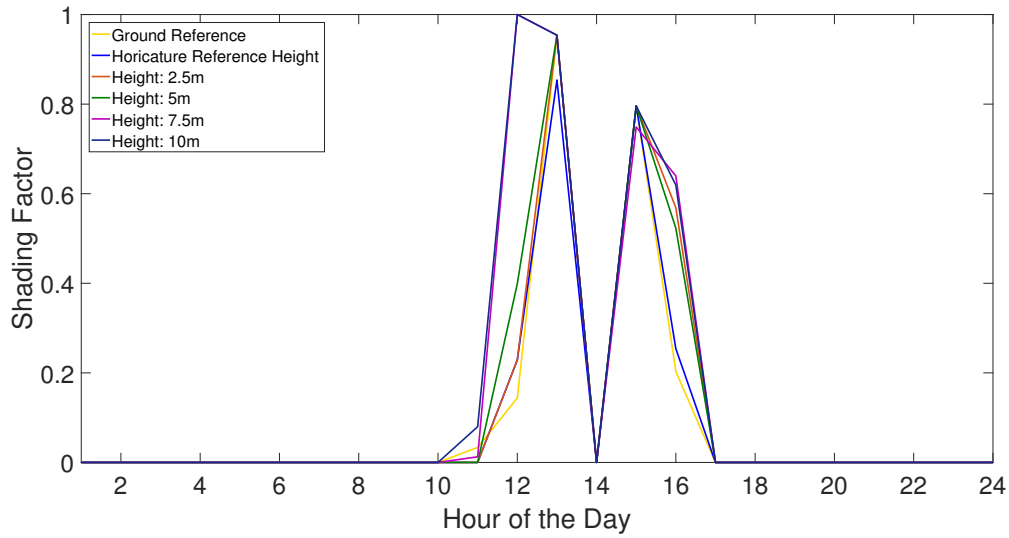


Figure 5-15: Comparison of shading factor on 21 December 2016 with various module heights.

5-2-5 Mutual shading

Mutual shading is a concept when modules are placed on the surface with an optimum orientation can shade the other module placed behind it, as illustrated in Figure 5-16 which can further lead to reduction in energy yield of the other PV modules placed besides the road. Therefore, to avoid this shading due to other PV modules, minimum distance have to be maintained between the poles which can be calculated with the help of Equation 5-9 [42] where D_p is the minimum distance between the poles, l_m is the length of the module, θ_M is the tilt angle of module, A_m is azimuth of the module, a_s is the altitude of the sun and A_s is the azimuth of the sun.

$$D_p = l_m \cdot [\cos(\theta_M) + \sin(\theta_M) \times \cot(a_s) \times \cos(A_m - A_s)] \quad (5-9)$$

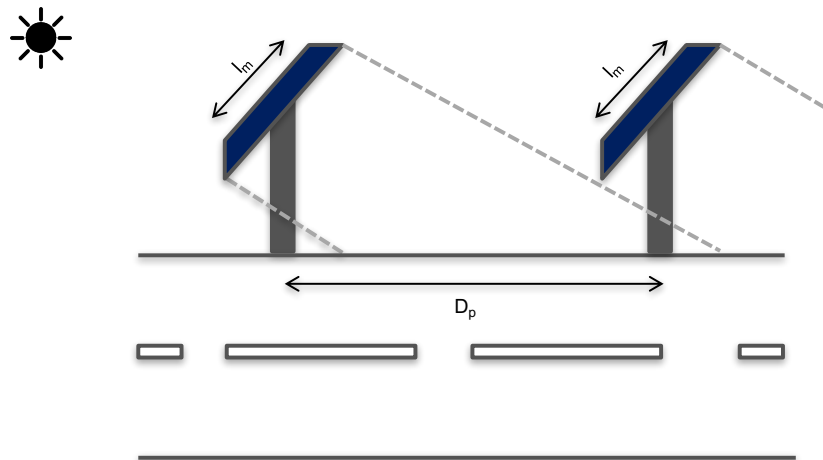


Figure 5-16: Mutual shading phenomenon.

Therefore, to analyse the minimum distance required between the poles with module placement at tilt angle 36° towards south is shown in Table 5-1. It should be noted that the distance determined is when module placed with short side, on the day of winter solstice considering shaded free between 9:00 to 15:00.

Table 5-1: Minimum Distance Required.

PV Module	Minimum Required Distance (m)
Simulated PV module	11.93
Sunpower P17 Module	8.91
Sunpower X21-345 Module	9.56

5-2-6 Module temperature

5-2-6-1 Fluid dynamic model

The module's performance is evaluated by considering the effect of both global irradiation and temperature. Moreover, for estimating the instantaneous temperature of the module annually, fluid dynamic model is developed according to the literature [42]. The constants applied in this model are mentioned in Table 5-2 and the meteorological data have been obtained with the help of Meteonorm. The temperatures of the sky and INOCT of the modules have been calculated using Equations 5-10 where T_a is the ambient temperature and 5-11, where T_{NOCT} is the nominal operating cell temperature. It should be noted that INOCT takes into consideration that the modules is raised above the ground.

$$T_{sky} = 0.0552 \cdot T_a^{1.5}, \quad (5-10)$$

$$T_{INOCT} = T_{NOCT} - 3^\circ C, \quad (5-11)$$

Furthermore, the module absorptivity, α , is calculated with Equation 5-12, where R is the reflectivity of solar module, and η is the module efficiency.

$$\alpha = (1 - R) \cdot (1 - \eta), \quad (5-12)$$

Now, convective heat of sky and ground can be calculated using Equation 5-13 and 5-14 respectively, where ε_{top} is the emissivity of front glass of module, ε_{back} is the emissivity of back of module, σ is the Stephan-Boltzmann constant, T_{gnd} is the ground temperature and T_M module's surface temperature.

$$hr_{sky} = \varepsilon_{top} \cdot \sigma \cdot (T_M^2 + T_{sky}^2) \cdot (T_M + T_{sky}), \quad (5-13)$$

$$hr_{gnd} = \varepsilon_{back} \cdot \sigma \cdot (T_M^2 + T_{gnd}^2) \cdot (T_M + T_{gnd}), \quad (5-14)$$

The convective heat transfer coefficients on the top surface of the module include two main components, i.e., free and forced, out of which the forced component is calculated taking into account both the laminar and turbulent contributions, which is further determined by applying Equations 5-15 and 5-16 where Re is the Reynolds number a function of the wind speed, w , hydraulic diameter, D_h and kinematic viscosity of air, ν . Furthermore, D_h is a function of the size of the module, as shown in the Equations 5-17 and 5-18.

$$h_{forced\ laminar} = \frac{0.86 \cdot (Re^{-0.5}) \cdot \rho_{air} \cdot c_{air} \cdot w}{Pr^{0.67}}, \quad (5-15)$$

$$h_{forced\ turbulent} = \frac{0.028 \cdot (Re^{-0.2}) \cdot \rho_{air} \cdot c_{air} \cdot w}{Pr^{0.4}}, \quad (5-16)$$

$$Re = \frac{wD_h}{\nu}, \quad (5-17)$$

$$D_h = \frac{2LW}{L + W}, \quad (5-18)$$

The forced is summation of laminar and turbulent flow as shown in Equation 5-19;

$$h_{forced} = h_{forced\ laminar} + h_{forced\ turbulent}, \quad (5-19)$$

And, free components is calculated with the help of Equation 5-20 where G_r is the Grashof number calculated with Equation 5-21, further in which g is the acceleration due to gravity on Earth and β is the volumetric thermal expansion coefficient of air, which is approximately equal to $\frac{1}{T_M}$.

$$h_{free} = \frac{k_{air} \cdot 0.21 \cdot (Gr \cdot Pr)^{0.32}}{D}, \quad (5-20)$$

$$Gr = \frac{g\beta(T_M - T_a)D_h^3}{\nu^2}, \quad (5-21)$$

Moreover, the mixed convective heat transfer coefficients is calculated with help of Equation 5-22;

$$h_{cT} = (h_{forced}^3 + h_{free}^3)^{1/3}, \quad (5-22)$$

The rear surface, which is a ratio of the actual heat loss from the back side is determined with Equation 5-23 where G_M is global irradiation and the backside convection coefficient is calculated with 5-24. And, as the heat transfer coefficient takes into account both front and back side of the module which is further calculated with Equation 5-25;

$$R = \frac{\alpha \cdot G_M - h_{cT} \cdot (T_{INOCT} - T_a) - \varepsilon_{top} \cdot \sigma \cdot (T_{INOCT}^4 - T_{sky}^4)}{h_{cT} \cdot (T_{INOCT} - T_a) + \varepsilon_{top} \cdot \sigma \cdot (T_{INOCT}^4 - T_{sky}^4)}, \quad (5-23)$$

$$h_{Bc} = R \cdot h_{cT}, \quad (5-24)$$

$$h_c = h_{cT} + h_{Bc}, \quad (5-25)$$

As the module's temperature have to be evaluated iteratively, the calculations have been performed in MATLAB, performing iteration five times and finally temperature of each module can be hence obtained with the help of Equation 5-26 [42].

$$T_M = \frac{\alpha \cdot G_M + h_c \cdot T_a + hr_{sky} \cdot T_{sky} + hr_{gr} \cdot T_{Gr}}{h_c + hr_{sky} + hr_{gr}} \quad (5-26)$$

where:

α is the solar road absorptivity, G_M is the irradiation on module, h_c is the overall heat transfer coefficient, hr_{sky} is the heat transfer coefficient between the top surface and sky, hr_{gr} is the heat transfer coefficient between the bottom surface and ground, T_a is the ambient temperature, T_{sky} is the sky temperature, T_{Gr} is the ground temperature, T_M is the module temperature.

Table 5-2: Constants used in fluid dynamic model.

Constant		Values
Stefan-Boltzmann constant, σ	W/m ² K ⁴	5.670367e-08
Kinematic viscosity of air, ν	m ² /s	1.460e-5
Back module emissivity, ε_{back}	-	0.89
Top module emissivity, ε_{top}	-	0.84
Prandtl's number, Pr	-	0.714
Specific heat capacity of air, c_{air}	J/KgK	1005
Air density, ρ_{air}	Kg/m ³	1.225
Air thermal conductivity, k	W/mK	0.025
Module reflectivity, R	-	0.1
Gravity constant, g	m/s ²	9.81

5-3 PV output analysis

5-3-1 PV module

In this section, PV modules used in the thesis is determined. For the analysis, there are three selected module types. Out of which one is Simulated PV module which is referred as Solar road module further in thesis and other two are Sun Power Modules. All parameters about these three modules are mentioned in Table 5-3.

Table 5-3: PV modules.

Parameters	Simulated PV module	SunPower Module P17	SunPower Module X21-345
Material	Poly-crystalline Silicon	Multi-crystalline cells	Monocrystalline Maxeon Gen III
Pmpp (W)	270	350	345
Imp (A)	6.75	8.12	6.02
Vmpp (V)	40	43.1	57.3
Voc (V)	49	51.7	68.2
Isc (A)	7.4	8.65	6.39

5-3-2 Global irradiation at module

As it was mentioned in section 5-2-3 the optimal tilt is at 36° placed towards south, the global irradiation on module for Roadside PV System at Mekelweg can be evaluated with the help of Section 5-2-2. Moreover, in the case of Roadside PV system detailed estimation of diffuse irradiation has been determined, as it has been assumed that SVF only depends on tilt angle of module according to Equation 5-4, which is not true as part of sky will also be restricted due to the surroundings [43]. Furthermore, as it a Roadside PV system the placement of module is height dependent which can lead to variation in sky view factor for different heights. Therefore, sky view factor for various heights and for particular module module tilt has been mentioned in Table 5-4. This data has been measured with the help of LIDAR data taken for 100000 rays which has accuracy of 0.001%.

Table 5-4: Sky view factor for different height of module placement.

Module Tilt ($^\circ$)	Module Height (m)	SVF
0	0	0.7074
36	0	0.6379
36	2.5	0.6985
36	5	0.7153
36	7.5	0.7254
36	10	0.7345

Now, global irradiation on module with optimum orientation at different height considering surroundings at this location are calculated using Equation 5-27 which are further compared for different heights in Table 5-5.

$$G_M^S = G_{mS}^{dir} + G_{mS}^{dif} + G_{mS}^{gnd}, \quad (5-27)$$

where:

$$G_{mS}^{dir} = I_{dir} * \cos\gamma * SF, \text{ where } SF \text{ is the shading factor}$$

$$G_{mS}^{dif} = I_{dif} * [A_i \cdot \cos(\gamma) + (1 - A_i) \cdot SVF] , \text{ where: } A_i = \frac{I_{dir} * SF}{E_a}$$

$$G_{mS}^{gnd} = GHI * (1 - SVF) * \alpha$$

Table 5-5: Global irradiation with for different height of module placement.

Module Tilt (°)	Module Height (m)	Irradiation (kWh/m ² /Year)
36	2.5	964.7
36	5	974.7
36	7.5	981.6
36	10	988.7

5-3-3 Module temperature

The module temperature for Roadside PV system which is computed with the help of fluid dynamic model described in subsection 5-2-6-1. Also, it is calculated with parameters shown in Table 5-2 and Equation 5-26.. The data for ambient temperature, and wind speed have been taken from Cabauw meteorological data centre as it is nearest data centre from chosen location i.e Delft.

5-3-4 PV module performance

5-3-4-1 Effect of irradiance

Effect of irradiance is the initial factor that has to be taken into considerations for solar system calculations which has direct effect on performance of module. This can be expressed with the help of Equations 5-28-5-31 [42], which can be seen that parameter's of the module are affected negatively with low value of irradiance. For the approximation of the maximum power output the Fill Factor (FF) applied is the same as the one determined as the ratio between $V_{mpp} \cdot I_{mpp}$ and $V_{oc} \cdot I_{sc}$ in Standard Test Conditions (STC).

$$V_{oc}(T_{STC}, G_M) = V_{oc}(STC) \cdot \ln \left(\frac{G_M}{G_{STC}} \right), \quad (5-28)$$

$$I_{sc}(T_{STC}, G_M) = I_{sc}(STC) \cdot \frac{G_M}{G_{STC}}, \quad (5-29)$$

$$P_{mpp}(T_{STC}, G_M) = FF \cdot V_{oc}(T_{STC}, G_M) I_{sc}(T_{STC}, G_M), \quad (5-30)$$

$$\eta(T_{STC}, G_M) = \frac{P_{mpp}(T_{STC}, G_M)}{G_M A_M}, \quad (5-31)$$

where, V_{oc} is the open circuit voltage, I_{sc} is the short circuit current, P_{mpp} is the maximum power, η is the module efficiency, T_{STC} is the temperature at STC i.e., 25 °C G_M is the irradiance, G_{STC} is the irradiance at STC i.e., 1000W/m² and A_M is the area of the module.

5-3-4-2 Effect of temperature

Next parameter that has an impact on performance of PV module is temperature which can vary significantly during the day due to the effect of ambient temperature T_a , wind speed, and directly mounted configuration. Furthermore, Section 5-2-6-1 describes the fluid dynamic model applied to evaluates the effects of the factors mentioned before on the module temperature.

Equations 5-32 - 5-35 [42] calculates the efficiency of PV after the effect of temperature on it.

$$V_{oc}(T_M, G_{STC}) = V_{oc} + \frac{\partial V_{oc}}{\partial T}(STC)(T_M - T_{STC}), \quad (5-32)$$

$$I_{sc}(T_M, G_{STC}) = I_{sc} + \frac{\partial I_{sc}}{\partial T}(STC)(T_M - T_{STC}), \quad (5-33)$$

$$P_{mpp}(T_M, G_{STC}) = P_{mpp} + \frac{\partial P_{mpp}}{\partial T}(STC)(T_M - T_{STC}), \quad (5-34)$$

$$\eta(T_M, G_{STC}) = \frac{P_{mpp}(T_M, G_{STC})}{G_{STC} A_M} \quad (5-35)$$

The differentials shown in aforementioned equations represents the temperature coefficients, which are for open circuit voltage, short circuit current and maximum power, that are further mentioned in PV module data sheets given in Appendix D.

5-3-4-3 Combined effect of irradiance & temperature

After determining the effect of irradiance and temperature, now evaluation of the overall instantaneous module performance is done which is further calculated using Equations 5-36 - 5-37 [42].

$$\eta(T_M, G_M) = \eta(T_{STC}, G_M) \cdot [1 + k(T_M - T_{STC})], \quad (5-36)$$

$$k = \frac{\partial \eta}{\partial T_M} \cdot \left(\frac{1}{\eta_{STC}} \right) \quad (5-37)$$

$$\frac{\partial \eta}{\partial T_M} = \frac{\eta(T_M, G_M) - \eta_{STC}}{T_M - T_{STC}}, \quad (5-38)$$

where $\frac{\partial \eta}{\partial T_M}$ is the efficiency temperature coefficient.

5-3-5 DC power output

After evaluating the irradiance, combined effect of irradiance & temperature, and area of modules, next step is to calculate PV power output of a module, which is determined with the help of Equation 5-39 [42],

$$P_{DC} = \eta(T_M, G_M) \cdot G_M \cdot A_M \quad (5-39)$$

where: P_{DC} is the DC power output of PV, $\eta(T_M, G_M)$ is the Efficiency of PV module after combined effect of irradiance & temperature, A_M is the Area of PV module.

5-3-6 PV modules requirement

To meet the load demand it is required to find the number of modules needed for the system. Furthermore, the total number of required modules can be calculated with Equation 5-40 [42].

$$N_T = \frac{E_{DC}^L \times SF}{A_M \times \int_{year} G_M(t) \times \eta(t) dt} \quad (5-40)$$

where, E_{DC}^L is the Yearly load energy demand, SF is the Sizing factor (Taken as 1.1), A_M is the Area of module (m^2), $\eta(t)$ is the Efficiency of module, $G_M(t)$ is the irradiance.

Chapter summary

In this chapter, insight about Roadside PV System was analysed in which it was determined that how this type of PV system beside road at Mekelweg, TU Delft will be designed. This analysis takes into account how the module was placed, considering height and distance of module and what was the effect of shading on module. Furthermore, it was decided to keep module at height of 10m and maintaining a minimum distance in between the poles to reduce the effect of shading. However, effect of irradiance and temperature on the energy yield on different kind of module are shown in chapter 6 with comparison to solar roads. Moreover, it will also compare number of modules required to charge E-bikes with these modules.

Chapter 6

Roadside PV & Solar Roads Comparison

Chapter Overview:

The aim of this chapter focuses on comparing Roadside PV with solar roads. This comparison will be based on irradiance, temperature, shading losses, module efficiency, energy yield analysis, number of modules required and area requirement. All the aforementioned parameters are further discussed in this chapter

Solar roads is one of the recent research development that has been undertaken by TNO in Netherlands [14]. In this innovation, solar panels are integrated with existing infrastructure and act as a massive source for generating electricity. The power generated with this novel concept of smart infrastructure can be used for charging electric vehicles, powering the electronic road signs, lightning of street lamps, supplying electricity to nearby houses or can be utilized to supply power to the grid [14], [3]. Additionally, there are other developments in the same area that are initiated by Colas-Ines [46], Solar Roadways [47] and Solmove [48]. Figure 6-1 shows solarroad which has been developed by TNO which is located in krommenie, Netherlands.

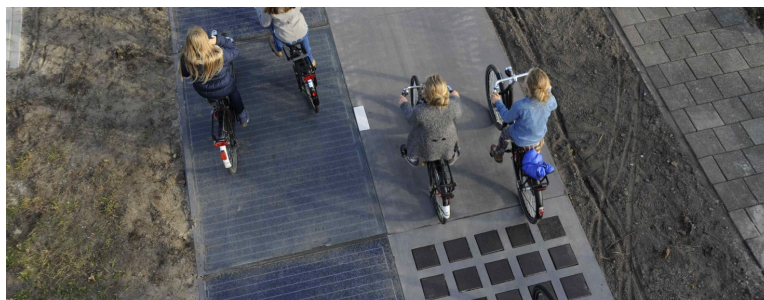


Figure 6-1: TNO Solarroad.
Image Source: [3]

In further sections solar roads are compared with Roadside PV on the basis of irradiance, temperature, shading, module efficiency, energy yield analysis, number of modules required and area requirement.

6-1 Overall comparison

This section provides the comparison of when modules are placed besides the roads with placement of module horizontally on roads i.e solar roads on the basis of irradiation, temperature, module efficiency, and energy yield of different kind modules with solar road modules with and without shading analysis. Moreover, it will also compare which will be based on number of modules required, coverage of area, maintenance, and installation.

6-1-1 Irradiation

Global irradiation reaching the module located at specific latitude and longitude has been calculated as explained in Section 5-2-2 in which data for direct and diffuse components have been taken from KNMI CESAR database for the year 2016 as shown in Appendix C.

As in solar roads, modules are placed horizontally on the surface, yearly solar radiation for them came to be around 1047 kWh/m^2 . And, for Roadside PV system, in which modules are placed besides the roads, for which it was optimal tilt angle and azimuth was determined, in which module tilt angle came to be 36° towards South. For roadside PV system, yearly solar radiation for them came to be around 1216 kWh/m^2 . The aforementioned mentioned values and Figure 6-2 compares the monthly radiation for solar roads which is placed on the roads and roadside PV which is optimally oriented besides the roads for a surrounded free area. This Figure 6-2 also illustrates that solar road will perform better in month of June and July, this is due to the optimum tilt should be much lower in these months (between 10° - 15° degrees) and as solar roads are placed at a lower degree they perform better.

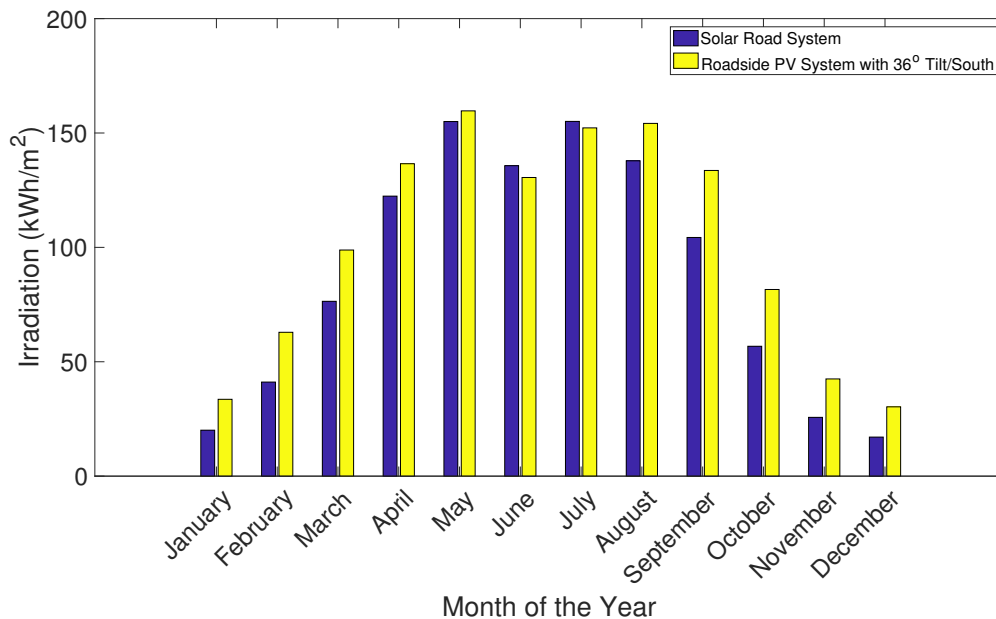


Figure 6-2: Comparison of irradiation receiving on Roadside PV and solar road system.

Moreover, in actual, the PV system in urban areas are never surrounding free and, there will be effect of shading due to buildings and trees surrounded by them. Therefore, Figure 6-3 depicts monthly radiation for solar roads which is placed on the roads and Roadside PV which is optimally oriented besides the roads with shading analysis. As it already mentioned in Chapter 5, that it will be placed on a height of 10m above the ground and will have less shading effect than module placed on the ground. Therefore, after taking shading effects into account due to surrounded buildings and tress, Roadside PV will perform better than solar roads in month of June and July as well. Furthermore, yearly irradiation is compared, then Roadside PV and solar road is approximately $989kWh/m^2$ and $840kWh/m^2$ respectively.

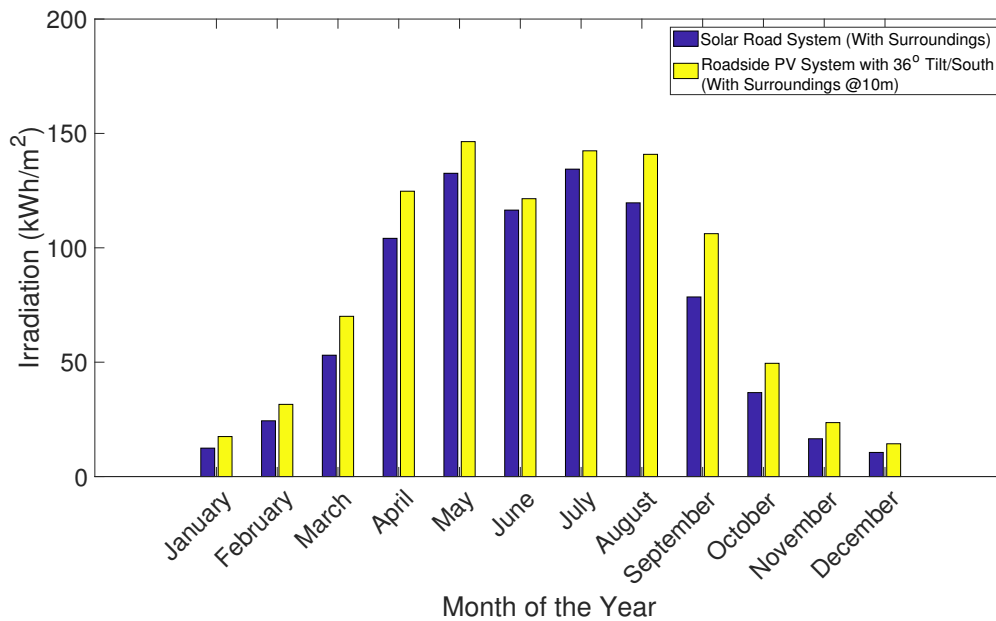


Figure 6-3: Comparison of irradiation receiving on Roadside PV and solar road system (with surroundings).

Furthermore, it should be noted that solar roads will also have a decrement in total irradiation due to number of people passing over it. However, this analysis is not done in this thesis, and according to [49], it has been determined that if the solar road is a bike path then there is further reduction of approximately $2\%/m^2$ in the total energy yield due to biker passing through it.

6-1-2 Temperature

The module's performance is also evaluated by considering module temperature. Therefore, for estimating the modules temperature accurately, temperature model has to be designed. The temperature model for Roadside PV was build according to the fluid dynamic model [42] which is also explained in Section 5-2-6-1 considering open air temperature. Furthermore, height can have a significant impact on modules temperature further in which wind speed has a direct effect, according to height of the module placement. As, it is decided in Chapter 5, the height of module is 10 m and the height at which wind speed is measured are same.

Therefore, no correction for wind speed is done in model while calculating modules temperature.

However, in the case for solar roads temperature model will be different due to placement of the modules within the concrete infrastructure. As modules in solar road are placed on the ground, there will be no bottom convection and the temperature model will be very different. And, it was not scope of thesis to build this model, therefore it was adopted from literature [49] which was modified according to the desired location i.e Mekelweg, TU Delft.

According to the respective models, temperature for solar roads was around 59.32°C and for roadside PV with same module was around 51.31°C taking surrounding into consideration. As for our analysis, in roadside PV system, different type of modules are used for the comparison with solar roads as shown in Table 5-3, for which temperature difference in these modules and solar road module are illustrated from Figures 6-4 - 6-7 (without surroundings) and Figures 6-8 - 6-11 (with surroundings).

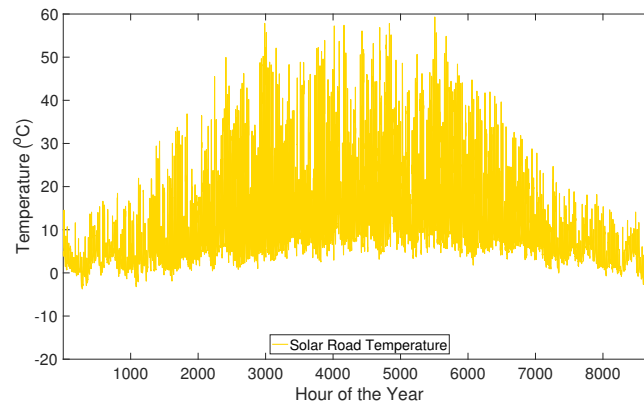


Figure 6-4: Solar road module temperature in Year 2016.

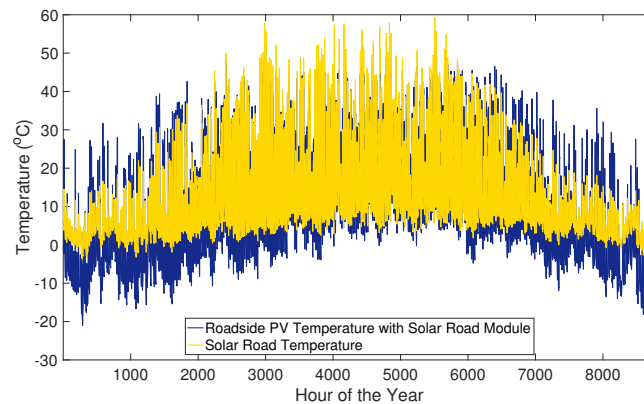


Figure 6-5: Temperature comparison of Roadside PV with solar road module and solar road in Year 2016.

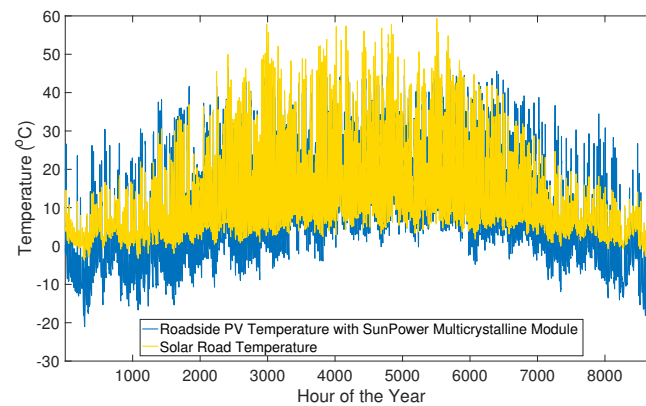


Figure 6-6: Temperature comparison of Roadside PV with SunPower multicrystalline module and solar road in Year 2016.

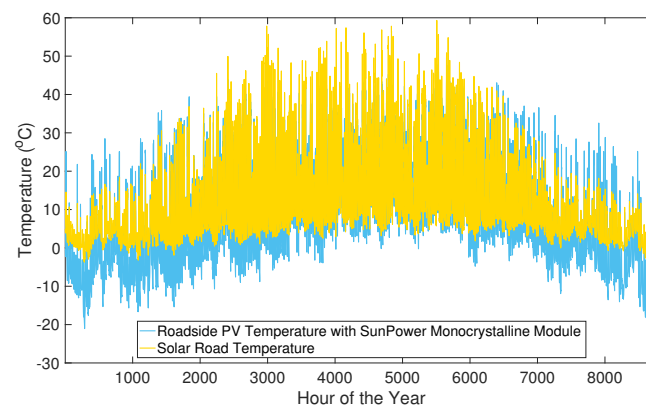


Figure 6-7: Temperature comparison of Roadside PV with SunPower monocrystalline module and solar road in Year 2016.

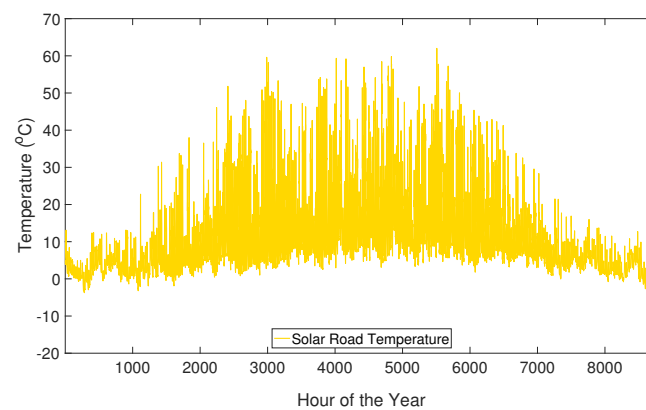


Figure 6-8: Solar road module temperature in Year 2016 (with surroundings).

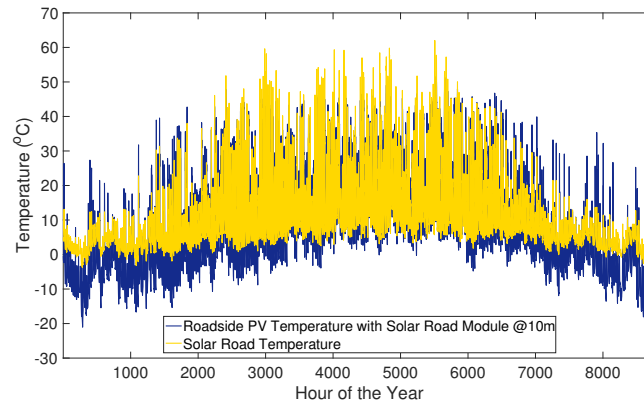


Figure 6-9: Temperature comparison of Roadside PV with solar road module and solar road in Year 2016 (with surroundings).

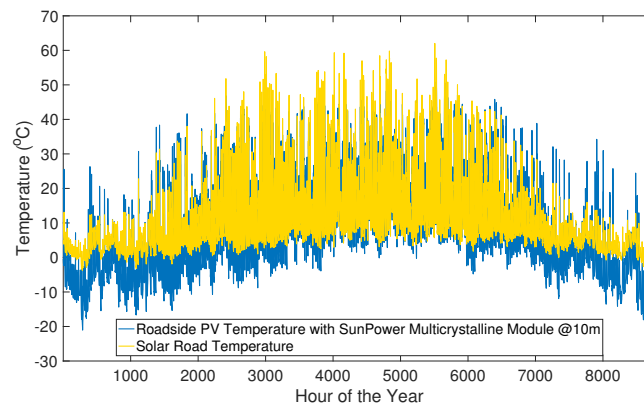


Figure 6-10: Temperature comparison of Roadside PV with SunPower multicrystalline module and solar road in Year 2016 (with surroundings).

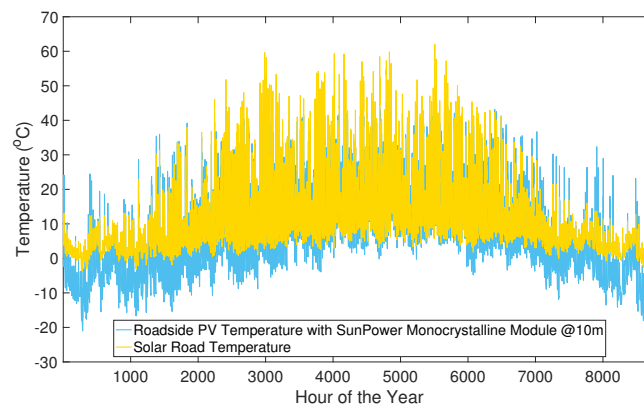


Figure 6-11: Temperature comparison of Roadside PV with SunPower monocrystalline module and solar road in Year 2016 (with surroundings).

6-1-3 Module Efficiency

The efficiency of the module can be evaluated with the help of Equation 5-36 after taking into account the combined effect of irradiance and temperature. Table 6-1, shows the various module efficiency with and without considering the surroundings.

Table 6-1: Module Efficiency.

Type of PV Module	Module Efficiency (%) (Yearly Average)	Module Efficiency (%) (Yearly Average) (with surroundings)
Solar Road Module	8.07	7.62
Solar Road Module (With Optimum Orientation)	8.16	7.75
SunPower Multicrystalline	11.81	11.18
SunPower Monocrystalline	14.70	13.89

6-1-4 DC energy yield analysis

After comparing irradiation, temperature and its effect on module efficiency when placed on the road or optimally beside the road, DC energy yield of the modules have to be determined.

The DC energy yield of a module is yearly integration of DC power output of PV module which was calculated with the help of Equation 5-39 which is mentioned in Section 5-3-5. Figure 6-12 shows the DC energy yield for surrounding free area for different PV modules when compared with solar road. It can be noticed that when solar road module is optimally placed it already produces around $20 \text{ Kwh}/\text{m}^2$ more what it is produced annually with solar road. It also shows DC energy yield with Sun power multi crystalline and monocrystalline modules which doesn't have any kind of laminations or anti-skid layers like solar road modules which produces $174.59 \text{ kWh/year}/\text{m}^2$ and $219.3 \text{ kWh/year}/\text{m}^2$ respectively.

Moreover, when surroundings are taken into consideration, optimally placed solar road module still produces $16.6 \text{ Kwh}/\text{m}^2$ more what it is produced annually with solar road which is also depicted in Figure 6-13. It also shows DC energy yield of different types of modules with surroundings when compare to solar road module.

Furthermore, if shading due to number of people passing over the solar road are also considered addition to the shading due to surroundings, then Roadside PV with solar road module produces around $18.3 \text{ Kwh}/\text{m}^2$ more what it is produced annually with solar road.

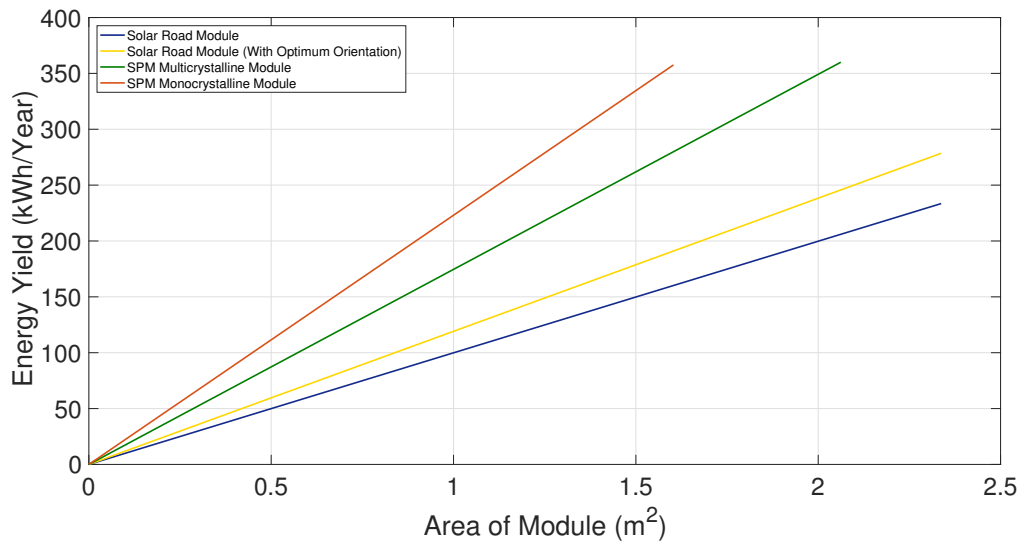


Figure 6-12: Comparison of Different PV Module Energy Yield in Year 2016.

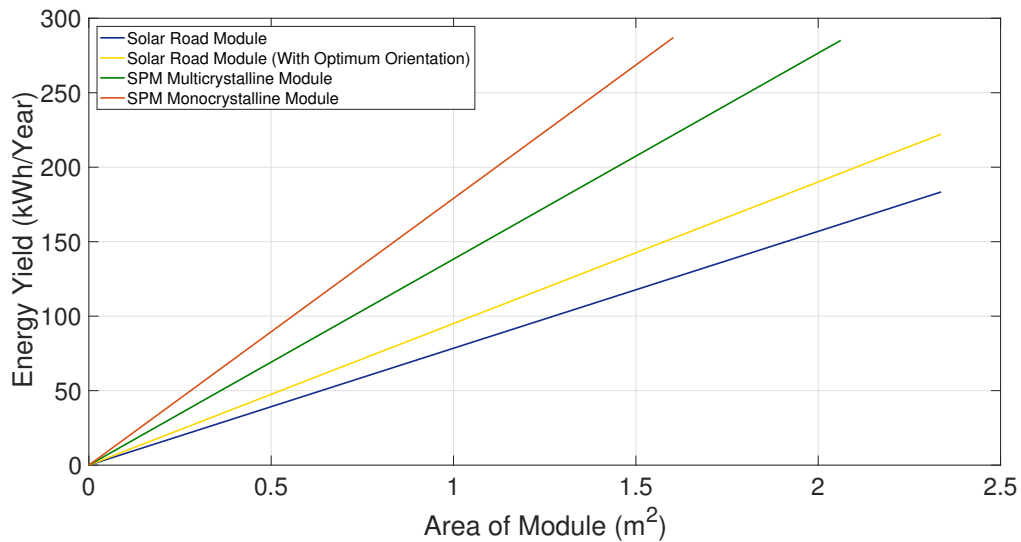


Figure 6-13: Comparison of different PV module energy yield in Year 2016 (with surroundings).

6-1-5 Modules requirement

According to Section, 5-3-6 number of required modules can be calculated according to the load and the type of PV module which also shown in Table 6-2.

Table 6-2: Module requirement.

Type of PV Module	Number of Modules Required
Solar Road Module	9
Solar Road Module (With Optimum Orientation)	8
SunPower Multicrystalline	6
SunPower Monocrystalline	6

From Table 6-2, it can be seen that three more modules are required by solar road when compared to the solar modules by sun power due to their higher power output. However, if the same solar road module is placed with optimal orientation still there is a reduction of 1 module.

6-1-6 Area covered

Now, placing the modules besides the road or on the road has to be compared on how much area it will covers which depends on number of required modules calculated in 6-1-5 which is also shown in Table 6-3.

Table 6-3: Area coverage comparison with different PV modules.

Type of PV Module	Number of Modules Required	Area Coverage (m^2)
Solar Road Module	9	21.04
Solar Road Module (With Optimum Orientation)	8	18.70
Sun Power Multicrystalline	6	12.38
Sun Power Monocrystalline	6	9.78

From Table 6-3, it can be seen that area required with Roadside PV System is lower when compared to the solar road.

6-1-7 Installation

Roadside PV System will be placed besides road in which modules will be placed with optimum tilt of 36° towards south mounted on a pole with a height of 10m. The minimal distance according to solar module type will be maintained as shown in Table 5-1 between various distributed on roadside to avoid mutual shading.

As an example that how the pole will actually installed besides the road is shown in Figure 6-14 ¹

¹It should be noted that this representation is just for giving an idea that how the future Roadside PV will look like, and this drawing design is not used in making the system.

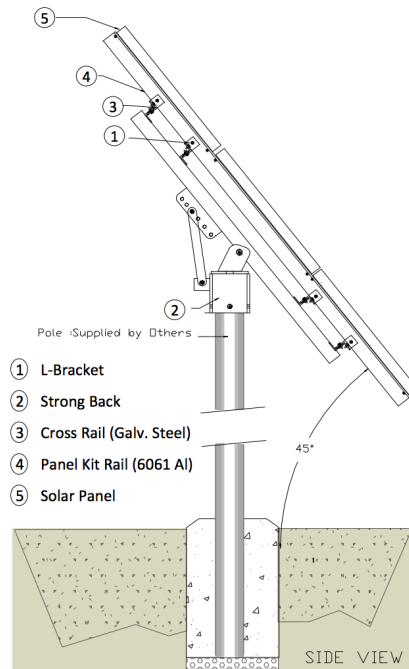


Figure 6-14: Top of solar pole mount.
Image Source: [13]

However, in the case of solar road where a block of concrete slab containing solar modules are mounted just above the road horizontally. The entire area of road have to be dug to place these modules. For instance, in Figure 6-15, installation of TNO SolaRoads have been illustrated.



Figure 6-15: TNO SolaRoad installation.
Image Source: [14]

6-1-8 Maintenance

Irrespective of type PV systems installed i.e Roadside or Solar road, maintenance is necessary. In the case of Roadside PV system, modules placement are at a height of 10m which can be a issue during the time of repairing. However, readily available solar modules can be used in this type of system.

Further, in the case of solar road, embedded solar module concrete slabs, have to be rebuild which has to be covered with anti-skid layer as it will be used to as a normal road with solar modules.

Chapter summary

Table 6-4 shows the comparison for solar road and roadside PV on the basis of tilt angle, DC energy yield produced, total received irradiation, module temperature, number of required modules and area required by different kind of module type.

Table 6-4: Comparison summary.

Type of PV Module	Solar Road Module	Solar Road Module (With Optimum Orientation @10m height)	Sun Power Multi crystalline (With Optimum Orientation @10m height)	Sun Power Mono crystalline (With Optimum Orientation @10m height)
Tilt/Azimuth Height	(°)/(Direction)	36/South 10	36/South 10	36/South 10
Irradiation	($kWh/m^2/Year$)	1217	1217	1217
(with surroundings)	($kWh/m^2/Year$)	989	989	989
Max Module Temperature	(°C)	51.31	50.59	47.80
Max Module Temperature	(°C)	51.56	50.84	48.02
(with surroundings)	($kWh/m^2/Year$)	119.2	174.59	219.3
DC Energy Yield	($kWh/m^2/Year$)	95.04	139.20	174.9
DC Energy Yield (with surroundings)	($kWh/m^2/Year$)	9	6	6
Required number of modules	-	8	6	6
Area Coverage	(m^2)	18.70	12.38	9.78
Module Efficiency (Yearly Average)	%	8.16	11.81	14.70
Module Efficiency (Yearly Average) (with surroundings)	%	7.75	11.18	13.89

Chapter 7

System Architecture

Chapter Overview:

This chapter discusses about the system design of the solar power electric bike charging station. It aims on how to supply power to the load i.e charging of E-bikes from PV, grid connection or storage based on the scenario. It also discusses what all components are required to build the system and how they are interconnected to each other.

IN DC SYSTEM topology the energy sources and loads can be supplied more effectively and efficiently by avoiding a few conversion stages and by selecting a suitable bus voltage. Moreover, the storage can be also be connected directly to the main DC bus or through a DC-DC converter.

Furthermore, DC interconnections can have many advantages that are mentioned as follows:

1. DC grid system with less power electronics components can reduce CO_2 emissions which is better for the environment [50], [51].
2. DC Interconnections can be reliable, stable, controllable and have better power quality of the system [50].
3. DC system topology have much lesser losses due to no skin effect [50], [52].

However, there are some disadvantage of using this system as well which are given as follows:

1. DC system has grounding and corrosion problems [50].
2. DC architecture's protection is much difficult when it is compared to Alternating Current (AC) system [50].

For this thesis, DC system topology is more suitable as the system needs to supply power only to DC loads. In further section, DC architectures with chosen bus voltage used for our system has been described.

7-1 DC architecture

Figure 7-1 shows the DC system architecture for the Roadside PV Powered E-bike charging station in which all the required components are shown and it also depicts how they are interconnected together. The system will have a DC bus voltage of 48 V due to components availability and safety reasons.

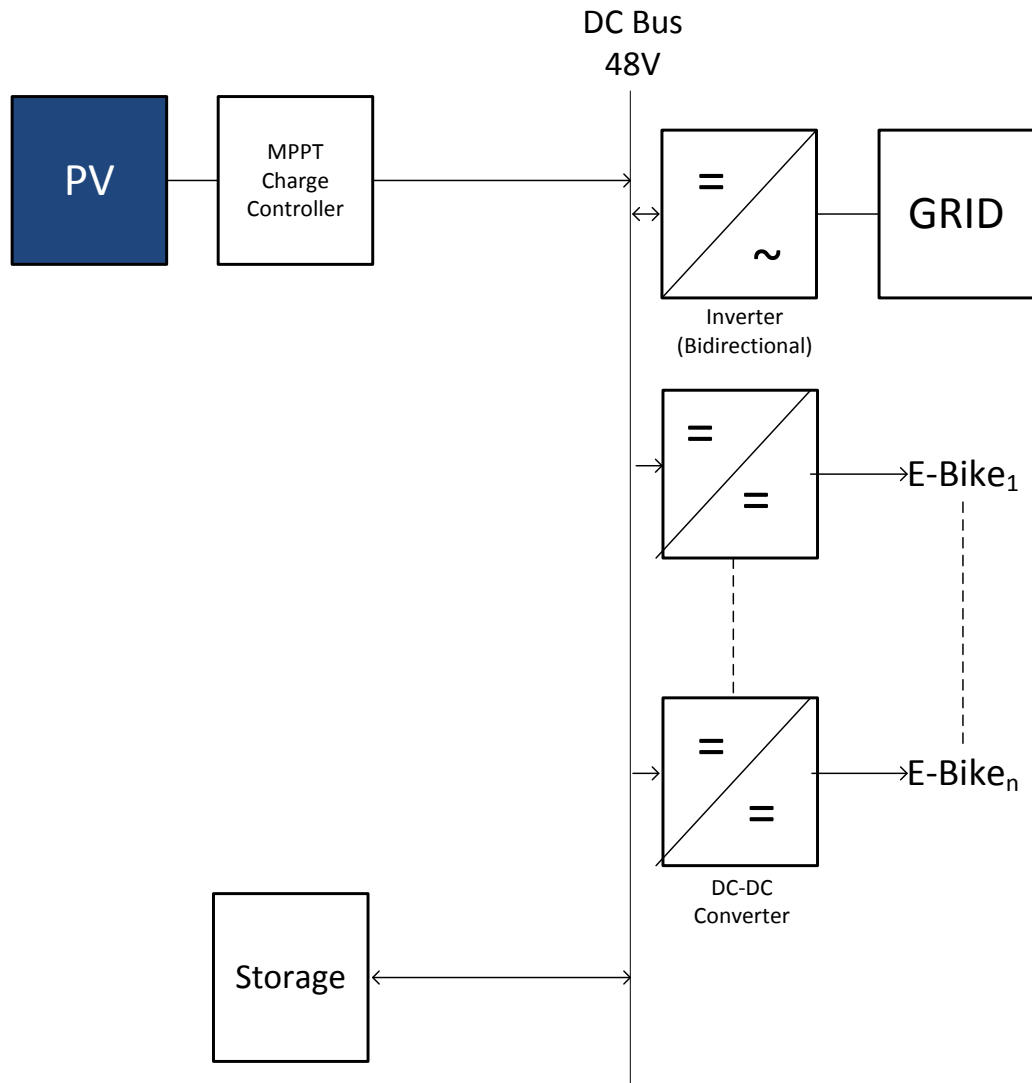


Figure 7-1: DC architecture.

As the connected loads are DC, therefore this kind of architecture is more suitable which requires lesser number of power conversion stages. However, still some power conversion are required as it is a grid connected DC system. Therefore, components required for system are given in following sections.

7-1-1 Required components

The required information about the components used in the system shown in Figure 7-1 have been mentioned as following:

7-1-1-1 PV generation

Figure 7-2 shows the annual DC power output generated with the help of multi-crystalline solar module by SunPower which has a output of approximately $140kWh/m^2$ annually whereas for mono-crystalline solar module has a output of approximately $175kWh/m^2$ annually.

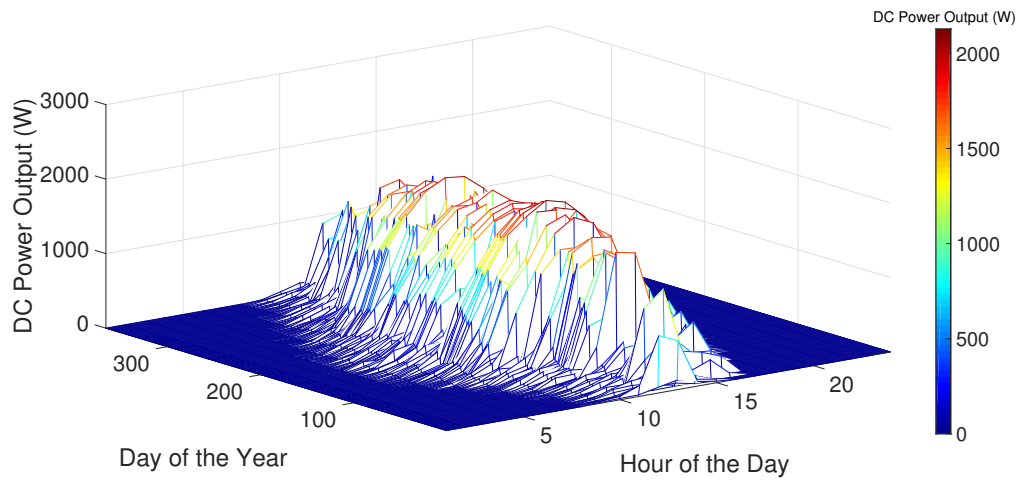


Figure 7-2: PV DC Power Output.

7-1-1-2 MPPT charge controller

Maximum Power Point Tracker (MPPT) charge controller ¹ is a power electronic DC to DC converter that optimizes the match between PV, the storage and grid. It is also important when battery charging is involved. Moreover, the MPPT has to match the bus voltage i.e 48 V in this case and also the maximum power delivered with PV. It also should be noted that its voltage should be greater than panels used in generation for solar power. For further analysis, MPPT charge controller from victron energy is used, i.e., Victron BlueSolar 150/70 is used which has maximum input voltage of 150V. Taking this into account, 2 modules are placed in series and 3 in parallel.

7-1-1-3 DC-DC converter

DC-DC converters in the system are used to convert system voltage that is much suitable for E-bike battery voltages. A DC-DC Converter used in the system has input voltage of 48 V and output that can be given which is suitable for E-bikes i.e 24/36/48V.

¹The topology and components used in the system are similar as present E-bike charging station at TU Delft Campus [37].

7-1-1-4 Inverter

An inverter¹ is required for the system so that surplus power generated by PV after satisfying load can be fed into the grid or in case when there is no solar or battery energy available, required load demand can be satisfied from the grid. Therefore, to choose an inverter it should be ensured that it's according to 48 V voltage DC bus. For further analysis, inverter from victron energy is used, i.e., Victron Multiplus 48/3000/35.

7-1-1-5 Storage

The storage¹ for this system is according to 48 V voltage DC bus. As the system is grid connected, optimal battery capacity has to be decided. Lead acid batteries are chosen as it is extensively used in the PV systems due to its cost effectiveness and robustness [37]. For further analysis, different battery capacities are used, i.e., i) 5.280kWh, ii) 10.560kWh, iii) 21.120kWh and iv) 31.680Wh. These batteries have voltage of 12V with current capacity as 110Ah, 220Ah, 220Ah, and 220Ah respectively. These are connected in such a way that it matches the DC bus voltage, i.e., 48V which will avoid an extra power electronic component.

7-1-2 Performance analysis

Performance analysis for the entire system is based on how the power is flowing to the loads i.e how the system interact with each other when there is excess load demand or when there is extra power delivered after meeting the load demands. This depends on how the power flow management is operated. Therefore, power flow management for this system is shown in Figure 7-3.

Furthermore, to calculate the total power exchange with the grid based on the DC system architecture can be calculated with Equations 7-1 and 7-2 respectively [53] where $P_{grid(fed)}$ is the power fed to the grid, $P_{grid(drawn)}$ is power drwan from grid, P_{PV} is power generated by PV, η_{MPPT} is the MPPT efficiency, η_{DC-DC} is DC-DC converter efficiency , $Load_{E-bikes}$ is the E-bike load demand, and η_{inv} is the inverter efficiency.

$$P_{grid(fed)} = [P_{PV} \times \eta_{MPPT} - \frac{Load_{E-bikes}}{\eta_{DC-DC}}] \times \eta_{inv} \quad (7-1)$$

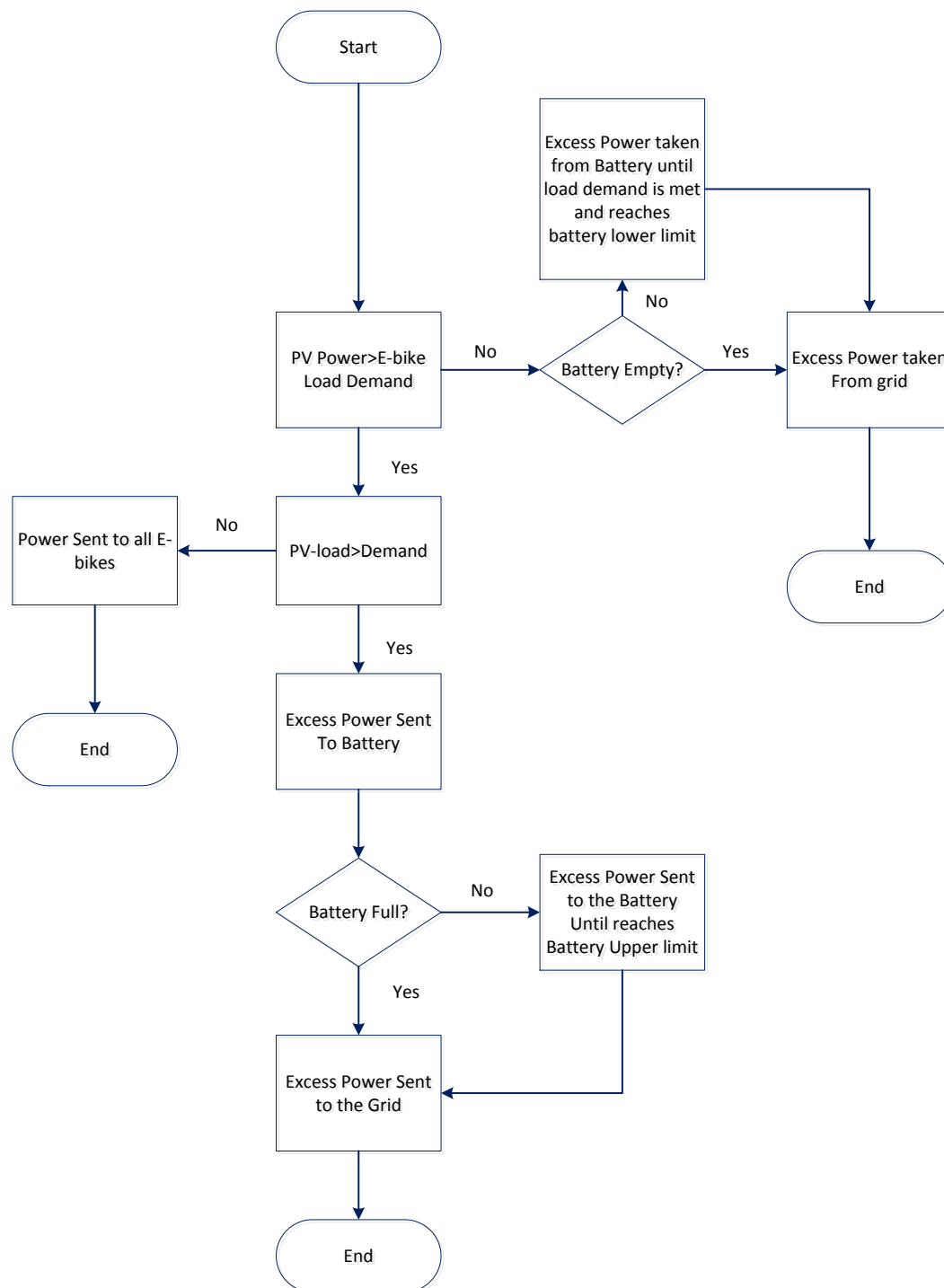
$$P_{grid(drawn)} = \frac{[P_{PV} \times \eta_{MPPT} - \frac{Load_{E-bikes}}{\eta_{DC-DC}}]}{\eta_{inv}} \quad (7-2)$$

Power loss in a DC cable is calculated with Equation 7-3 [42], where I is the current flowing through it, σ is the conductivity of conductor, l and A are the length and cross sectional area of the cable respectively.

$$P_{DC \text{ cable}} = I^2 \cdot \frac{1}{\sigma} \cdot \frac{l}{A} \quad (7-3)$$

Total system efficiency is calculated with the help of Equation 7-4 [53] where $E_{E-bikes}$ is the E-bike energy demand, $E_{grid(fed)}$ is energy fed to grid, E_{PV} is the energy from PV, $E_{grid(drawn)}$ is the energy drawn from grid.

$$System \text{ Efficiency} = \frac{E_{E-bikes} + E_{grid(fed)}}{E_{PV} + E_{grid(drawn)}} \times 100 \quad (7-4)$$

**Figure 7-3:** Power Flow Management.

The Figure 7-3, shows that if there is surplus energy flowing in the system, it is first checked that if battery SOC is between 20% to 80% then only it is charged otherwise it fed to the grid. On other hand, when there is need of extra energy in the case of less energy generated by PV panels, then it is first checked that if battery SOC is between 20% to 80%, then only it is discharged otherwise it taken from the grid.

However, the decision has to be made between the optimal battery size for the system, which is done on the basis of system efficiency calculated with Equation 7-4 and shown in Figure 7-4. It is illustrated that more the battery capacity better the system efficiency as one step of power electronic component is reduced when the energy is exchanged with battery rather than grid. Moreover, it is better to use battery capacity with 10.560kWh compared to other battery capacity due to: i) maximal increment in system efficiency, ii) it has least parallel connection, i.e., 1 which is beneficial as according to [42], as parallel connections can increase the effect of ageing of entire storage, iii) reduction in number of batteries.

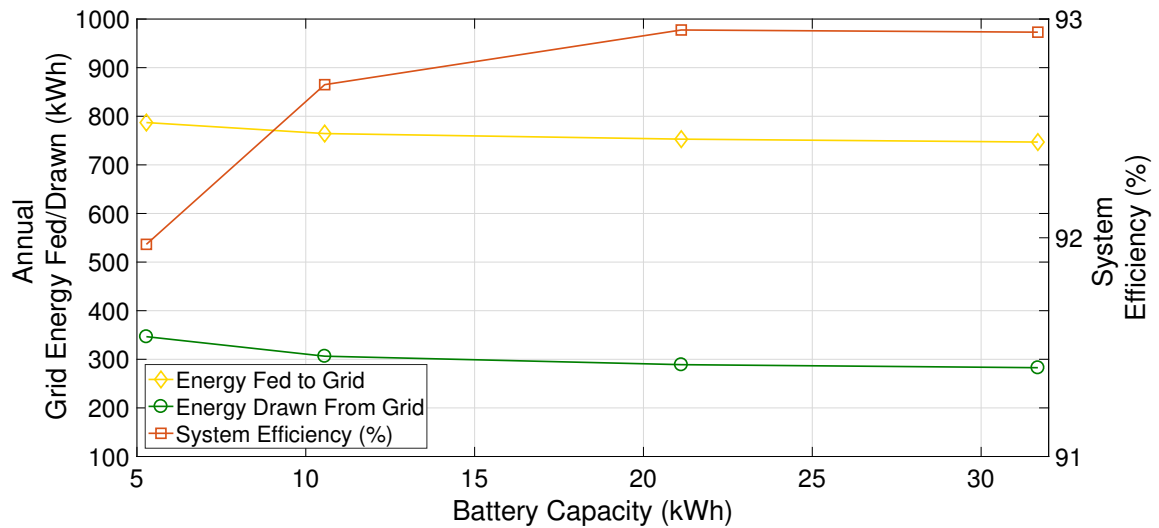


Figure 7-4: Battery state of charge.

Figure 7-5 and 7-6 shows the selected battery SOC, and grid exchange over the year respectively. From Figure 7-6, it can also be seen that total energy given and taken to/from the grid is approximately 772kWh and 306kWh respectively.

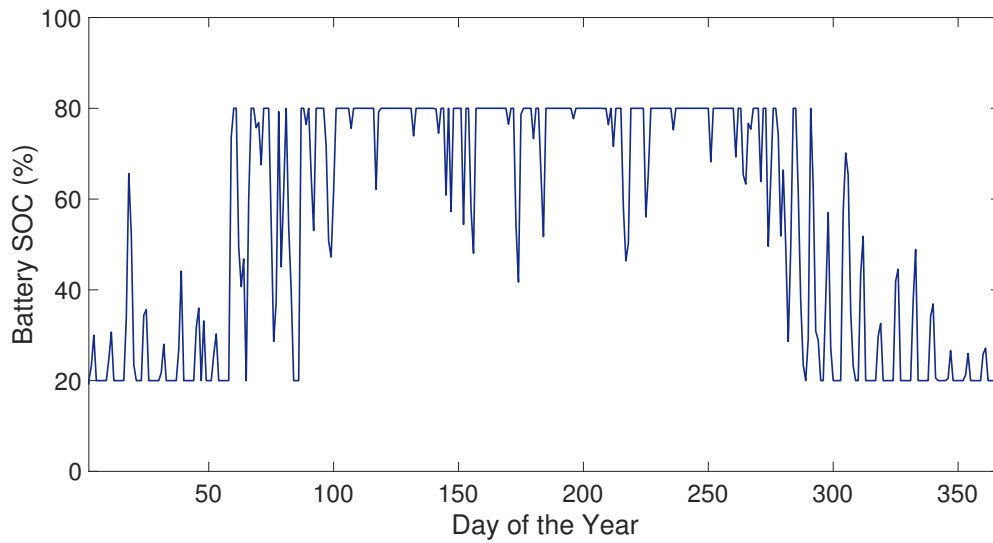


Figure 7-5: Battery state of charge.

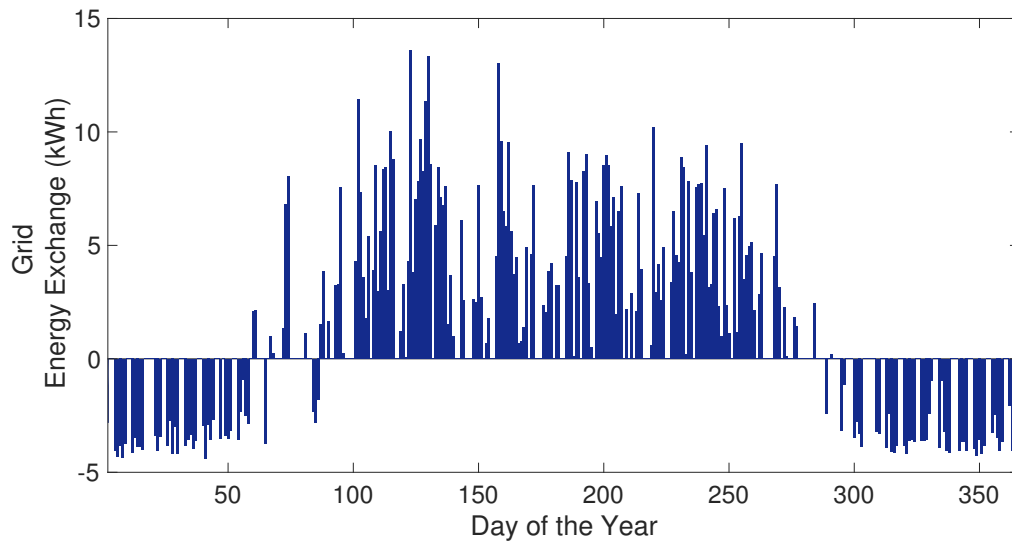


Figure 7-6: Grid Exchange.

The aforementioned analysis is done with the multi crystalline solar module by Sun Power. For comparing, this data with mono crystalline by Sun Power and solar road module are summarized in Table 7-1. It can be seen that solar road module has more excess power generated by PV as required number of solar modules are more i.e 8 whereas, in the case of Sun power multicrystalline and monocrystalline modules are 6.

Table 7-1: System information with different types of modules

PV Module	Energy Fed to Grid (kWh)	Energy Drawn from Grid (kWh)	System Efficiency (%)
Sun Power Multi crystalline	764.13	306.4	92.70
Sun Power Mono crystalline	811.1	312.6	92.76
Solar Road Module	873.4	307.7	92.76

Chapter Summary

In this chapter, system architecture for Roadside PV system for charging E-bikes was discussed. In this system design, a 48V DC bus is used, further in which all components required to build the system and their interconnections are determined. In addition, comparison on storage size, according to system efficiency was analysed and decided to use 10.560kWh battery for this system type. Also, battery SOC and grid exchange for this system in comparison with various module type was discussed as well.

Conclusions & Recommendations

Chapter Overview:

This chapter summarizes the key results of the project and also recommends further research scope in future.

8-1 Conclusions

1. *What application is chosen for designing the grid connected Roadside PV system?*

The application chosen for designing grid connected Roadside PV system are E-bikes.

- 1.1. *What are specifications and requirements of the chosen application?*

It was found through the literature study that E-bike uses 24/36/48 voltages. However, most E-bike uses 36V for the batteries.

- 1.2. *How power consumption of the chosen application is decided?*

With the help of E-bike dynamic consumption model the power consumption was decided. It was seen that the total energy consumed for 400 Wh E-bike battery is approximately 8.4Wh/km.

2. *What should be the design of Roadside PV system to meet specific load demands?*

It was analysed that when Sun Power multi crystalline and mono crystalline modules were used in Roadside PV system, total of 6 solar modules were required, which were placed in 2 series and 3 parallel configuration. However, when solar road module was used in Roadside PV system number of modules got increased to 8.

2.1. *What should be the optimal orientation of Roadside PV system for specific location?*

It was determined that optimal azimuth and tilt of Roadside PV came to be 36° towards south for Mekelweg, TU Delft campus which maximizes the energy production.

2.2. *What is the annual energy yield output that can be expected from the Roadside PV system?*

It was found that when solar road module were used with Roadside PV system with optimal orientation, the energy yield came out to be around $119.2 \text{ kWh/m}^2/\text{year}$. However, when Sun Power multi crystalline and monocrystalline modules were used the energy yield for the same system came out to be around $174.59 \text{ kWh/m}^2/\text{year}$ and $219.3 \text{ kWh/m}^2/\text{year}$ respectively.

2.3. *What factors effects the energy yield of the Roadside PV System?*

Shading due to surroundings is one of the reason because of which energy yield of PV system can be affected. As, the solar modules are going be placed beside the roads mounted on a pole the height of this pole can vary. Therefore, shading factor was calculated with the help of LIDAR data images and Meteonorm for various heights, which show that height of module placement and shading has inverse relationship, which means higher the module placement less is the effect of shading. Therefore, considering this, PV Modules are mounted at a height of 10m while maintaining minimal distance between other modules to avoid mutual shading.

3. *How is PV system design beside the roads different from Solar roads?*

It was seen that Roadside PV system design which has optimum tilt and azimuth of 36° towards south respectively receives approximately 16.5 kWh/m^2 more than solar roads annually after considering the surroundings. It was also seen that total area coverage with same solar road module when placed with optimal orientation was around 2.34 m^2 less for the same amount of load.

4. *How architecture of Roadside PV system will be designed?*

DC System architecture with 48 V DC bus was decided for Roadside PV as it needs to supply power only to DC loads, i.e., E-bikes. All components required to build the system and their interconnections were determined. A comparison on storage size, according to system efficiency was analysed and decided to use 10.560 kWh battery for this system type. It was determined that if Sun power multi crystalline modules are used then the system will have 92.70% system efficiency whereas if Sun power mono crystalline modules are used then the system efficiency would be 92.76% for the same battery type.

8-2 Recommendations

8-2-1 Roadside PV system mount pole

As previously described in the thesis, that Roadside PV system will be mounted on top of the pole. Design and construction of this type of structure at height of 10m which can handle the weight of PV module(s) still have to taken care upon.

8-2-2 Charging station

In this thesis, total charging points were decided according to assumption of 30 incoming E-bikes in a day which might increase in future. Therefore, an queuing system with an software application can be built which communicate with user if the charging plug is empty or not. This application can also be used to tell about the status of their E-bike charging. Furthermore, a design was initiated for charging station having E-bike stands along with charger on the pole itself. However, this can be modified.

8-2-3 Charging Control Strategy

Smart charging control algorithm can be developed for the E-bike charging station having various strategies.

Appendix A

E-bike Dynamic Consumption Data

A-1 Plots

A-1-1 Acceleration/Deceleration plots

This section provides the plots for acceleration/deceleration of UN/ECE Extra-Urban Driving Cycle (Low Powered Vehicles) velocity profile. Figure A-1 shows the acceleration/deceleration w.r.t time and Figure A-2 shows the same but with respect to distance.

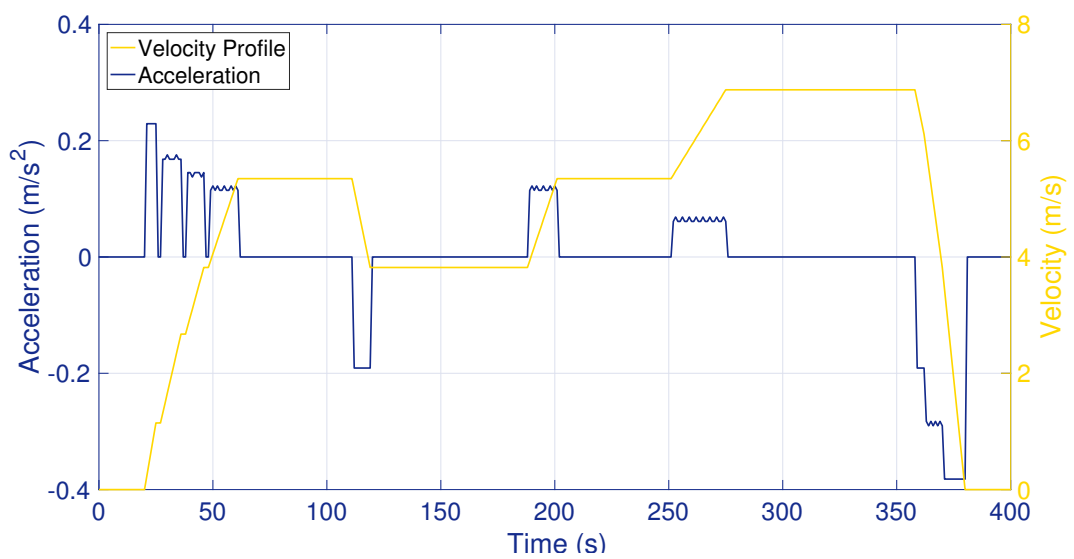


Figure A-1: Acceleration and velocity plot versus time equivalent plot.

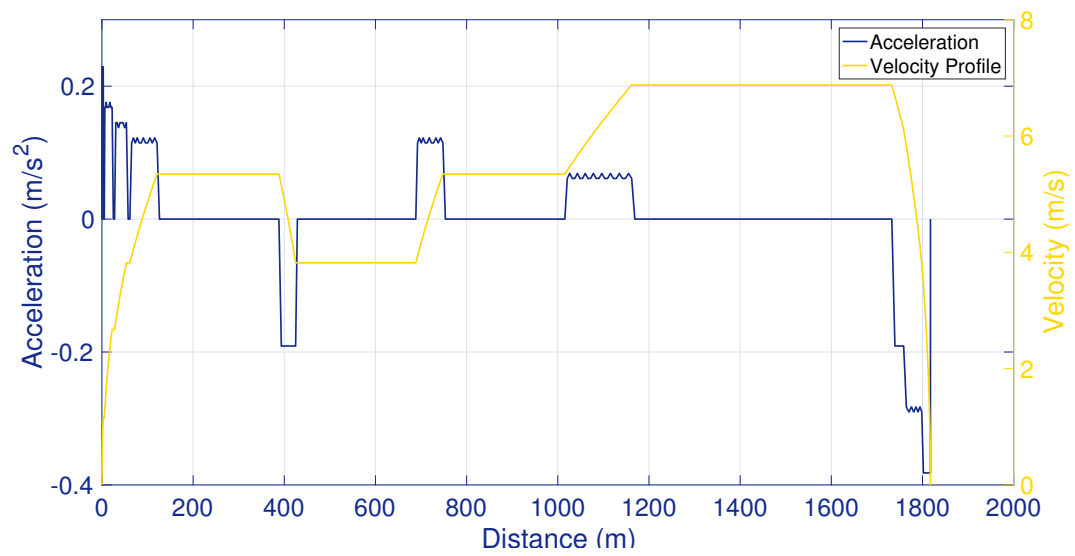


Figure A-2: Acceleration and velocity plot with respect to distance travelled.

A-1-2 Battery power plot

This section provides the plots for power supplied and recovered by e-bike battery which are calculated with the help of equation 3-8 and 3-9 respectively which is further shown in Figure A-3.

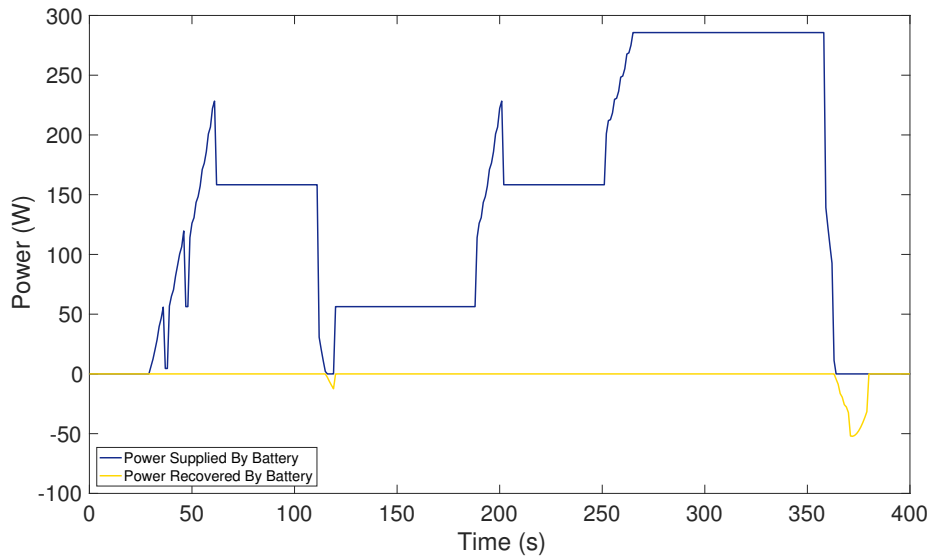


Figure A-3: Battery power

A-1-3 Energy plot

This section provides the total energy consumed for entire distance travelled by an E-bike which is further shown in Figure A-4.

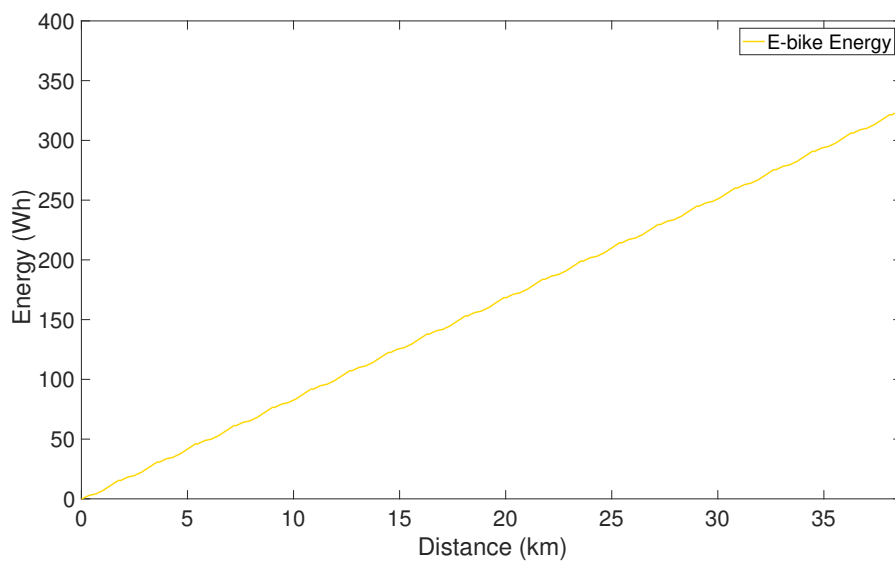


Figure A-4: Energy plot for E-bike.

A-1-4 SOC of E-bike battery plot

This section provides the SOC of E-bike battery for entire distance travelled, which is further shown in Figure A-5.

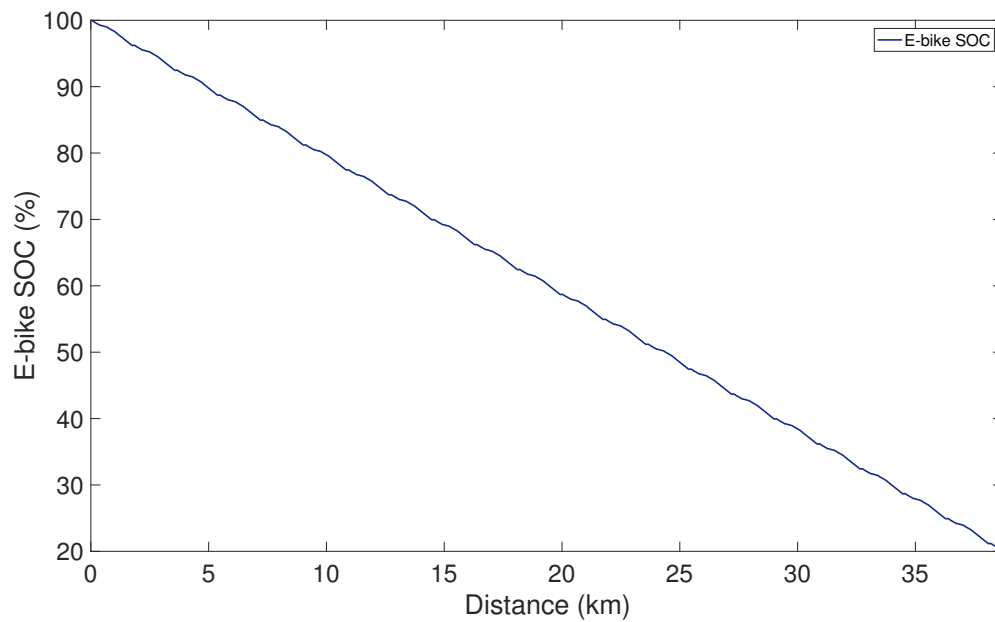


Figure A-5: SOC plot for E-bike.

Appendix B

Sun Position Calculator

Firstly, it is advantageous to calculate the time elapsed since Greenwich noon D for determining the position of sun, which is shown in equation B-1, where JD is defined as Julian date which is the number of days from January 1, 4713 BC or November 24 4717 BC in Gregorian calendar [42]. After that, it is needed to calculate the mean longitude of the Sun, q with the help of equation B-2 [42]. But this q has to be corrected with mean anomaly, g due to elliptic orbit of the Earth which is given by Equation B-3 [42].

$$D = JD - 2451545, \quad (B-1)$$

$$q = 280.459^\circ + 0.98564736^\circ D, \quad (B-2)$$

$$g = 357.529^\circ + 0.98560028^\circ D, \quad (B-3)$$

Therefore, ecliptic longitude of the sun, λ_s , can be determined with equation B-4, while the latitude, β_s , can be approximated to zero [42].

$$\lambda_s = q + 1.915^\circ \sin g + 0.020^\circ \sin 2g, \quad (B-4)$$

It is also beneficial to approximate the distance between Sun and Earth in astronomical units for evaluating radiation which is given by equation B-5 [42].

$$R = 1.00014 - 0.01671 \cos g - 0.00014 \cos 2g, \quad (B-5)$$

When the system is on Earth it is more appropriate to convert the above mentioned result in equatorial coordinates which can be done by tilting the ecliptic plane with angle ε , given in equation B-6 [42].

$$\varepsilon = 23.429^\circ - 0.00000036^\circ D, \quad (B-6)$$

Now, for calculating position of the sun with respect to the position of the observer it is required to determine the ‘local mean sidereal time’, $LMST$, which is defined as function of

the Greenwich mean sidereal time, $GMST$, where Greenwich is taken as reference and it is given by equation B-7 (in degrees) [42].

$$\theta_L = GMST \frac{15^\circ}{\text{hour}} + \lambda_0, \quad (\text{B-7})$$

where:

$GMST$ is the $18.697374558 \cdot h + 24.06570982441908 \cdot h \cdot D + 0.000026 \cdot h \cdot T^2$

λ_0 is the longitude of the observer

T is the number of centuries since Greenwich noon = $\frac{D}{36525}$

h is the hour angle

Therefore, the specific position of the sun for a particular date and time, according to the observer location with latitude, ϕ_0 , and longitude, λ_0 , can be calculated by implementing equations B-8 and B-9 respectively [42].

$$\sin a_s = \cos \phi_0 \cdot \cos \theta_L \cos \lambda_s + (\cos \phi_0 \cdot \sin \theta_L \cdot \cos \varepsilon + \sin \phi_0 \cdot \sin \varepsilon) \sin \lambda_s, \quad (\text{B-8})$$

$$\tan A_s = \frac{-\sin \theta_L \cdot \cos \lambda_s + \cos \theta_L \cdot \cos \varepsilon \cdot \sin \lambda_s}{-\sin \phi_0 \cdot \cos \theta_L \cos \lambda_s - (\sin \phi_0 \cdot \sin \theta_L \cdot \cos \varepsilon - \cos \phi_0 \cdot \sin \varepsilon) \cdot \sin \lambda_s}, \quad (\text{B-9})$$

where:

a_s is the Solar Altitude

A_s is the Solar Azimuth

ϕ_0 is the Latitude

θ_L is the local mean sidereal time (LMST)

λ_s is the Latitude of the sun in ecliptic coordinates

ε is the Axial tilt of the earth

Appendix C

PV System Meteorological Data

C-1 Direct & diffuse component

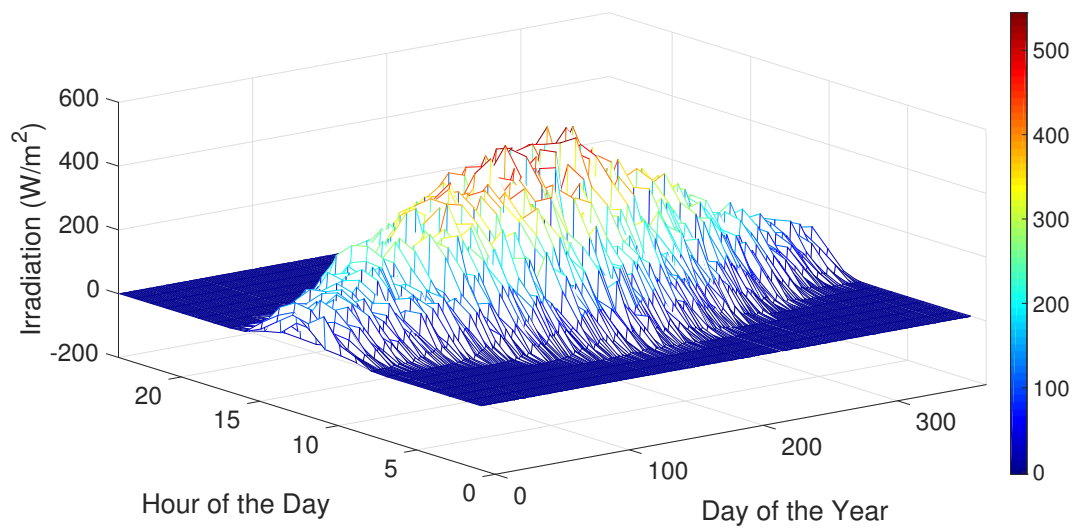


Figure C-1: DHI.

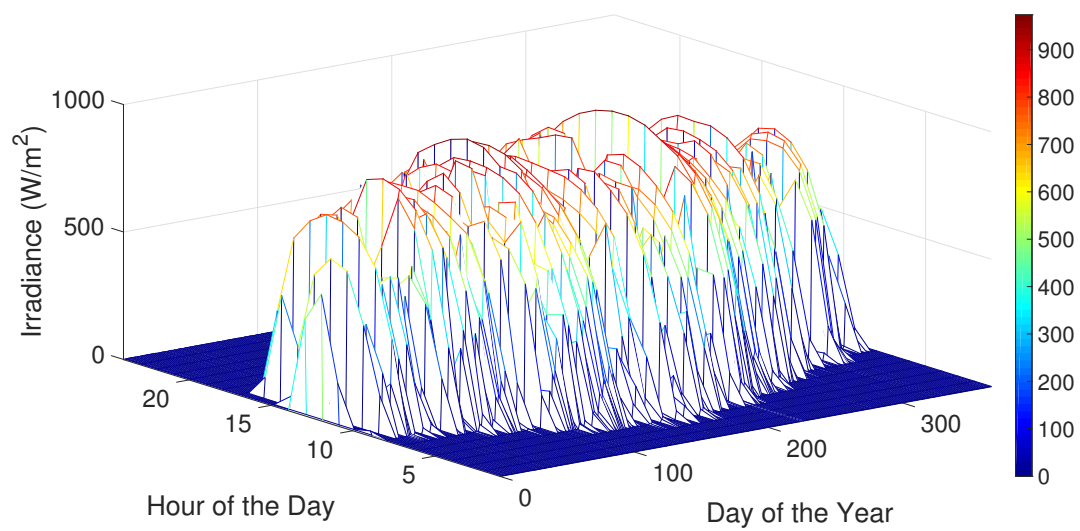


Figure C-2: DNI.

C-2 Ambient temperature

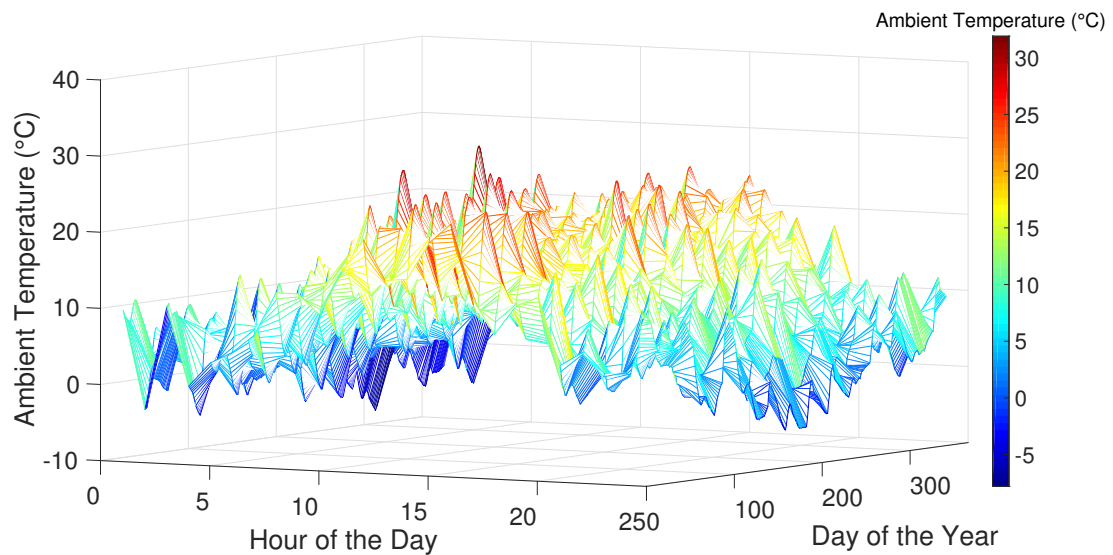


Figure C-3: Ambient temperature.

C-3 Ground temperature

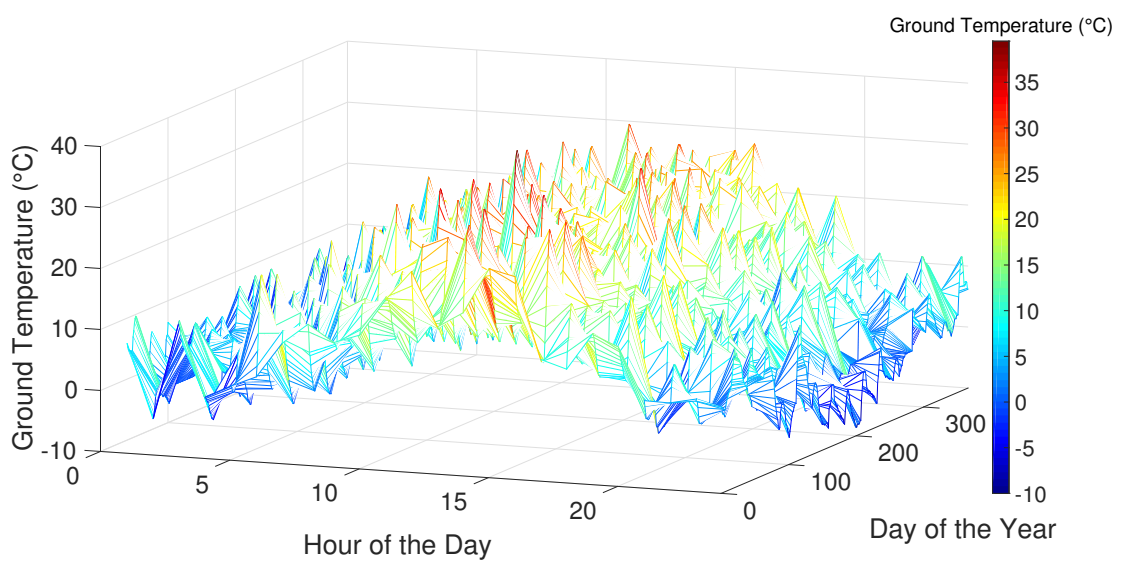


Figure C-4: Ground temperature.

C-4 Wind data

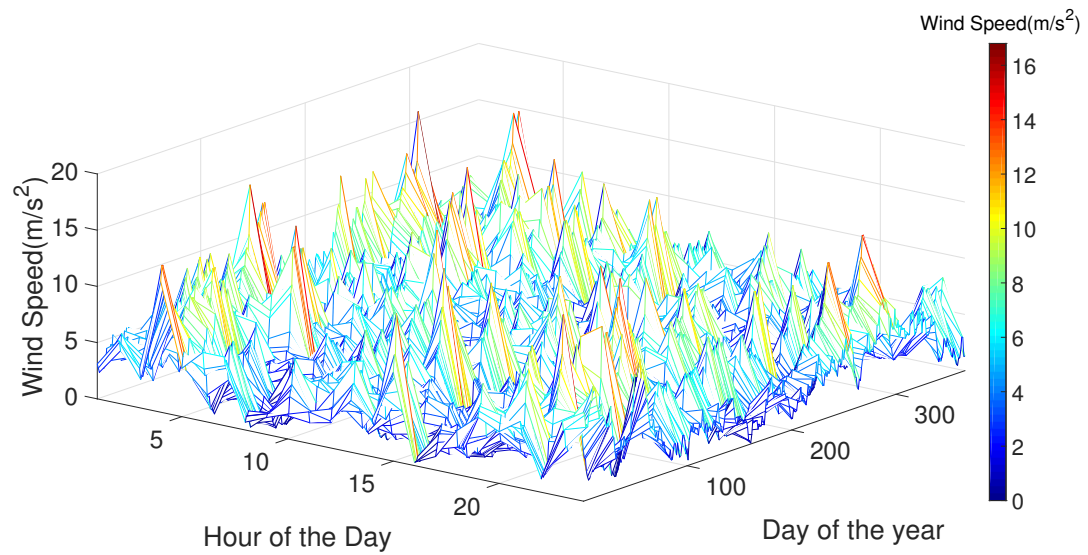


Figure C-5: Wind speed.

Appendix D

PV Modules

D-1 External parameters of the Simulated PV module

Table D-1: Simulated PV module parameters

Parameter		Description
Material		Poly-crystalline Silicon
<i>STC : 1000W/m², 25°C, AM 1.5</i>		
Peak Power (P_{mpp})	Wp	270
Peak Power Voltage (V_{mpp})	V	40
Peak Power Current (I_{mpp})	A	6.75
Open Circuit Voltage (V_{oc})	V	49
Short Circuit Current (I_{sc})	A	7.4
<i>Temperature Coefficients</i>		
Open Circuit Voltage	%/°C	-.32
Short Circuit Current	%/°C	0.057
Maximum Power	%/°C	-.48

D-2 Multi crystalline SunPower module



SunPower® Performance Series | P17

SunPower® Performance Series panels are designed to deliver consistent performance for many decades in commercial applications.

Increased Energy Production

The Performance Series modules deliver more energy due to higher performance in row-to-row shading, enabling closer row spacing and more energy from the same area. The unique parallel circuitry limits shading loss to the shaded area only instead of much larger sections of energy loss in conventional panels.¹

Design Tip: When modeling P-Series energy performance be sure to use linear shading losses. For more detailed guidance please visit <https://us.sunpower.com/sites/sunpower/files/media-library/manuals/mn-sunpower-p-series-modeling-guide.pdf>

Higher Efficiency

The Performance Series design minimizes white space between solar cells, eliminates reflective metal lines on the cells, and lowers electrical resistance between cells, increasing efficiency compared to Conventional Commercial Panels.²

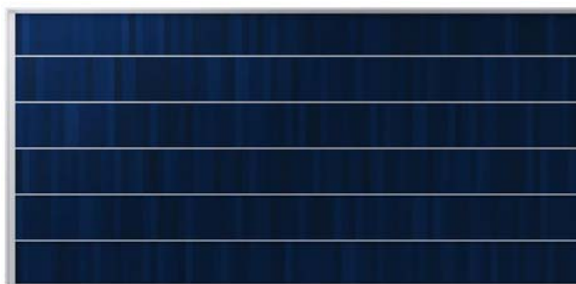
High Reliability

Innovative panel design uses flexible and redundant electrical connections between solar cells to deliver enhanced reliability.

SunPower Quality

Tested to SunPower's rigorous quality standards, and backed by the industry's best Combined Power and Product Warranty.

High Performance & Excellent Reliability

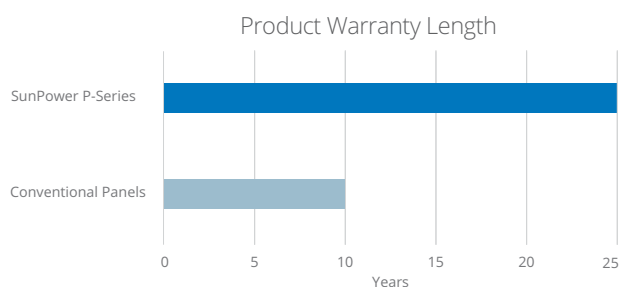


SPR-P17-350-COM

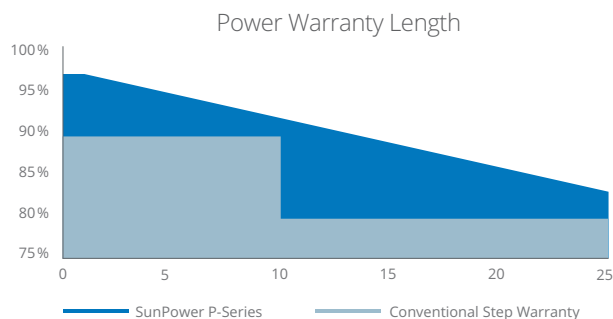


25 Year Combined Warranty

Protect your investment



SunPower provides the best 25 year Combined Power and Product warranty in the industry, providing coverage regardless of product defect or power loss.



SunPower's Performance Series is warranted to produce more than 97% power in the first year, then declining by 0.6% per year, ending at 82.6% power after 25 years.

SunPower® Performance Series | P17

Electrical Data, STC ³					
Model	SPR-P17-350-COM	SPR-P17-345-COM	SPR-P17-340-COM	SPR-P17-335-COM	SPR-P17-330-COM
Nominal Power (P _{nom})	350 W	345 W	340 W	335 W	330 W
Power Tolerance	+5/-0%	+5/-0%	+5/-0%	+5/-0%	+5/-0%
Efficiency	17.0%	16.7%	16.5%	16.2%	16.0%
Rated Voltage (V _{mpp})	43.1 V	42.8 V	42.5 V	42.2 V	41.9 V
Rated Current (I _{mpp})	8.12 A	8.06 A	8.00 A	7.94 A	7.88 A
Open-Circuit Voltage (V _{oc})	51.7 V	51.5 V	51.3 V	51.1 V	50.9 V
Short-Circuit Current (I _{sc})	8.65 A	8.57 A	8.52 A	8.51 A	8.47 A
Power Temp. Coef.	-0.37% / °C				
Voltage Temp. Coef.	-175.8 mV / °C	-175.1 mV / °C	-174.4 mV / °C	-173.7 mV / °C	-173.1 mV / °C
Current Temp. Coef.	3.6 mA / °C				
Maximum System Voltage	1000 V UL & 1000 V IEC				
Maximum Series Fuse	15 A				

Operating Condition And Mechanical Data	
Temperature	-40° F to +185° F (-40° C to +85° C)
Impact Resistance	1 inch (25 mm) diameter hail at 52 mph (23 m/s)
Appearance	Class B
Solar Cells	Multicrystalline cells
Tempered Glass	High-transmission tempered anti-reflective
Junction Box	IP-65, 23.6 in (600 mm) cables / MC4 compatible
Weight	51 lbs (23.1 kg)
Max. Load	Wind: 50 psf, 2400 Pa, 245 kg/m ² front & back Snow: 112 psf, 5400 Pa, 550 kg/m ² front
Frame	Class 2 silver anodized; stacking pins

Tests And Certifications	
Standard Tests ⁴	UL1703 (Type 2 Fire Rating), IEC 61215, IEC 61730
Quality Certs	ISO 9001:2008, ISO 14001:2004
EHS Compliance	OHSAS 18001:2007, PV Cycle
Ammonia Test	IEC 62716
Desert Test	10.1109/PVSC.2013.6744437
Salt Spray Test	IEC 61701 (maximum severity)
PID Test	Potential-Induced Degradation free: 1000 V
Available Listings	UL, CEC, TUV, FSEC

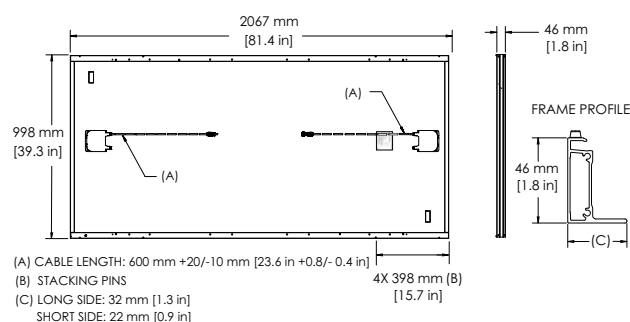
REFERENCES:

1 Actual results depend on module orientation and time of day. Independent Shade Study by CFV Laboratory.

2 Compared to a Conventional Commercial Panel (310 W, 16% efficient, approx. 1.93 m²).

3 Measured at Standard Test Conditions (STC): irradiance of 1000 W/m², AM 1.5, and cell temperature 25° C.

4 Type 2 fire rating per UL1703:2013, Class C fire rating per UL1703:2002 and IEC 61730.



Read safety and installation instructions before using this product.

sunpower.com

Document # 516031 Rev H /LTR_US

D-3 Mono crystalline SunPower module



SunPower® X-Series Commercial Solar Panels | X21-345-COM

Helix™ Roof Compatible Modules

Factory-installed clips enable tool-free panel installation, decreasing installation time and minimizing business disruption.¹

More than 21% Efficiency

Captures more sunlight and generates more power than conventional panels.

Maximum Performance

Designed to perform in demanding real-world conditions of high temperatures, partial shade from overhead wires, and low light.^{2,3,5}

Commercial Grade

Intended for commercial sites where maximum energy production is critical.



Maxeon® Solar Cells: Fundamentally better

Engineered for performance, designed for reliability.

Engineered for Peace of Mind

Designed to deliver consistent, trouble-free energy over a very long lifetime.^{4,5}

Designed for Reliability

The SunPower Maxis Solar Cell is the only cell built on a solid copper foundation. Virtually impervious to the corrosion and cracking that degrade conventional panels.⁴

Same excellent durability as E-Series panels.

#1 Rank in Fraunhofer durability test.¹⁰

100% power maintained in Atlas 25+ comprehensive durability test.¹¹

High Performance & Excellent Reliability



SPR-X21-345-COM



Highest Efficiency⁶

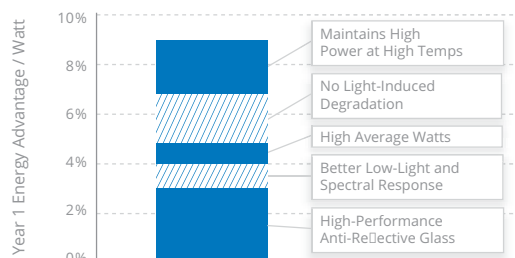
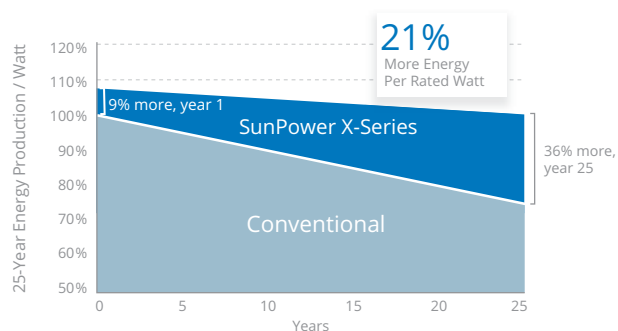
Generate more energy per square foot

X-Series commercial panels convert more sunlight to electricity by producing 38% more power per panel² and 70% more energy per square foot over 25 years.^{2,3,4}

Highest Energy Production⁷

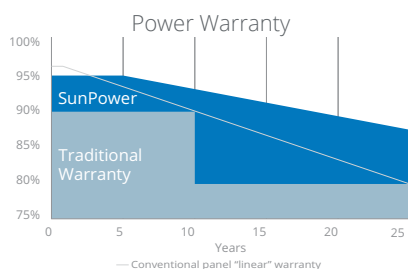
Produce more energy per rated watt

More energy to power your operations. High year-one performance delivers 8–10% more energy per rated watt.³ This advantage increases over time, producing 21% more energy over the first 25 years to meet your needs.⁴

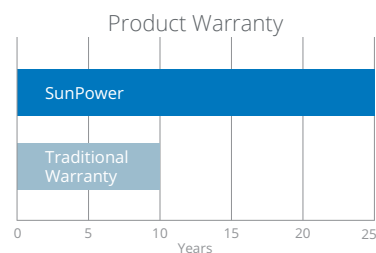


SunPower® X-Series Commercial Solar Panels | X21-345-COM

SunPower Offers The Best Combined Power And Product Warranty



More guaranteed power: 95% for first 5 years,
-0.4%/yr. to year 25⁸



Combined Power and Product defect 25-year coverage⁹

Electrical Data

	SPR-X21-345-COM	SPR-X20-327-COM
Nominal Power (P _{nom}) ¹²	345 W	327 W
Power Tolerance	+5/-3%	+5/-3%
Avg. Panel Efficiency ¹³	21.5%	20.3%
Rated Voltage (V _{mpp})	57.3 V	57.3 V
Rated Current (I _{mpp})	6.02 A	5.71 A
Open-Circuit Voltage (V _{oc})	68.2 V	67.6 V
Short-Circuit Current (I _{sc})	6.39 A	6.07 A
Max. System Voltage	1000 V UL & 1000 V IEC	
Maximum Series Fuse	15 A	
Power Temp Coef.	-0.29% / °C	
Voltage Temp Coef.	-167.4 mV / °C	
Current Temp Coef.	2.9 mA / °C	

REFERENCES:

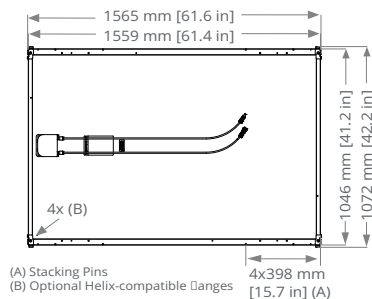
- Helix-compatible modules may not be compatible with other racking systems.
- All comparisons are SPR-X21-345 vs. a representative conventional panel: 250 W, approx. 1.6 m², 15.3% efficiency.
- Typically 8-10% more energy per watt, BEW/DNV Engineering "SunPower Yield Report," Jan 2013.
- SunPower 0.25%/yr degradation vs. 1.0%/yr conv. panel. Campeau, Z. et al. "SunPower Module Degradation Rate," SunPower white paper, Feb 2013; Jordan, Dirk "SunPower Test Report," NREL, Q1-2015.
- "SunPower Module 40-Year Useful Life" SunPower white paper, May 2015. Useful life is 99 out of 100 panels operating at more than 70% of rated power.
- Highest of over 3,200 silicon solar panels, Photon Module Survey, Feb 2014.
- 1% more energy than E-Series panels, 8% more energy than the average of the top 10 panel companies tested in 2012 (151 panels, 102 companies), Photon International, Feb 2013.
- Compared with the top 15 manufacturers. SunPower Warranty Review, May 2015.
- Some restrictions and exclusions may apply. See warranty for details.
- X-Series same as E-Series, 5 of top 8 panel manufacturers tested in 2013 report, 3 additional panels in 2014. Ferrara, C., et al. "Fraunhofer PV Durability Initiative for Solar Modules: Part 2", Photovoltaics International, 2014.
- Compared with the non-stress-tested control panel. X-Series same as E-Series, tested in Atlas 25+ Durability test report, Feb 2013.
- Standard Test Conditions (1000 W/m² irradiance, AM 1.5, 25° C). NREL calibration Standard: SOMS current, LACCS FF and Voltage.
- Based on average of measured power values during production.
- Type 2 fire rating per UL1703:2013, Class C fire rating per UL1703:2002.

Tests And Certifications

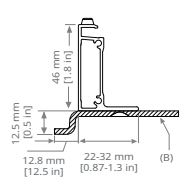
Standard Tests ¹⁴	UL1703 (Type 2 Fire Rating), IEC 61215, IEC 61730
Quality Certs	ISO 9001:2008, ISO 14001:2004
EHS Compliance	RoHS, OHSAS 18001:2007, lead free, REACH SVHC-163, PV Cycle
Ammonia Test	IEC 62716
Desert Test	10.1109/PVSC.2013.6744437
Salt Spray Test	IEC 61701 (maximum severity)
PID Test	Potential-Induced Degradation free: 1000 V ¹⁰
Available Listings	UL, TUV, JET, CSA, CEC

Operating Condition And Mechanical Data

Temperature	-40° F to +185° F (-40° C to +85° C)
Impact Resistance	1 inch (25 mm) diameter hail at 52 mph (23 m/s)
Appearance	Class B
Solar Cells	96 Monocrystalline Maxeon Gen III
Tempered Glass	High-transmission tempered anti-reflective
Junction Box	IP-65, TE (PV4S)
Weight	41 lbs (18.6 kg)
Max. Load	Wind: 50 psf, 2400 Pa, 244 kg/m ² front & back Snow: 112 psf, 5400 Pa, 550 kg/m ² front
Frame	Class 2 silver anodized; stacking pins



FRAME PROFILE



Please read the safety and installation guide.
Clips installed on Helix Roof compatible modules only.
Clips are not removable and may not be compatible with non-Helix-branded racking.

See www.sunpower.com/facts for more reference information.
For more details, see extended datasheet: www.sunpower.com/datasheets.

Document # 505815 Rev B /LTR_US

Appendix E

LIDAR Data Images

Figure E-1, E-3, E-5 & E-7 shows the images at 2.5 m, 5 m, 7.5 m & 10 m height respectively from the ground that has been obtained with the help of LIDAR data. Furthermore, Figure E-2, E-4, E-6 & E-8 shows the LIDAR data images at 2.5 m, 5 m, 7.5 m & 10 m height respectively from the ground that has been obtained with the help of Meteonorm.

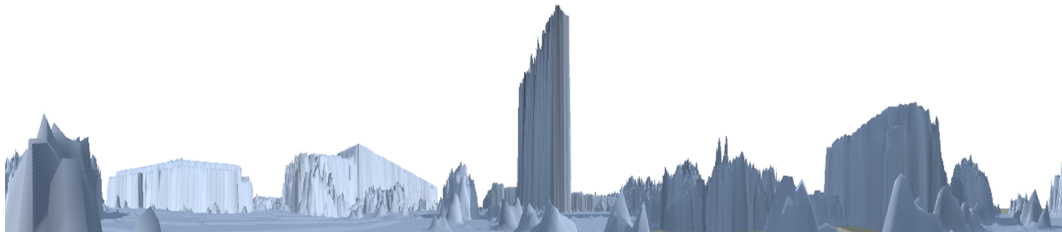


Figure E-1: LIDAR Data Image at 2.5 meters from ground

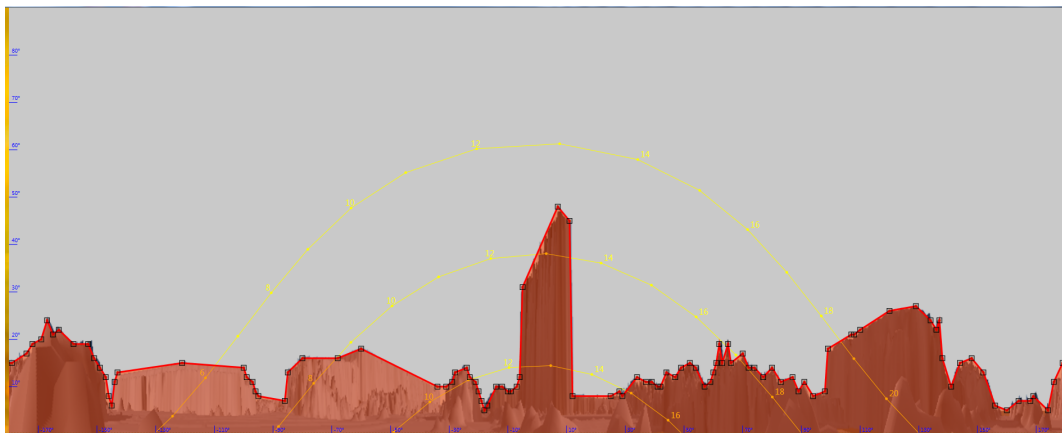


Figure E-2: LIDAR data image at 2.5 meters from ground with customized horizon.

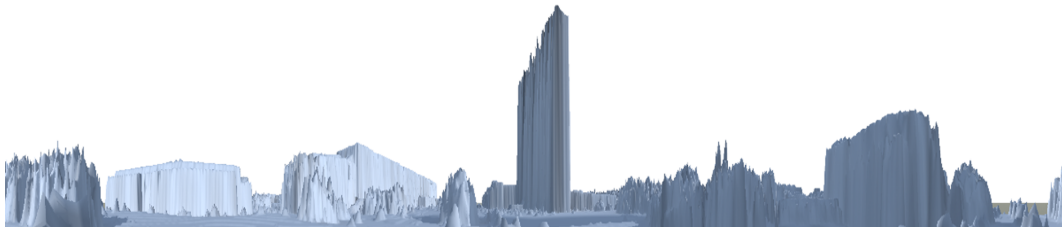


Figure E-3: LIDAR data image at 5 meters from ground.

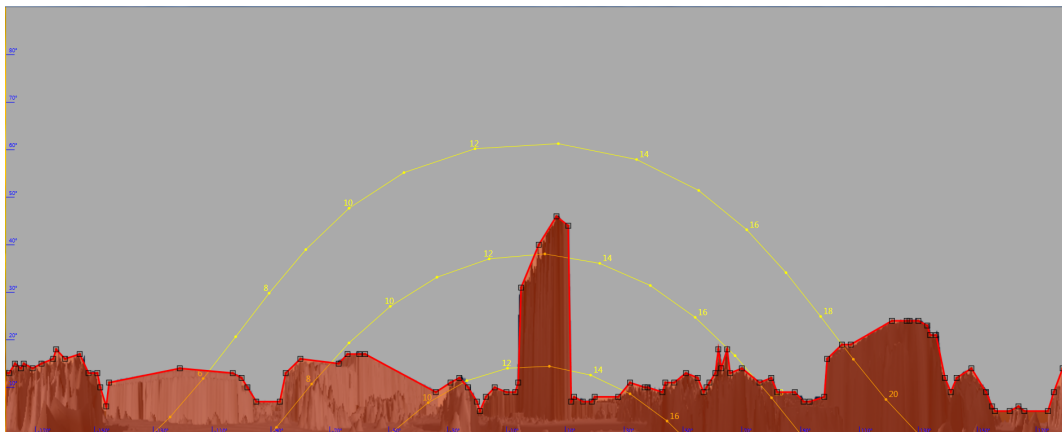


Figure E-4: LIDAR data image at 5 meters from ground with customized horizon.

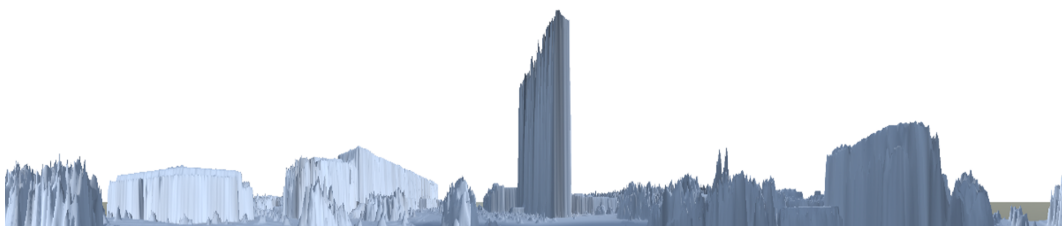


Figure E-5: LIDAR data image at 7.5 meters from ground.

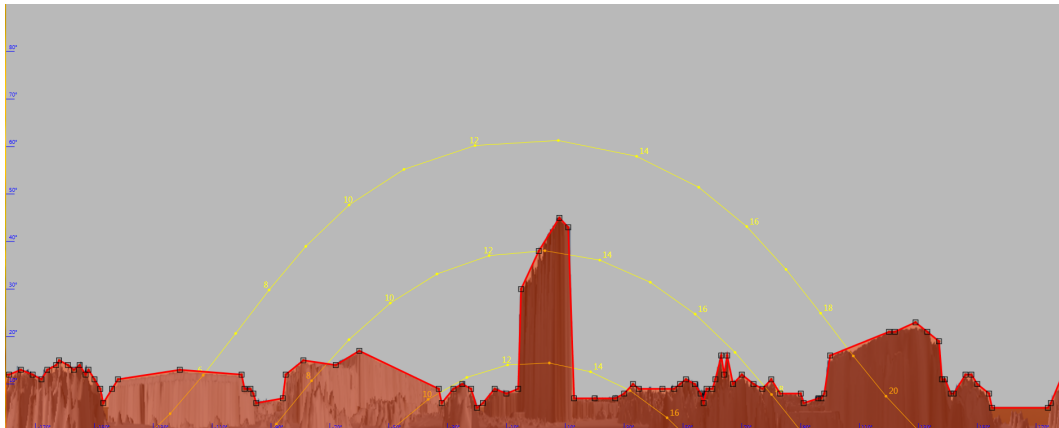


Figure E-6: LIDAR data Image at 7.5 meters from ground with customized horizon.

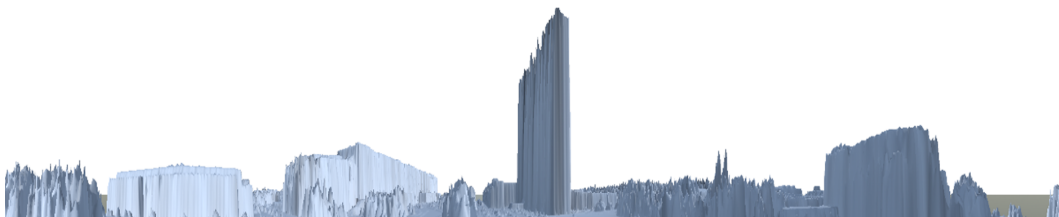


Figure E-7: LIDAR data image at 10 meters from ground.

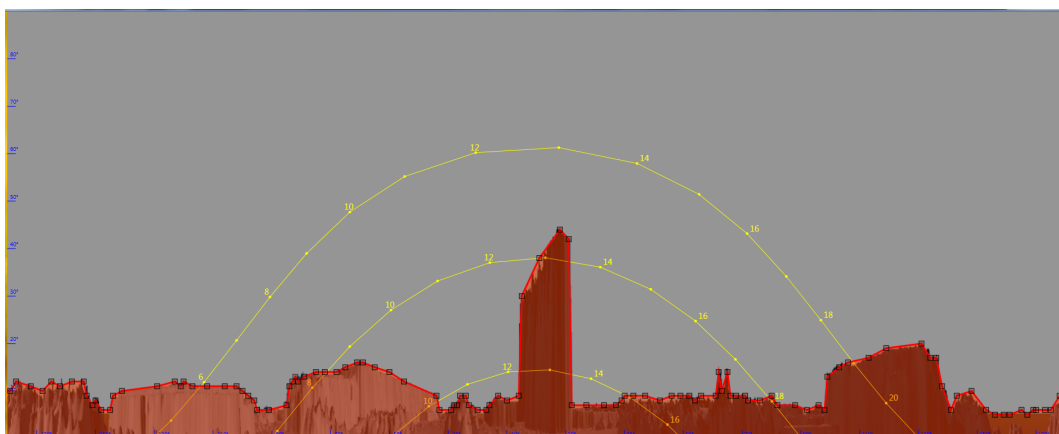


Figure E-8: LIDAR data image at 10 meters from ground with customized horizon.

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