Department of Mechanical and Aerospace Engineering

Project

Inductive Charging on the go for Ev´s driving on a Highway.

Feasibility to produce the energy requirements coming from Solar Energy installed alongside the Highway.

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Abstract

As a principal aspect towards a green society, a change of the current way of transport, based in fossil combustion engines must be made. The European Union as well as, the Scottish and UK Government have been set an ambitious target to reduce the levels of pollution coming from the transport for been achieved in the coming years. Two alternatives have been planned to be developed from now on. First, to invest in a better, cleaner and more reachable public transport system, restricting the use of private cars into the city centres, as it has been already deployed in cities around the world such as London, Madrid or Oslo. Second, to promote and subside the use of electric cars instead of the internal combustion engines and look for new and faster ways to charge the electric cars, instead of the slower and fewer existing alternatives nowadays. Assessing other alternatives that the one that suppose spread all over the place electric charging points.

This project aims to investigate the opportunity for an innovative way of road electrification, charging the electrics vehicles; meanwhile they are driven in a road. Also, the energy requirements with real traffic data for a real highway is investigated. Showing which per cent of these energy requirements could be produced for renewables energy sources alongside the road, in this project a photovoltaic mathematical model has been developed to shows the energy output for any given location around the world, putting into practice a real case in the United Kingdom. The investigations in this project are designed to examine the range and size that the PV installation would have if it has to give all the energy requirements that the electric cars would have for a given road, and examination for an average PV panels, how much energy the PV installation will produce in excess of least throughout the year.

The outcome of this study shows the feasibility of a contactless power system installed along the M8 highway between the United Kingdom cities of Glasgow and Edinburgh. Considering the average electric car consumption given for a mathematical model developed in this project, taking real traffic data from ten different massive traffic highways around UK, and showing the energy produce per month for a PV installation installed alongside the M8. The results demonstrate that the feasibility of this road electrification is possible shortly, and alternatives ways of producing renewable energy for the electric car's consumption must be considered, most especially in sparsely sunny countries as the UK.

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advice, thank you motivate me to jeopardise and take that crucial decision that I took, came to Glasgow to do an MSc in the best possible University.

Nomenclature

Mt CO_2e

(CWD): Charging-while-driving

Lat: Latitude

Lng: Longitude

Day of the Week: DoW

The month of the Year: MoY

Day of the Year: Doy

Hour Angle: HA

Solar noon: SN

Sunrise Time: ST

Sunset Time: St

Sunlight duration: Sd

Solar declination: ɣ

Equation of time: EoT

Solar Time: Sm

Hour Angle: w

β_s: Solar Altitude

α_s: Solar Zenith Angle

α_f: Surface Solar-Azimuth

β_f: Optimal angle of the PV module

i_b: Surface Solar Incidence Angle

IBN: Beam portion of solar radiation, normal to the rays

A: Apparent Extraterrestial Flux

$\mathrm{m} =$ Air Mass ratio

$\mathrm{k} =$ Optical Depth

I_{BS}: Direct-Beam radiation striking a tilt PV Panel

$\theta =$ Angle of incidence of an equator facing surface in degrees

I_D: Diffuse radiation striking a tilt PV Panel

C: Diffuse Factor

I_R: Reflected radiation striking a tilt PV Panel

Gr: Ground reflected value

I_T: Total Hourly Irradiance (W/m^2)

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1. Introduction

1.1. Background and Problem definition

As a principal aspect towards a green society, a change of the current way of transport, based in fossil combustion engines must be made. Over the past few years, many projects have been done all over Europe in order to start initiatives of transport changing, such as car sharing, better, faster and cheaper public transport facilities and most especially the electric car has been promoted for every single European county government. The European Union as well as, the Scottish and UK Government have been set an ambitious target to reduce the levels of pollution due to the transport for been achieved in the coming years.

In order to achieve a lower pollution emissions scenario in the coming years, all the harmful gases for the human health, such as NO_X, $S0_2$, C0 and the greenhouse gases such as $C0_2$, must be cut it down. Beyond these objectives, a change in the current way of transport up to a sustainable transport system will bring as a result in the development of the manufacturer vehicle market sector, increasing the research to get better, cheaper and more environmentally friendly vehicles, increasing as well the employment in the sector.

To reach out a lower pollution emissions scenario The European Union decarbonisation goal has been fixed by the 2030 climate & energy framework whit a greenhouse gas emissions reduction of 40% cuts regarding the greenhouse gas emissions levels accounted in 1990 (Climate Action - European Commission, 2019). Enabling the EU to move towards a low-carbon economy implement its commitments under the Paris Agreement. Looking into a long-term, the EU goal has set itself a greenhouse gas reduction of 80-95%, compared to the 1990 emissions levels. (Energy - European

Commission, 2019). Therefore, the electrification of the transport sector is essential to accomplish the European Union goals of decarbonization and energy security, as it accounts for 27% (1226 Mt CO_2e), *(“Greenhouse gas emissions from transport,” n.d.)*, of all $C0_2$ emissions in Europe. Of which, 72% of the total transport $C0_2$ emissions are caused by road transport as *Figure 1* shows. Being the cars the major contributor of greenhouse gas emission, with 12% (535.8 Mt CO_2e) of the total annual emissions, one and half times more than the emissions produced by Business, Waste Management and Public Sector Buildings together in whole a year.

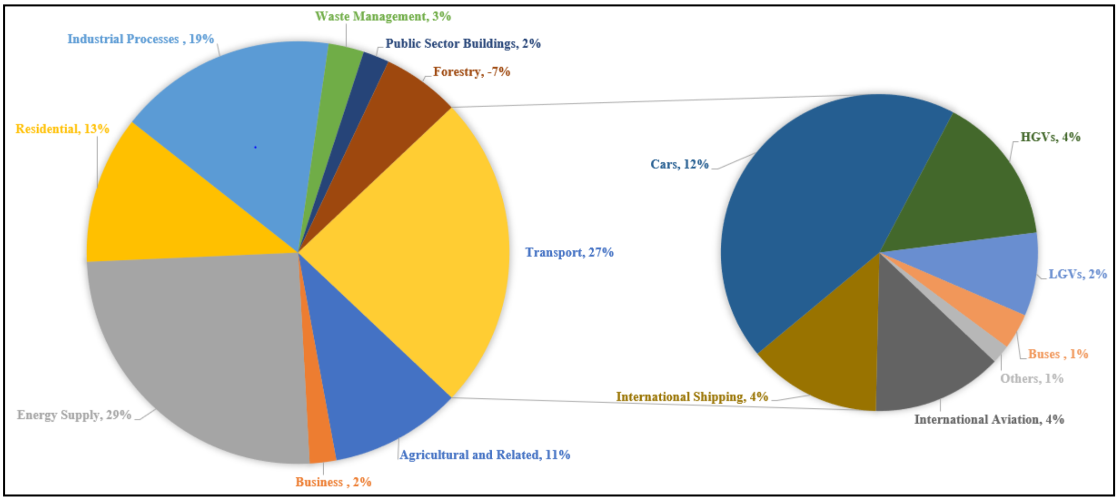


Figure 1: EU greenhouse emissions by sector. Specifying in the Transport Sector (European Environment Agency, 2019).

The electrification of transport not only will involve a cut down on the greenhouse emissions, if not that it would bring a reduction of the emissions of the following air pollutants: Carbon Monoxide (C0), non-methane volatile organic compounds (NMVOCs), Sulphur oxides (S0x), Nitrogen Oxides (NOx) and particulate matter emissions such as $PM_{2.5}$ and PM_{10}. Even when the emissions of the air pollutants due to the transport has been reducing since 1990 (“Emissions of air pollutants from transport,” 2016), the Road Transport is still nowadays the more prominent contributor for every single air pollutant mentioned above, as it is shown in the following graph:

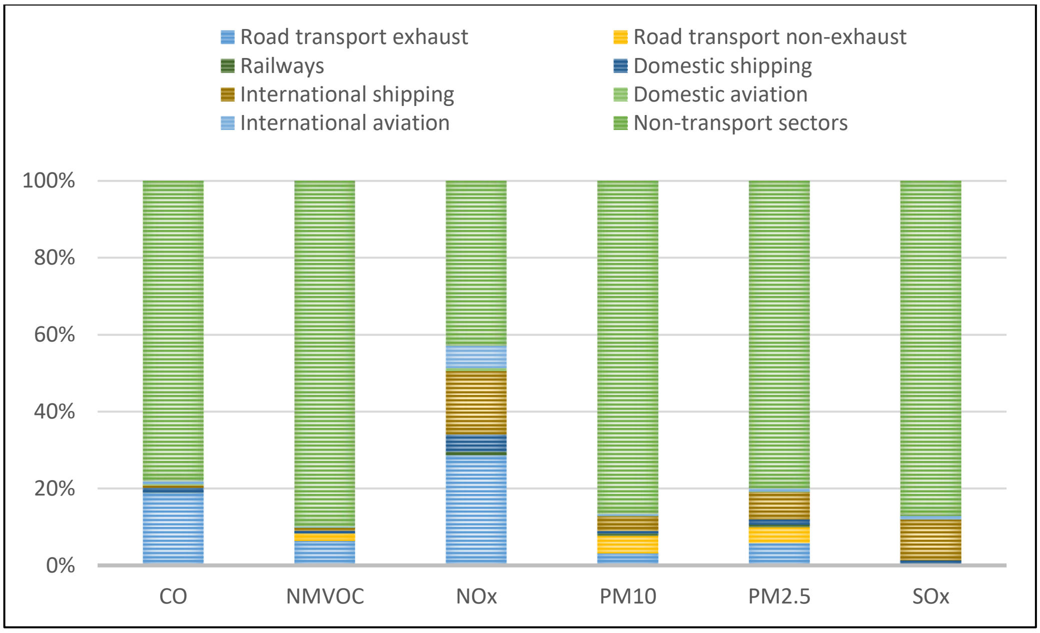


Figure 2: Contribution of the Transport sector to total emissions of the primary air pollutants in the EU ("Emissions of air pollutants from transport," 2016)

As the figure above shows, the Road Transport Exhaust (Particles released into the air when the vehicles are on used due to the combustion of fossil fuels) and the Road non-exhaust (Refers to particles released into the air from brake wear, tyre wear, road surface wear and resuspension of road dust during on-road vehicle usage) are the most significant contributors of every single air pollutant. C0 (18,84%), NMVOC (8,29%), NOx (28,65%), PM_{10} (7,71%), $PM_{2.5}$ (9.97%) except the S0x where the largest contributor is the International Aviation (5.75%).

At the same time, the UK targets for a transition to lower pollution emissions future are also ambitious, fixing the reduction in greenhouse gases emissions by 57% in 2030, and by 80% in 2050 compared to the 1990 levels. As well as in the rest of Europe the transport sector stage as the massive contributor for the air pollutant emissions and the greenhouse gas emissions, contributing by 27% (125.9 Mt CO_2e) of the total $C0_2$

emissions on 2017 and having even further relevance the cars $C0_2$ emissions 55% of the total, as can be seen in Figure 3.

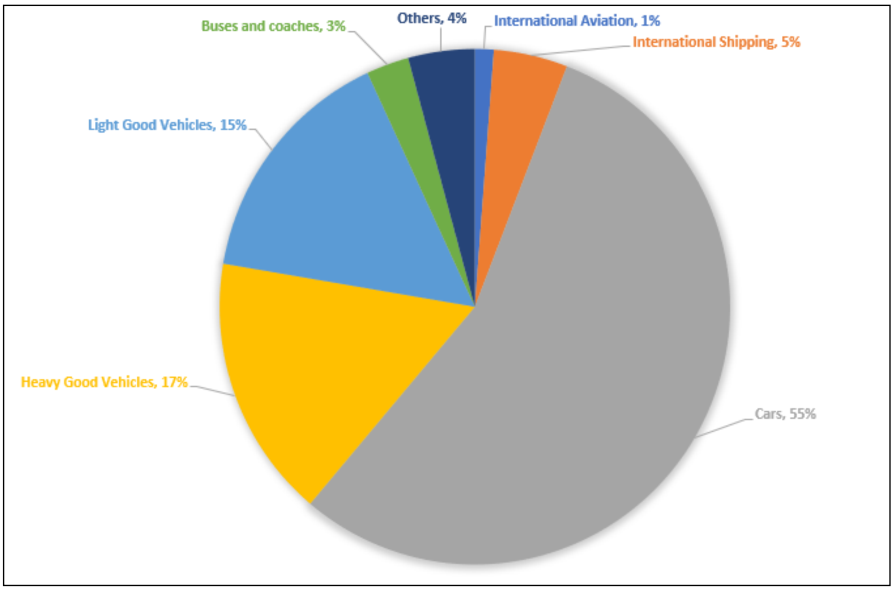


Figure 3: UK Transport C02 emissions 2017. (Department for Business, Provisional UK greenhouse gas emissions national statistics)

In the specific case of Scotland as a case of study (8. Case of Studies), the transport sector accounts for even a higher percentage than in the rest of the UK, 37% (14.4 Mt CO_2e) of the total $C0_2$ emissions on 2017. It is again the cars the most significant $C0_2$ emissions contributor accounting with 42% of the total transport emissions and in the second place the international shipping industry with 16% of the total transport emissions, as being Scotland in a strategic geolocational for this economic activity as it is shown in ***Error! Reference source not found.***.

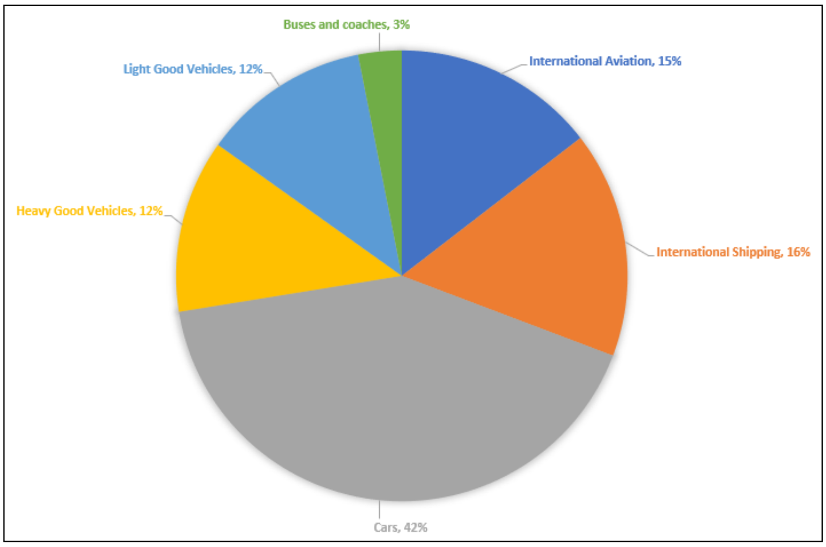


Figure 4: Scottish Transport C02 emissions 2016. ("Scottish greenhouse gas emissions 2016 - gov.scot," 2016.)

Therefore, as the above graphs show (Figure 1, Figure 2, Figure 3, Figure 4) the main contributor to the annual greenhouse emission in Europe, the UK and Scotland is the transport sector. They are outstanding road transport C02 emissions. For this reason, to become a decarbonised and less air pollutant future society, the electrification of transport plays a crucial role. As it has been stated as the transport emission reduction targets for the EU, UK and Scotland displayed below.

EU (Anonymous, 2016)	Scotland (1)
20% reduction from 2008 levels by 2030	37% reduction from 2008 levels by 2032
60% reduction from 1990 levels by 2050	Will be free from harmful tailpipe emissions from land transport

Table 1: C02 reductions targets in the transport sector by the Governments of EU, UK and Scotland

(1) (“Climate Change Plan: Third Report on Proposals and Policies 2018-2032: Summary Document,” n.d.)

Consequently, the problem to achieve is the gradual reduction of the $C0_2$ and air pollutant emissions levels coming from the transport sector, focusing on road transport emissions. For that purpose, the electrification of transport is one of the most fundamental factors to achieve that goal. Requiring the integration of vehicles into a reliable and affordable as well as ease of use infrastructure for the supply of energy, by static or dynamic (conductive or wireless) charging, battery swapping or hydrogen tank filling. It goes without saying, of course, that this integration it would not be possible if Renewable Energy Sources provide the surplus of electricity required to power all the new electric vehicles coming into the market.

1.2. Aim and Motivation

This thesis aim is to develop a method for electrification of the road system, with inductive charging system on the go, and demonstrate the application of the method to an example case.

Electrification of the road, more precisely focusing on the Highways, through inductive charging on the go is going to be analysed. Electrifying the road for supply on-go energy to all range of vehicles such as cars, buses and trucks is proven as achievable, although in this thesis the core of the modelling is based on the cars, due to the cars are the most significant contributor to the air pollution and greenhouse emissions gases. The second objective is providing all the energy demand nearly coming from renewable energy sources. The available renewable sources carefully to the road will be analysed. Given the impossibility to fulfil all the demand coming from renewable energy sources, the grid connection resolution would be considered as an ultimate resort.

The primary motivation of this thesis is to investigate the feasibility of the approach over various timescales.

An electrification of the road systems, will carry on a reduction of the battery size of the electric cars. Wiith all that implies, less raw materials on the cars assembly line such as cooper and rare earths, as well as, a reduction on the price of the electric cars. As being the battery one of the most expensive elements of the car. Also, it would not be necessary to fill out the cities and roads of static electric charging points, leading to a better cities design.

1.3. Project Objective and Scope

The objective of this project is to study the feasibility of the electrification of a highway, throughout the inductive charging on the go, alongside the length of the highway. The vehicles of study are the utility cars. The thesis also covers the feasibility to produce the energy requirements for the cars driven on the highways, given by renewable energy sources strictly to the highway. In this thesis, a methodology to calculate the energy resources coming from the Sun locally and the energy power output that could be produced daily from a given world location is analysed. The focus of the project is to analyse the energy demand that a specific highway would have (in any given location of the world) if one of traffic lane for each of the direction is electrified by charging-while-driving (CWD) system, by the vehicles driving on it. The project scope will analyse the energy requirements for all the vehicles driving on the highway for an average year, as well as how many energy resources would be needed in order to provide all the energy requirements for any specific locations all over the world. To show the feasibility of the thesis, one case of study has been developed. Any single location of the world has different Sun Irradiance value throughout the year, and also different traffic flow rates, but to follow a similar pattern, on the thesis has been considered the annual traffic flow data from the UK government as an example to be extrapolated to different locations on the world. Finally in the conclusion section, an in-depth analysis is it made in order to stipulate if the electrification on the road, producing all the energy requirements coming from Photovoltaic Installations alongside the Highway it feasible all over the world. Or just as one might expect, in the places of the world where most irradiance coming from the Sun is received over the course of a year.

1.4. Methodology

To fulfil the objective of this report, numerous steps have been taken. Firstly, a literature review was done in order to get knowledge of the field and see if a similar project has been done all around the world. Once the similar project such as **Error! Reference source not found.** and **Error! Reference source not found.** has been analysed, the following steps have been followed:

1. Power Consumption Analysis: Where a set of factors that will take relative importance in order to get the average power consumption per car have been analysed. Also, factors that have not been considered but also have an essential relation to getting power consumption are analysed.
2. Energy Consumption Scenarios: A study of the current electric vehicles sector in the UK has been analysed. To this effect, the most common electric vehicles sold last year (2018) in the UK has been displayed, and a mathematical simulation to get the final power consumption rates for a different driven condition are displayed. I am these extrapolate to the rest of the case of studies analysed. Therefore, a different future scenario is also examined. Then a final energy consumptions results are provided in (km. kWh, mi. kWh).

3. Total Energy Consumption: For a given Highway length and taking the traffic flow data to form the UK highways. A Total Energy consumption requirement is displayed depending on the different scenarios analysed before.
4. Inductive Power Transfer Design: An analysis of the structure needed to design a contactless power transfer highway is has been developed. Also, the designs factors are analysed one by one, in order to know how much energy requirements would be needed for every single electrified highway length.
5. Analysed and select the most reliable on-road charging technology (Conductive or Inductive).
6. Energy supply by Renewable Energy Sources alongside the highway: A mathematical model to get the hourly, daily, monthly and annual global solar irradiance (kW/m^2) for any input location point of the world, has been developed.
7. Energy output for a Solar Photovoltaic Installation: Taking the solar irradiance data for any given location. A set of equations have been followed to get the hourly power output for a given model PV panels.
8. Case of studies: the United Kingdom, most specifically in the highway that connect the two biggest cities in Scotland, the M8 between Glasgow and Edinburgh, being 40 miles highway long.
9. They are identifying the match between the energy requirements coming from the electric cars driving along the electrified highway, and the energy supply is given from the Photovoltaic Installations alongside the Highways. How much PV panels would be needed to provide all the energy requirements? Is it feasible? If not, how much energy match supply would be throughout the year for an average PV panel?

2. Literature Review

2.1. Introduction

This section reviews the various literature that has been covered to study the principles of on-road charging electric vehicles and give a background of the technology. An understanding of the structure and design needed for the system. Also, a review of the different existing technologies available in the markets are presented (Inductive and Conductive). Also, some of the successful projects that have been already made around of the world are identified, as well as the companies currently working on the development and establishment of this technology in a real case of study. In the end, an analysis of the technical barriers to uptake are explained, and a future improvement that this technology could have in the coming years are presented as well.

2.2. Electric Road Systems (ERS)

The Electric Road Systems are defined as road supporting conductive or inductive power transfer system (PTS) to the vehicles from the roads in where they are driving on. The power transfer system could be based on different technologies transferring the power from the road to the vehicle from above, from the side, or from under the vehicle. The technology for transferring the power from the above it has already existed since almost one century, the most known example are the city trams, the trolleybuses or more recently the Heavy Good Vehicles (HGV) such as the hybrid trucks powered via overhead lines in the publics Autobahns in Germany ("Germany Open Its First eHighway System for Trucks," 2019), Figure 5.

Figure 5: Electrified eHighway for trucks developed by Siemens in Germany

However, such as idea is suitable for the HGV transport segment, but it is unable to carry out in the standard traffic road system that encompasses the passenger's vehicles, just because the collector needed for transferring the power from the overhead line to the vehicles would be extremely long. Transmitting electricity from the side of the road would cause danger to the vehicles driving on the road as well as would have a more environmental impact than any other solution. Consequently, the most suitable solution to transfer the energy from the road to the vehicle is from below the car. One of the most advantages that this system has is that it could be extrapolated either to passengers' cars than for HGV, buses or any other electric vehicle. Therefore, the infrastructure and design needed would be shared.

2.3. Energy transfer technologies solutions

Electric vehicles (EV´s) can be charged by Power Transfer (PT) systems while driving. These systems can be installed alongside an existing road. Multiple papers have already studied the implementation of such contactless power transfer systems, such as (Stamati and Bauer, 2013), ("Prospects for Electrification of Road Freight - IEEE Journals & Magazine," 2017), (Connolly, 2017). Although primarily, there are two different ways to transfer the energy from the electrified road to the vehicles, these are conductive and inductive charging.

An electrified road system is already feasible for railroad applications. Huge investment on-road transportation will lead to the deployment of the physical structure that is needed to implement these systems. On the other hand, if these systems are implemented in a vast scale, it will have a significant advantages such as a cut down in the air pollution levels as well as the greenhouse emissions gases, noise reduction. In addition it has the potential to reduce the vehicle maintenance cost since the components of an electric engine are more straightforward and lighter than a traditional internal combustion engine (ICE).

Figure 6: Model of an Electric Road System (e-Highway)

2.4. Conductive power transfer technology

In a conductive energy transfer system, the power is transferred by physical contact between the vehicle and a conductor built into the road. Real projects (“eRoadArlanda,” 2018) have been already kick-off; this project is part of the Swedish Transport Administration. The project uses an electric rail installed in the road to power and recharge vehicles during their journey, almost two kilometres of electric rail has been built along a public road outside Stockholm. The power is transferred through a movable arm, this detects the location of the rail in the road, and as long as the vehicle is above the rail, the physical contact will be in a lowered position, as it is shown in Figure 77. When overtaking, the contact is automatically raised.

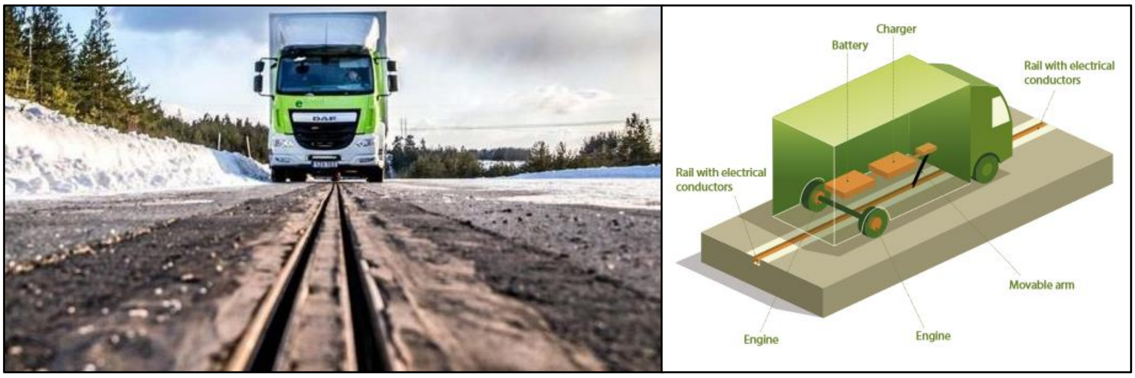


Figure 7: eRoadArlanda project in Sweden.

Meanwhile, the rail which is connected to the national power grid has an automatically functionality as well. It is divided into sections, and each section is powered only when a vehicle is above it. When a vehicle stops, the current also is cut. The power transfer by rail enables the vehicle´s battery to be recharged while the vehicles are driving. The system also automatically calculates the vehicle´s energy consumption, which enables electricity costs to be charged in the vehicle user account.

2.5. Inductive Charging

Electric vehicles (EV´s) can be charged by Contactless Power Transfer (CPT) or Wireless Power Transfer (WPT) systems, without the need to use any physical component that make a contact between the road and the vehicle wirelessly through an elongated magnetic coil that is built into the road and connects to a pick-up point in the vehicle.. These systems can be installed alongside a road, in the meantime can charge the vehicles while driving.

Transfer of wireless power has been a fact since the first invention of the mode of wireless power transfer by Nikola Tesla ("Tesla's multi-frequency wireless radio controlled vessel," 2008). The magnetic resonance wireless has been used as a method to be implemented by its facilities of efficiency and considerable charging distance. It is already a method that is used daily in different appliances such as cell phones or biomedical implants.

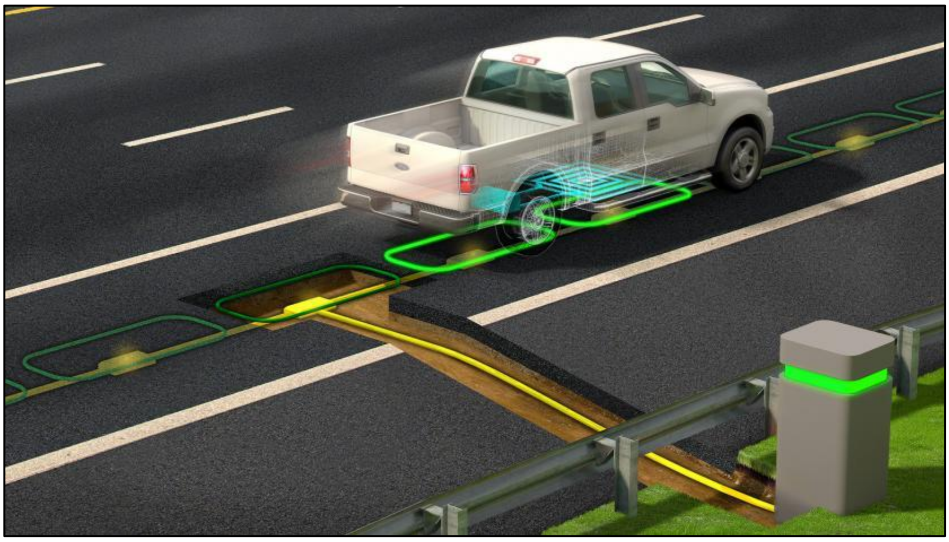


Figure 8: Inductive wireless charging on the go pictogram

The technology has been improved over the years; nowadays, the overall efficiency is around 90%, and the wireless power transfer system of this sort is presently the standard. For an effective and suitable contactless power transfer system is needed three requirements: A large air gap between the road and the vehicle, high power output and high efficiency. Different studies (Hutchinson et al., 2019), divided the wireless power transfer into two primary forms, near field and far-field. Being the far-field commonly used in signal broadcasting as power levels are deficient, but energy transfer is very far. Meanwhile, the near field is capable of higher power levels, but being limited for transferring energy in a single wavelength from the transmitter, in this form the power decreases proportionally to the transfer distance. The Inductive Power Transfer (IPT), is a form of near field WPT. It is made up for inductive coupling between two magnetic fields generated by wound coils. One of the advantages of these systems is that the transferred energy remains within proximity to the transmitter, reducing issues concerning human exposure to the energy and magnetic fields. The most sophisticated WPT for EV applications is the On-Line Electric Vehicle (OLEV) system, having a higher potential power transfer while using a lower resonant frequency.

2.6. Effects of electric roads in the future power demand

The electricity demand related to implemented an electric road system has been analysed in different studies ("Hourly electricity demand from an electric road system – A Swedish case study | Elsevier Enhanced Reader," 2018), where an annual electric demand increase of 4% respect the previous country power demand is being analysed. Also, the peak power demand is analysed, showing that passed from 1100 MWh/h to 1550 MWh/h from 4 PM to 5 PM. Also, the paper shows how an Electrified Road system for the five roads with the highest traffic flows in Sweden will increase the transportation efficiency from 31% to 77% and will reduce the energy demand by 9%, and also will reduce the CO_2 emissions coming from the road transport system by 19%. Also, the paper covers the possible expansion of the electrification of the road system for 49% of all the country road system, increasing the peak power demand by 11%.

2.7. State of the Art (SoT)

Several organisations is developing both static and dynamic wireless power transfer system, either on already available on the market of still been develop under laboratory and experimentation conditions. One of the most advanced technologies already on the market concerning dynamic wireless power transfer are the systems developed by Bombardier (Railway company), Qualcomm and The Korea Advanced Institute of

Science (KAIST). Also available in the market, is the system developed by Siemens (SIVETEC) and WiTricity system developed by the Massachusetts Institute of Technology, both are static wireless power transfer systems.

Regarding dynamic wireless power system, KAIST seems to be in a further step up about other systems. Their On-line Electric Vehicle (OLEV) project has been in development since 2009. Achieving meaningful advances passing from a power system output of 3 kW over a 1 cm air gap, and with a misalignment tolerance of just 3mm and with a transfer efficiency of 80% to their most update system with a power transfer of 100 kW over a 20 cm air gap, with a misalignment tolerance up to 20 cm and with a transfer efficiency of 83%. However, reducing the air gap, the transfer efficiency will be higher than 90%. This system is already in operation since 2010 for a public bus line in South Korea. A directional indicator is used by the driver to align the power rail and the bus receiver pad to maximise the power transfer. Due to the high-power transfer, the bus battery capacity has been reduced in five-time its original size.

2.8. Stakeholder implications

To carry out a massive implementation of electrification of the road systems, a set of actors must be involved. Since the local government to the manufactures passing through the electric car users.

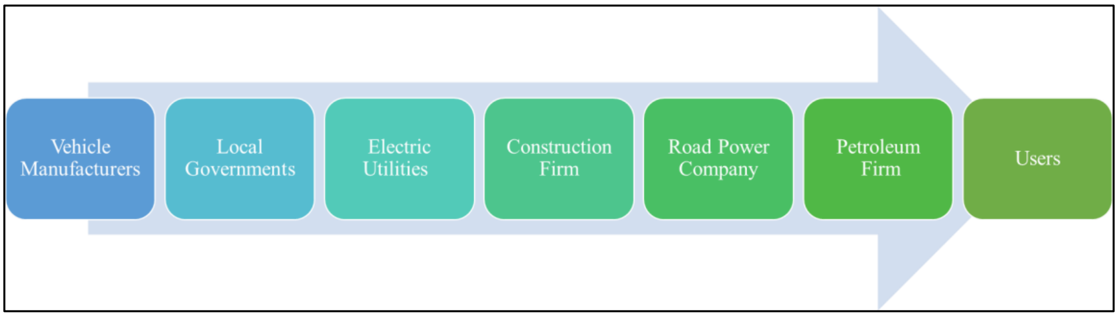


Figure 9: Stakeholders involved in the implementation on the electrification of the road system

- Vehicle manufacturers: They will need to change its current business core and pass from the conventional road system (based on fossil fuels engines) to the electrification road system. As better as advanced technology they have a higher market share will have

- Local Governments: The primary motivation for the local governments is to reduce the environmental impact that the conventional model of road transport has, also to reduce the dependency of oil exports from unstable countries and increase the energy efficiency by switching from fossil fuels to electrification. The governments have the power to provide more manageable and more comfortable to apply regulations as well as they have the obligation to provide funding for any possible idea or project that bring out on the sector. The money saved in oil imports could be reinvested in the electrification of the national road system and also in new renewable energy project to produce all the energy requirements that the electrification of the road system will have. Being a country leader in this technology can lead the country to be technology exported and provide a new market and thus increase incomes for states and agencies.

- Electric utilities: For the electric companies, their traditional business that was to sell electric power to households, companies and industries will expand. In the electrification of the road system the fuel is going to be the electricity, so, an increase in power consumption is expected, then more significant economic benefits are also expected.

- Construction firm: Have the role in integrating the transfer technologies as well as the electric grid into the road construction. Once the issue of financing the construction of electric road systems have been solved, new construction projects will open new market opportunities for public-private partnerships, where the construction companies will build, operate and maintain the electric road for local governments.

- Road power company. Engineers companies that will be on charge of the design, producing and delivering complete road power systems. The Railway industry is taken advantage of the market, due to their long experience designing conductive charging systems for trams and trains. Companies already in the market such as (“VOLTERIO - Automatic Charging for E-Mobility,” 2018), (“Algret Innovations - Dynamic Power Transfer,” 2019), (“Electreon,” 2019).
- Petroleum firm: they are going to have a crucial roll in the road transport system still. Because it would not be afforded electrification of all the road transport system in a short period. Although the role of these companies could change from being the leading fuel supplier to a secondary fuel supplier. However, these companies are already investing hundreds of billions to be competitive with electricity utility suppliers. As it has been already doing companies such as Shell (“Shell Aims to Become World's Largest Electricity Company”. Financial Times.2018)
- Users: They are the last link of the chain being beneficiaries from the higher energy efficiency in the vehicles compared to diesel or petrol engines and thus potentially lower fuel costs. Despite this, if the infrastructure is undeveloped as it is needed, the users might be reluctant to change from their conventional fuel vehicles towards the electric ones.

2.9. The Primove Highway system in Sweden

An inductive power transfer solution for the electrification, for a transport truck application on the E4 highway between Stockholm and Jonkoping, is working since 2013. The Primove Highway system in an inductive charging system with primary winding installed in 20 m segments.

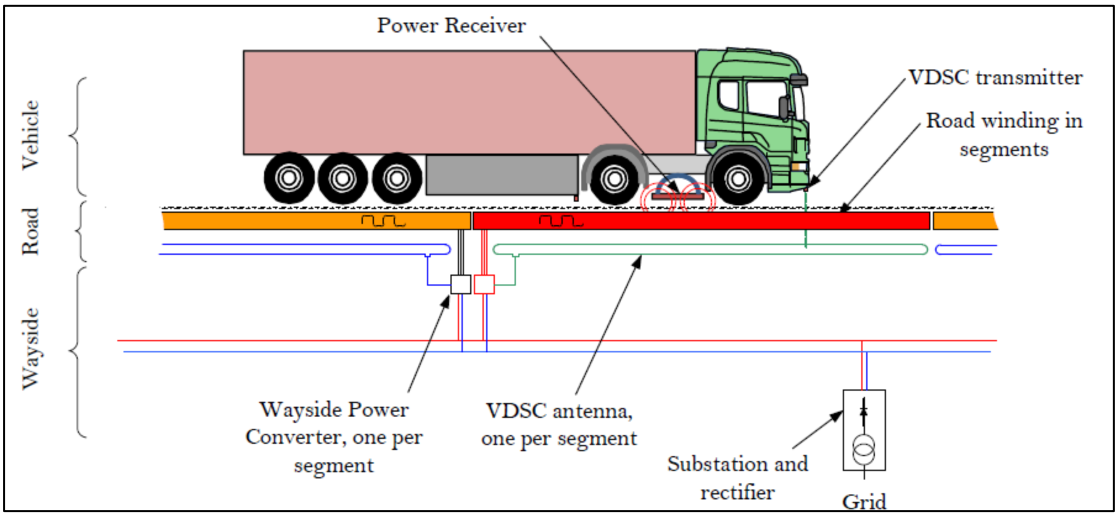


Figure 10: The Primove structure design for a transport trucks application.

As Figure 10: The Primove structure design for a transport trucks application. shows segments are powered and transfer energy when it detected, and primove-equipped vehicle and is moving at 50km/h or faster. A secondary winding within a pickup on the vehicle will provide power to run the electric motor a charge the battery on the go. Energy delivery will be tracked, and payment calculated via the transponder when the truck exits the primove Highway.

The system technology consists of the transfer of energy from the roadway to the vehicle using the transformer principle. The transformer has a laminated iron core that directs the magnetic flux from the primary winding through the secondary winding with little leakage. The primary windings are installed in segments of 20 m each, embedded in the road and covered with asphalt, so there are no exposed cables or connections.

The dimension load for the electric road system analysed has been set to 1,4 MW/km. The ERS structure design is as follows:

3. The average Power demand for electric vehicles

To get the total power consumption required for all the electric vehicles driving alongside a given highway, first, it is needed to calculate the average power consumption of the most common electric vehicles on the market.

To this effect, in this thesis a list of the most top sold electric cars of the United Kingdom in 2018, is presented as follows *Table 2: (Electric vehicle market statistics 2019 - How many electric cars in the UK ? 2019)*.

Car Model and Brand	***Type of Electric car***
MITSUBISHI OUTLANDER	PHEV
BMW 530E	PHEV
NISSAN LEAF	EV´s
VOLKSWAGEN GOLF GTE	EV´s
BMW I3 & I3S (REX)	EV´s
MINI COUNTRYMEN COOPERS E	PHEV
RENAULT ZOE	EV´s
TESLA MODEL S	EV´s
BMW 225xe	EV´s
TESLA MODEL X	EV´s

Table 2: (Electric vehicle market statistics 2019 - How many electric cars in the UK ? 2019)

To get an accurate average power consumption per electric vehicles, in this thesis, it has been considered the power consumption of the pure-electric cars (EV´s). Also, it has been considered two electric car models as an example to get the data from; these are Renault Zoe 2018 and Nissan Leaf 2018.

3.1. Methodology to get the average power consumption for an Electric Vehicles (EV´s)

To achieve an average power consumption per car and km (W/km), a process flow diagram has been developed (*Figure 11: Power Analysis Consumption*).

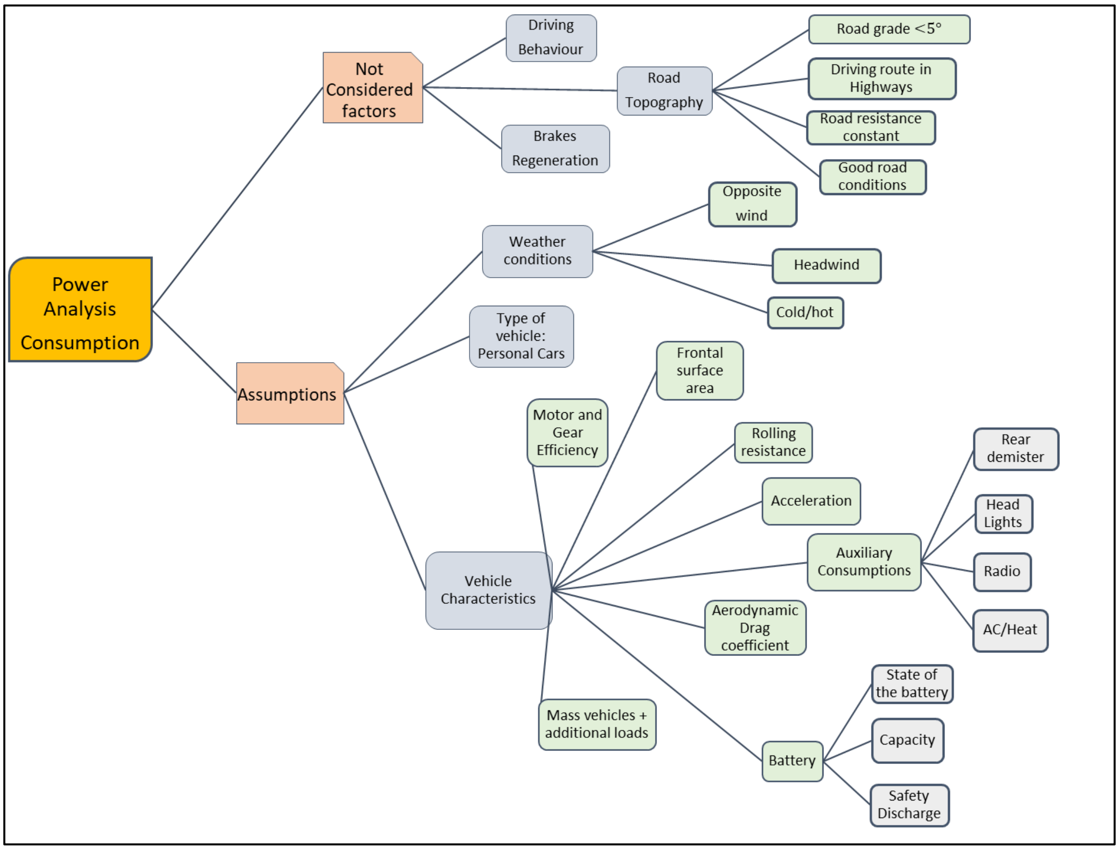


Figure 11: Power Analysis Consumption

Where it is indicated the assumptions that will have a considerable impact on the overall power consumption for an electric car, such as:

- Weather conditions, where it has been considered wind in the same and opposite direction of the car, and cold or hot weather conditions, which would have an impact on the auxiliary power consumption of the car.

- Type of electric vehicles. In this thesis have been analysed just passengers' cars.

- Vehicle technical specifications, where vital factors of the car such as the battery, aerodynamic drag coefficient, vehicle mass.

Also, the aspects that would have an influenced on the overall power consumption, such as driving behaviour, road topography or brakes regeneration but in the thesis are not taken into account are mentioned as well.

3.1.1. Not considered factors

In order to get an accurate and truthful mathematical method to get the average power consumption in a given electric car, an important factor should be taken into account. On this thesis, a simplified mathematical model has been developing, where the most critical factors that affect the final power consumption rate have been considered. Consequently, the following factors, have been not reckoned as a decisive to get the final power consumption, these are:

- Driving behaviour: Needless to say, this is one of the most important factors to be considered into the final power consumption range, but also belong together as one of the furthest challenge factors to be predicted. Is not the same a driver that usually drives in a constant and homogeneous drive speed, that the one that usually overuses the car brakes. As constant the driver speed is lower, the power consumption will be.

- Road topography: Equally important is the road condition. As higher the road slope is as more significant the power consumption will be because the road resistance is higher. Therefore, all the mathematical method has been developing, taking into account a constant road slope of lower than $<5^{o}$. Also, a good road condition and constant road resistance have been considered. For this reason, in this thesis, just a Highway has been taken as a real drive case of study because it is where most of the above conditions are constant. Typically, a Highway relies on right asphalt conditions, mostly straight road and slight road angles.

3.1.2. Assumptions are taken

To build a mathematical procedure as precise as possible to get the average power consumption for a given car, a range of assumptions have been considered, those are:

- Type of electric vehicle: Nowadays a variety of electric vehicles are available on the market, such as buses, heavy freight trucks, light freight trucks, bikes and cars. In this thesis, all the mathematical model has been developing around electric cars. Because, it is a most performed technology, more comfortable to be a charge and represent around 87% of the total vehicle fleet driving around the United Kingdom ("Transport," 2019).

- Traffic conditions. It has been assumed and not traffic congestion simulation because it would be challenging to achieve an accurate methodology considering the traffic jams in a given highway. Therefore, it is considered a constant power consumption along the highway. Even when, the power consumption is much higher in low speeds and constant acceleration and brakings than in a constant and invariant driven speed.

- Weather conditions. Every single weather condition will affect the total vehicle power consumption, rain, snow, wind, sun, cold, dust. However, on account of the extremely difficulty to predict a driven condition with any the weather conditions mentioned above, in this mathematical model, it has just been considered the following:

  - Head Wind, meaning having the wind in the same direction as the driven direction is. So, a lower power consumption rate will be.
  - Opposite Wind, meaning having the wind on the opposite direction as the driven direction is. So, a higher power consumption rate will be.
  - Hot or Cold conditions, meaning the auxiliary power consumption due to the air conditioning or the heating will increase.

- Vehicles characteristics, to simplified this model and as it has been said before in *Table 2: (Electric vehicle market statistics 2019 - How many electric cars in the UK ? 2019)*. Two electric car models have been considered to develop the mathematical procedure. Those have been chosen cause are one of the most common electric models available on the market and also because they are a utility vehicle which can be used on a daily basis, driving in a highway condition. With standard physical characteristics, such as tyres size, area, acceleration, engine and capacity. Within the characteristics considered, in the mathematical procedure have been taken the following:
  - Motor and Gear efficiency (η_e, η_g), where both mechanical components are essential for the overall efficiency of the car electric building blocks.
  - Frontal surface area (A_v) will be an essential factor to get the power needed to overcome the aerodynamic force. As more significant the are is, higher will be the power consumption.
  - Rolling resistance coefficient (f_{rr}), typically will be taken as 0.01, being the value for car tyres driving on concrete or asphalt, but in the thesis is calculated as follows:

$$* f_{rr} = 0.01 * \left(1 + \frac{V}{100}\right) \quad (Equation\ 33)$$

- Where v: Car speed (m/s)

- Acceleration (a_x) is the longitudinal vehicle acceleration value. The value is constant depending on the car model and brand. In this study case is 3.52 m/s^2 for the Nissan Leaf and 2.42 m/s^2 for the Renault Zoe.

- Auxiliary consumptions
  - Heating and Air Conditioning (2000/2300 W), (Wang et al., 2015)
  - Radio (52 W)
  - Heads lights (200 W)
  - Rear demister (200 W)

- Aerodynamic drag coefficient (C_d), The value is constant depending on the car model and brand. In this study case is 0.32 m/s^2 for the Nissan Leaf and 0.29 for the Renault Zoe.

- Battery
  - State of the charge (SOC), obviously this factor will have enormous importance in order to predict the final power consumption needed for the electric car. Being this task nearly impossible, in this mathematical procedure has been considered a healthy state of the charge of less than 10%. In other words, all the energy that the inductive charging on the go system will provide to the electric car is going to be considered as net energy output. According to the average power consumption per car and

the travel highway distance, every single vehicle will need a specific amount of energy.

    - Capacity, as most of the electric car manufacturers said, the optimal charging point is reached until 80% of the battery capacity. Once, this level achieved the last 20% takes much longer to be charged. Therefore, in this thesis, a full capacity battery has been considered. Just because it will be demonstrated how the battery size could be reduced if the inductive charging on the go system is implemented.

    - Safety discharge, it is also mentioned for all the electric manufacturers in their technical specification date sheet, a minimum of 2 kWh gap in the battery, should not be considered as part of the total range of the vehicle. Because, this 2 kWh is needed as a battery reservoir, in case of difficulties to have a close charging point where the vehicle can be a charger. In this thesis will be proved the reliability of inductive charging on the go system will reduce the necessity of a big range battery as well as the necessity of safety discharge gap. Because the vehicles will be driven on the road at the same time that they are charged.

- Vehicle mass (Mv) and added load, aside from the own car weight, it should be considered any added load such as Passengers, luggage or other, because as more substantial the car is as higher the power consumption will be.

3.1.3. Total power consumption output

Once the assumptions and no consideration have been taken to specify which is going to affect the total power consumption output, a set of force has been calculated. The aggregate of all of them will be the total force that is needed to overcome all the force that influenced against the car movement, then multiplied for the vehicle driven speed and divide by the gear, and engine efficiency will have the total power consumption output to keep moving the car. Adding auxiliary power consumption, it will have a total power consumption output. All the equations are explained as follows:

$$* Fd = \frac{1}{2} * \rho * Cd * Av * (v - W)^2, (Equation\ 34)$$

$$* Fr = frr * Mv * g * \cos(\alpha), (Equation\ 35)$$

$$* Fa = Mv * Ccf * Ax, (Equation\ 36)$$

$$* Fg = Mv * g * \sin(\alpha), (Equation\ 37)$$

$$* F_T = Fd + Fr + Fa + Fg, (Equation\ 38)$$

- Where:
    - Fr: Rolling Resistance Force
    - Fa: Force to overcome power loss in acceleration
    - Fg: Force originating from the road slope
    - Fd: Force to overcome the aerodynamic force
    - Ft: Total force needed to move a vehicle
    - ρ : Air density, it is taken as a constant (1,225 kg/m³)
    - v: Vehicle driven speed (m/s)
    - W: Wind speed at the same direction as the driving is

- g: Gravity constant (9.81 m/s2)
- α: Road slope inclination angle (º)

Then, the total power demand per electric vehicles will be as follows:

$$* P_{demand} = (F_T * v)/(\eta e + \eta g), (Equation\ 38)$$

$$* P_{consumption} = Pdemand + Pauxiliaty + Plosses, (Equation\ 39)$$

Where the P losses have been considered as the aggregate of the vehicle train loss + battery discharge losses+ Cabling losses+ Inverter losses+ Motor and Gearbox losses, and it has been averaged between 2 and 10 kW per vehicle.

3.1.4. Average power consumption per car

Taking all the equations described above, a set of different scenarios have been considered to get different power consumption depending on the assumptions also described above, then these scenarios are described following:

1. Ideal Conditions, (most of the power consumptions rate given for the vehicle manufactures are considered under an ideal driven condition, that are:
    - Head Wind of 20 km/h in the same direction as the driving is
    - Not added loads, just the own vehicle weight
    - Power consumption coming from the auxiliaries, not considered
2. Scenario 1:
    - Head Wind of 20 km/h in the opposite direction as the driving is
    - Not added loads, just the own vehicle weight
    - Power consumption coming from the auxiliaries, not considered
3. Scenario 2:

   - Head Wind of 20 km/h in the opposite direction as the driving is
   - Added loads, another passenger considered (80 kg) with his luggage (20kg)
   - Power consumption coming from the auxiliaries, 500 W

4. Scenario 3:

   - Head Wind of 60 km/h in the opposite direction as the driving is
   - Added loads, three passengers considered (80x3=240 kg) with their luggage (20x3= 60kg)
   - Power consumption coming from the auxiliaries, 2000 W

Being the different scenarios established, thereupon the technical specifications of the two electric car models chosen are described below:

Car Model	Cd	Av	Mv	Ccf	Motor efficiency	Gear efficiency	ax
Nissan Leaf	0.32	2.30	1580	0.05	0.96	0.97	3.52
Renault Zoe	0.29	1.86	1460	0.05	0.95	0.96	2.42

Table 3: Technical specifications for the given electric cars

Nissan Leaf

Speed (mi/h)	Speed (km/h)	Ideal Conditions (W/km)	Scenario 1 (W/km)	Scenario 2 (W/km)	Scenario 3 (W/km)
70	112	0.24	0.32	0.35	0.51
60	96	0.18	0.24	0.27	0.39
50	80	0.14	0.18	0.20	0.30

Table 4: Nissan Leaf, power consumptions in different scenarios

Summarizing what has been described, every single power consumption value per scenario, electric vehicle model considered, and taking the driving speed conditions considering the traffic UK rules (70,60,50 mph) as it has been shown in **Error! Reference source not found.**, Table 5: Renault Zoe, power consumptions in different scenarios.

Renault Zoe

Speed (mi/h)	Speed (km/h)	Ideal Conditions (W/km)	Scenario 1 (W/km)	Scenario 2 (W/km)	Scenario 3 (W/km)
70	112	0.24	0.32	0.35	0.51
60	96	0.18	0.24	0.27	0.39
50	80	0.14	0.18	0.20	0.30

Table 5: Renault Zoe, power consumptions in different scenarios

Finally, a table summarises the average power consumption for each of the scenarios taking under consideration both electric vehicles models, as the next table shows:

Average consumption per Scenario

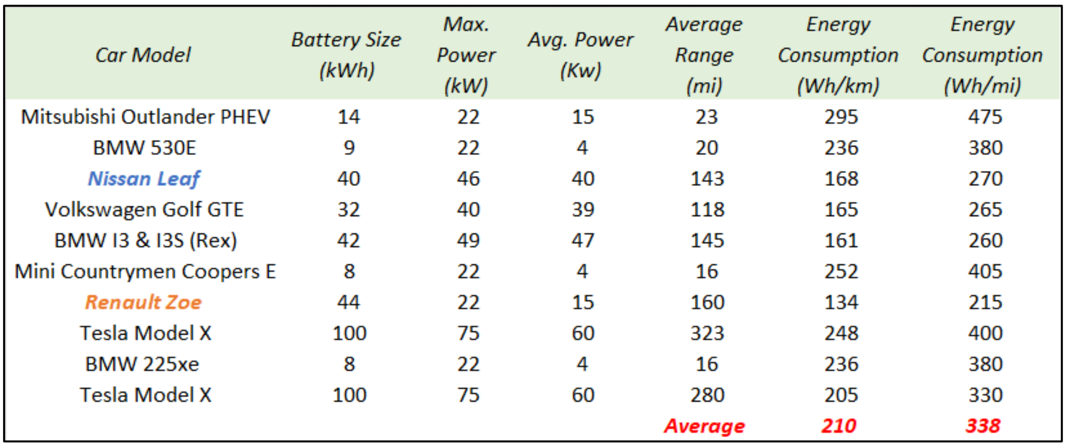
Speed (mi/h)	Speed (km/h)	Ideal Conditions (W/km)	Scenario 1 (W/km)	Scenario 2 (W/km)	Scenario 3 (W/km)
70	112	0.21	0.29	0.32	0.45
60	96	0.18	0.24	0.27	0.39
50	80	0.12	0.16	0.18	0.27

Table 6: Average power consumption per Scenarios

Then for the following calculations that have been taken throughout the thesis, the average power consumption rate taken is coming from the average power consumption of the table Table 6: Average power consumption per Scenarios. So, the result taken in the upcoming equations is ***260 Wh/km***.

3.1.5. Power consumption validation data

A validation data must be defined, to ensure that the average power consumption that has been calculated in section *3.1.4. Average power consumption per car* is accurate data than can extrapolate to the real driving test and can be contrasted with the official data given by the vehicle manufactures. Consequently, the following table shows the data provide by the manufacturers for electric vehicles most sold in the UK in 2018.



Car Model	*Battery Size (kWh)*	*Max. Power (kW)*	*Avg. Power (Kw)*	*Average Range (mi)*	*Energy Consumption (Wh/km)*	*Energy Consumption (Wh/mi)*
Mitsubishi Outlander PHEV	14	22	15	23	295	475
BMW 530E	9	22	4	20	236	380
Nissan Leaf	40	46	40	143	168	270
Volkswagen Golf GTE	32	40	39	118	165	265
BMW I3 & I3S (Rex)	42	49	47	145	161	260
Mini Countrymen Coopers E	8	22	4	16	252	405
Renault Zoe	44	22	15	160	134	215
Tesla Model X	100	75	60	323	248	400
BMW 225xe	8	22	4	16	236	380
Tesla Model X	100	75	60	280	205	330
				Average	***210***	***338***

Figure 12: Energy consumption value is given for the vehicle manufacturers

The Figure 12: Energy consumption value is given for the vehicle manufacturers above shows, the average consumption of the most sold electric vehicles in the UK by 2018, considering pure electric vehicles (PEV) and Plug-in Hybrid Electric vehicles (PHEV) is 210 Wh/km. As is have been said before, the vehicle manufactures always publish the energy consumption data for the most convenient scenario, that is, without headwind in the opposite direction, any auxiliary load, constant and lows driven speed.

Then, the data provide for the manufactures compared with the data taken from the mathematical model that has been developing in the thesis is not similar (210 Wh/km against 258 Wh/km). However, for ratifying that the mathematical model is accurate and valid, the data obtained in the ideal conditions for the Nissan Leaf and Renault Zoe (152.5Wh/km) is compared with the same vehicle model but taken the data provided by the manufacturers (151 Wh/km). They are having considering driving speed of (100 km/h).

To double up the validation process, real data taken from the on-board computer system of electric vehicles (***Nissan Leaf*** and ***Renault Zoe***) belonging to the University of Strathclyde has been taken, and it is shown in the following pictures:

Figure 14: Average Real Energy Consumption of a Nissan Leaf (mi./kWh)


Onboard computer

Since	26-06-2019
Total distance	88.4 mi
Average speed	26.2 mph
Average consumption	3.8 mpkwh
Total consumption	22.0 kWh

Figure 13: Average Real Energy Consumption of a Renault Zoe (mi./kWh)

A final validation table is presented, summarising the value given by the mathematical model developed in the thesis, manufactured data and real data taken from the vehicle on-board system. In the below table (Table 7: Power consumption validation method), the power consumption has been calculated through the mathematical model, taking into account every single power consumption for the consumption scenarios that have been shown before in the section *3.1.4. Average power consumption per car*. Therefore, the average power consumption has taken and has been multiplied for 1000 to get kW and also times 1.61 (1 mi.=1,61 km). Obtaining the following results:

Power Consumption (mi. kWh)		
Validation Method	*Nissan Leaf*	*Renault Zoe*
Mathematical Model	3.79	3.85
Manufacturer data	3.70	4.65
Real Data	3.60	3.80

Table 7: Power consumption validation method

Therefore, it can be assumed that the mathematical model to get the average power consumption for given electric vehicles is precise and validated with real data provided by the vehicle manufacturers.

4. Power Demand for the vehicles passing-by

To establish a relation between the energy consumption that the electric vehicles driving on the highway will have, and the number of electric vehicles driven per hour in a specific highway, two methods have been developed.

4.1. Customizable method

In this method, a user can customise the different inputs to get the power demand of the vehicles driven in a specific highway in a specific hour. So, using an excel spreadsheet, it can be calculated an estimation of the power demand that will be required, in order to figure out the energy production coming from the PV installations (as it has been seen in the chapter (*7. Solar Photovoltaic installations design*). This method is the easiest way to get a final power consumption needed and then see how many PV Panels would be needed along a year depending on the highway location.

Taking into account the average power consumption per electric vehicle, that it has already calculated before (*3.1.4. Average power consumption per car*), 260 Wh/km = 3.84 km. kWh. The total power output can be calculated as follows:

Numbers of cars	
Highway length (km)	
Average Power consumption (km. kWh)	3.84
Power requirements (kWh)	0

Table 8: Customize the method for calculating the total power consumption for a given

Being the numbers of cars and the highway length inputs, to get the final power requirements value to go back and calculate how many PV panels would be needed for these conditions. This method counts with the uncertainty of the inputs data since those values required for a more precise method to be taken on, such as real traffic data for the highway given position.

4.2. Average daily traffic data

Being the option of real traffic data achievable, but hardly implemented, due to the needed to extract the data from public webpage resources for every single place, and those data are also hardly dependent of the weather conditions, traffic accidents or public holidays/working days. Therefore, an average hourly/daily/weekly/monthly traffic data model has been developed. In this thesis, ten of the most UK´s congested highways have been taken as a model of study, being these disseminated throughout the country. These congested highways are listed in the next table, showing the location of the highway, the traffic flow in each of the highway direction and the numbers of cars, driven on that ten congested highways in an average annual period. In other words, the table shows the regular traffic flow per day on an average annual basis.

Location	Direction	Cars
M8, near Livingston	E	23,758
	W	23,924
M4, Wales, Neath Port Talbot	E	28,220
	W	23,199
A720, Edinburgh bypass	E	34,582
	W	31,438

M8, Renfrewshire	N	58,068
	S	55,502
M8, Glasgow City	E	54,162
	W	51,278
M25, near London. Hillingdon	N	82,270
	S	86,640
M4, near London, Hounslow	E	38,322
	W	44,005
M25, near London, Kent	E	46,676
	W	43,805
M53, Liverpool, Wirral	N	26,400
	S	26,663
M62, Liverpool-Manchester	E	41,462
	W	44,088
Average daily	***43,223***	

So, according to the table showed above there is an average of 43,223 cars driving in the UK´s highways daily. The successive is to get the percentage of electric cars to respect the total number of cars are in the UK. To this effect has turned out to the statistics of licensed vehicles in the UK on the first quarter of the year 2019 ("Statistics at DfT," 2019), indicating the following.

Licensed Vehicles UK	32,670,000
Licensed E-Vehicles UK	198,842
Percentage of EV´s respect the total number of cars	*0.61%*

Table 9: Percentage of Licensed Electric Vehicles in UK respect to the total number of licensed vehicles

Therefore, the daily average number of electric vehicles driving in the UK´s are 263. To be more accurate and with the help of the statistics taken from The UK Department of Transport ("Statistics at DfT," 2019), the following daily, monthly cars flow chart can be displayed.

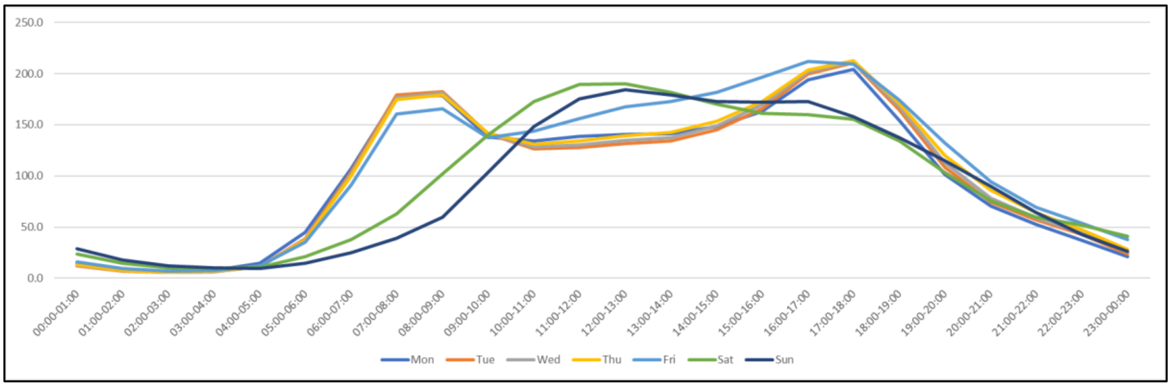


Figure 15: Car daily flow chart

The **Error! Reference source not found.**, shows the traffic flow variability over the week in the UK´s highways, in the horizontal axis shows the day hour and in the vertical axis shows the numbers of vehicles driven on that time (in hundreds of thousands). As it can be seen the pick of traffic match with the arrival (08:00-09:00) and departure (17:00-18:00) working times. Also, it should be said that Fridays are the day of the week with more flow traffic, over 10% of the traffic that usually are on Mondays. Saturdays and Sundays are the lowest traffic flow weekdays, 5% and 10% respectively compared with the traffic flow on Mondays. Analysing these data, it should note that the weekly peak flow rates are thus where more power consumptions will be required are also match with periods of low solar irradiance and therefore low power production. Except for the weekend days, where the pick hour cars flow rate to match with the daily maximum solar irradiance hours.

Error! Reference source not found. it is displayed the numbers of cars driving in the UK´s highways by month. As it can be seen, August is the month with most flow density (almost 10% over May) followed by July and June, coinciding with the Summer holidays and also when more sun irradiance is received in the earth, at least in the Northern Hemisphere (Opposite in the Southern Hemisphere). Moreover, the months with less flow car density are January (20% less traffic than in August), February (16%

less traffic than in August) and December (14% less traffic than in August), coinciding with the month of the year with less solar irradiance is receive on the earth´s as well.

4.3. Monthly power consumption requirements

Then, the annual power consumption requirements can be done taking into account the daily and monthly average flow cars and the average number of electric cars driving in the UK´S highways; these annual requirements are shown in Figure 17: Monthly power consumption (kW/km), considering all the UK traffic data. Where the vertical axes show the power consumption in kW per month and the horizontal axis shows the month of the year.

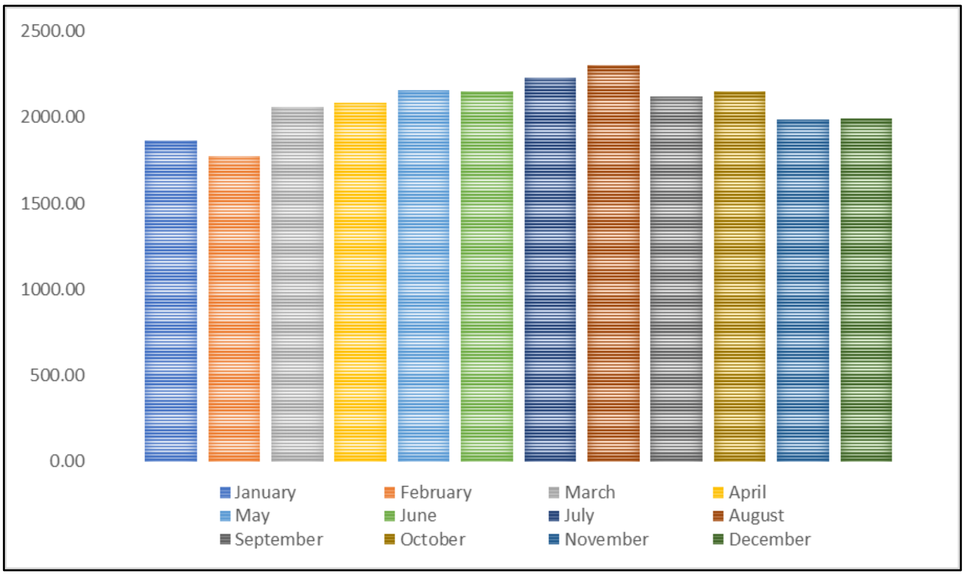


Figure 16: Monthly power consumption (kW/km), considering all the UK traffic data

5. Inductive Charging on the go system

5.1. Contactless Power Transfer (CPT)

Electric Road System (ERS), are road transportation systems based on technologies that support electric power transfer from road to vehicles in motion, travelling on them. An

Electric Road System has several subsystems such as the road, the electric vehicles (Car, Truck or Bus), the power transfer technology (*5.2 Power Transfer Technologies: Inductive and* Conductive) and the power grid and stations. The technology itself is to build a road infrastructure that could provide constant energy to a power transfer system, and this instance provides enough energy to drive an electric motor content in a vehicle. The electrical power is transmitted while the vehicles are in motion at driven speeds throughout a charging system as it is described in the next chapter (*5.2*). The electric vehicles are supposed to be either battery electric vehicles (BEVs) models such as Renault Zoe, Nissan Leaf or Plug-in Hybrid Vehicle (PHEV) such as; Mitsubishi Outlander or BMW 530e. For the calculations, this thesis has been considered the average consumption rates of pure electric battery vehicles, using a mathematical model that takes into account different driving conditions that will affect the final power consumption.

5.2. Power Transfer Technologies: Inductive and Conductive

The power transfer technologies currently on the market and with a certain degree of development and reliability are related with the Inductive and Conductive charging. Both systems have already been in use in multiple environments such as trains, buses and electric devices chargers.

The conductive charging method, is the most well known for being develop since the 19th century on the first-ever electric passenger train taking the electricity supplied from a third insulated rail between the tracks, tested on Berlin in 1879 and developed for Werner von Siemens (“On track – Siemens presents the world’s first electric railway,” n.d.). Since then, the conductive charging method taking the electricity from overhead cables or electrified rail beneath the vehicle has been part of the underlying transport system of any country in the world, also for its efficiency and reliability. Recently Siemens has develop a system to electrified the road freight transport (“eHighway,” n.d.), throughout a pantograph, capable of connecting while driving at any highway speed, being the energy supply system based on two-pole catenary system leads to a level contact wire that enables stable current transmission, even at high speeds. The energy is supply from substations installed along the road, as it is shown in Figure 5: Electrified eHighway for trucks developed by Siemens in Germany.

The Inductive charging used a technology known as contactless power transfer (CPT) where the power ins transferred electro-magnetically with no physical contact, field coil already in used since Nicola Tesla do its first experiments at the beginning of the XX century. The electricity is transferred through an air gap from one magnetic coil in the charger to a second magnetic coil fitted to the car.

5.3. CPT System for charging Electric vehicles

A Contactless Power Transfer System (CPT), is a system where the power can be transferred electro-magnetically with no physical contact. It is made of an air-core transformer with two windings. The efficiency of the transformer depends on the parameters of the primary and the secondary winding, the coupling factor, also is depending on the load and the operating frequency. A typical Contactless Power Transfer System is shown in Figure 18: Typical CPT system for electric vehicles.

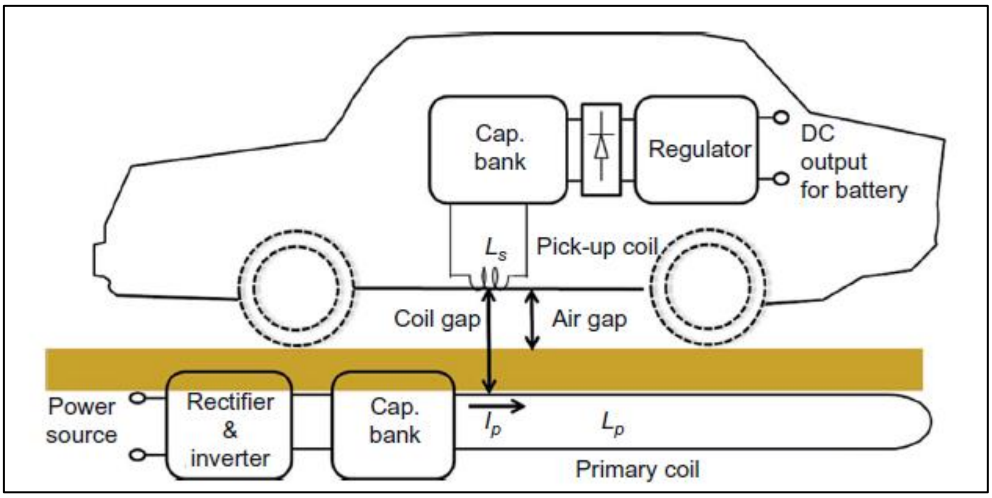


Figure 17: Typical CPT system for electric vehicles (Chun, 2017)

The system includes several stages in order to charge the electric vehicle's wireless. Firstly, the energy provides by the utility or in this thesis provide by the PV Solar installation alongside the road AC power is converted to a DC power source by an AC to DC converter with a power factor correction. Then the DC power is converted again to a high-frequency AC power to drive the transmitting coil through a compensation network. For extra safety and protection, an isolated high-frequency transformer must be inserted between the DC-AC inverter. The AC voltage receives in the coil is produce for the alternative magnetic field that is generated for the high-frequency current. The transferred power and efficiency are improved by secondary resonating. The last stage is when the AC power is rectified to charge the electric car battery.

Being the main difference between a CPT system with the conductive system, the inexistence of the transformer, been replaced by a set of loosely coupled coils.

The electrified road system should be robust, cheap and easy to maintain for severe road environments and should be economical to install over a long distance, whereas the onboard subsystem should be compact in size and light in weight.

5.4. CPT system disaggregation

The CPT system can be disaggregated in three different subsystems, which in turn has other subdivision, described as follows:

1. Control system:
    - Power control
        - Position sensors
        - Communication links
        - Inverter on/off the controller
2. Wireless Power Transfer System
    - Electrified Road System
        - 50 Hz Power source
        - Rectifier
        - Inverter
        - Capacitor Bank
        - Power Supply Rail
            - Electric Part
                - Core
                - Power Cable
                - Insulator
            - Mechanical Part
                - Supporting Structure
                - Roadway construction
    - Electric vehicle Subsystem
        - Pick-up coil
            - Electric part
                - Power Cable

            - Core
            - Insulator
        - Mechanical Part
            - Structure

3. Electric vehicle system
    - Power train subsystem
        - Battery
        - Traction Motor and Inverter
        - Transmission
    - Control system
        - Electric vehicle controller
        - Communication link

5.5. Energy Transferred from the CPT system to the vehicles

The energy transferred from the contactless power system to the vehicle is proportional to the power of the system and the time the vehicle is on top of it. The time duration is the speed of the vehicle divided by the length of the CPT system. Therefore, to have more energy transferred to the car, two options are available, either longer road distance where the CPT system is installed or lower driven speed. Being the system installed on highways, the last of the option must be discarded because the lower driven speed in which a vehicle can drive in a highway is 50 mph (80km/h). Then, a longer part of the highway covered by the CPT system is analysed.

Then, it resumes that the only two factors that will affect the energy transferred from the CPT system to the car will be the power transfer of the CPT and the length of the system. Consequently, such facts as driver behaviour, non-constant driving speed, traffic or adverse weather conditions are not considered.

5.6. Structure of the CPT segments

The primary windings must be installed under the road and can be installed by segments, meaning that the CPT systems and some not will cover some parts of the road. The length of every single CPT system segment can be varied and the distances between them as well. Every segment consists of one or multiple primary coils place adjacent to each other and can be distributed over the road, sparsely, densely or can be only one long segment. It should be considered that every primary winding will require an inverter to create a high-frequency AC supply.

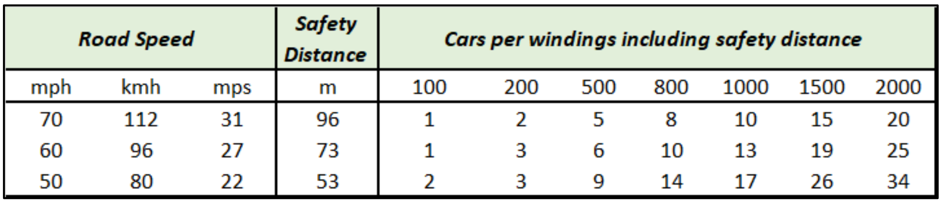
Hence, the total length of the CPT system along a highway is expressed as the percentage of the road covered with primary windings. This percentage will be dependent on the total length of each of the primary winding and the maximum power transferred output of each of the primary winding as well. Being this values explained further on.

5.6.1. Parameters of CPT primary windings

As far as the power transfer capability of the system is concerned, there is an upper limit to some hundreds of kilowatts (P. Bauer and M. Castilla, 2013). Consequently, this will lead to a limitation of the number of vehicles that can be powered by a single one primary winding. Therefore, it will carry on to a limitation on the length of the primary winding.

5.6.2. Length of the primary windings

For calculating the length of the primary winding, first, it should be taken into account the safety distance between cars, for driven in a Highway under safety conditions (“Stopping distances made simple | RAC Drive,” 2017). Then, once the safety-driven distances are known, the following table has been created, where it is displayed how many vehicles per length winding segment will be driven at the same time for a given driven speed, also it should be taken into account that an average car length of 5,5 m per car has been considered to develop the table.

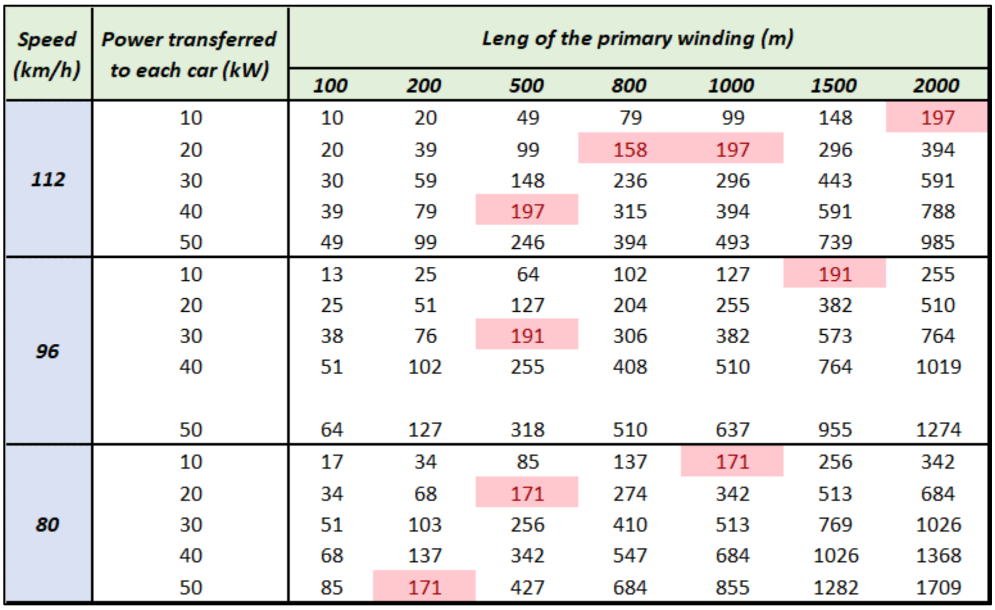


Road Speed			***Safety Distance***	***Cars per windings including safety distance***						
mph	kmh	mps	m	100	200	500	800	1000	1500	2000
70	112	31	96	1	2	5	8	10	15	20
60	96	27	73	1	3	6	10	13	19	25
50	80	22	53	2	3	9	14	17	26	34

Table 10: Numbers of cars per primary winding length for a given driven speed

For instance, the above table shows that for a driven speed of 60 mph (96km/h), and considering a safety distance between cars of 73 m, in 500 m of primary winding length six cars would be able to drive at the same time in the same primary winding.

Secondly, and considering the maximum power transfer system already on the market that can transfer a primary winding power up to 200 kW, with reported efficiency of 92% for 610 mm air gap, developed by Momentum Dynamics (“Momentum Dynamics - Wireless Charging for Electric Vehicles,” 2018). A table with the total power capacity of the CPT primary winding system in kW, is exposed (**Error! Reference source not found.**). Where in red are highlighted the winding power transfer power output below or equal to 200 kW for a given transferred power to each car (kW).

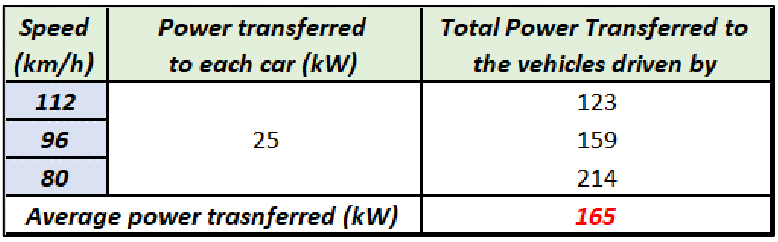


Speed (km/h)	**Power transferred to each car (kW)**	**Leng of the primary winding (m)**						
		100	**200**	**500**	**800**	**1000**	**1500**	**2000**
112	10	10	20	49	79	99	148	197
	20	20	39	99	158	197	296	394
	30	30	59	148	236	296	443	591
	40	39	79	197	315	394	591	788
	50	49	99	246	394	493	739	985
96	10	13	25	64	102	127	191	255
	20	25	51	127	204	255	382	510
	30	38	76	191	306	382	573	764
	40	51	102	255	408	510	764	1019
	50	64	127	318	510	637	955	1274
80	10	17	34	85	137	171	256	342
	20	34	68	171	274	342	513	684
	30	51	103	256	410	513	769	1026
	40	68	137	342	547	684	1026	1368
	50	85	171	427	684	855	1282	1709

Table 11: Power transferred for a primary winding power of 200 kW for a given driven speed

Then as can be seen, in the above table and taking in consideration that the maximum power transfer in a primary winding is 200 kW. `Primaries of 1000 or 1500 m long are possible only for transferring few kW to every car, as can be seen in red in the above table (For a 1500 m primary length and giving 10 kW to each car, the total power output of the CPY system will be 148 kW, and for a 2000 m primary length and giving 10 kW to each car, the total power output of the CPT system will be 197 kW). In order to transfer between 20-30 kW, primary windings of 500 m length are more realistic and feasible.

Therefore, and taking the data already displayed in the Table 12: Power transferred for a primary winding power of 200 kW for a given driven speed, for a primary winding design of 500 m length and a power transfer of 25 kW per car, the total power output of the CPT system will be as follows:



Speed (km/h)	Power transferred to each car (kW)	Total Power Transferred to the vehicles driven by
112	25	123
96		159
80		214
Average power trasnferred (kW)		**165**

Table 12: Average power transferred for a 500 m primary winding length

So, a primary winding of 500 m length with a maximum power transferred the output of 200 kW, will be able to transfer 25 kW to every car in three different driven speed conditions.

5.7. Operating frequency of the CPT system

There is also a factor that should be taken into consideration, that is the operating frequency of the CPT system. Because, there is a maximum upper limit for the primary length, due to the "lumper element model" that suggest that the length of an electric circuit should be of a lower order of magnitude compared to the circuit´s operating wavelength (Stamati and Bauer, 2013).

The wavelength is calculated as follows:

$$\gamma = c/f$$

$$\gamma = wave\ legnth\ (km)$$

$$c = speed\ of\ the\ light\ (3{,}00x10^5\ km/s)$$

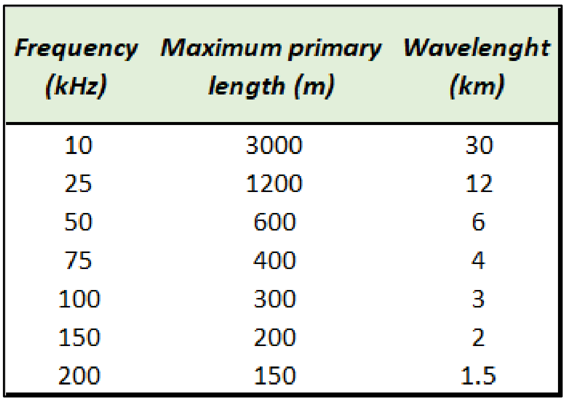
$$f = frecuency\ (kHz)$$

If the primary length is like the wavelength, the electromagnetic wave reflection will be significant, affecting the efficiency of the CPT system, also causing faulty functioning of the electronic devices. So, for that purpose a relation between the primary length and the wavelength has been established, is the following:

$$L = \frac{1}{10} * \gamma$$

$$L = Primary\ length\ (m)$$

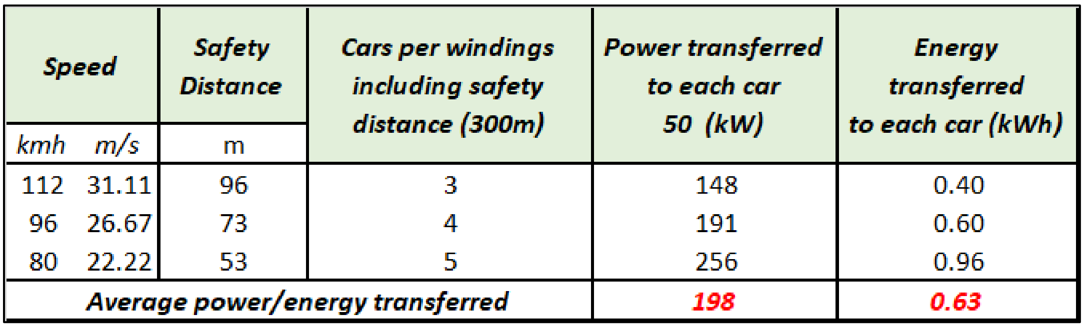
So, the following table represents the relation between primary length and wavelength for a given frequency.



Frequency (kHz)	Maximum primary length (m)	Wavelenght (km)
10	3000	30
25	1200	12
50	600	6
75	400	4
100	300	3
150	200	2
200	150	1.5

Table 13: Maximum length of the primary winding for a given frequency

As the last table shows, for a frequency of 50 kHz, the maximum primary length for an avoiding the electromagnetic reflection will be 600m. However, the efficiency of the overall CPT system increased when the system operates at high frequency (above 100 kHz). Therefore, for 100 kHz frequency system operation and for avoiding electromagnetic reflection, the primary length must be of 300m. Consequently, the total power transfer of the CPT system will change, being the following:



Speed		***Safety Distance***	***Cars per windings including safety distance (300m)***	***Power transferred to each car 50 (kW)***	***Energy transferred to each car (kWh)***
kmh	*m/s*	m			
112	31.11	96	3	148	0.40
96	26.67	73	4	191	0.60
80	22.22	53	5	256	0.96
Average power/energy transferred				***198***	***0.63***

Table 14: Energy transferred to each car for a primary winding of 300 m length and 200 kW maximum power output

Where the total power transferred to the cars driven on the primary winding at a given driven speed, is calculated at the primary winding power transfer to each car 50kW times the numbers of cars driven at a given driven speed taking into consideration the safety distance between cars. Moreover, the energy transferred to each car is calculated having the time that the car is passing on the primary winding for a given speed. So, 300 m primary length divided by the driven speed, i.e. 31 m/s times the power transfer to each car 50 kW.

Therefore, as the Table 15: Energy transferred to each car for a primary winding of 300 m length and 200 kW maximum power output shows. Comparing different primary length dimensions, for a 300 m length primary winging the CPT systems will be physically able to transfer a power output of 0.40 kWh per car for a driven speed of 112km/h, or 0.60 kWh at 96 km/h or even more 0.96 kWh at 82 km/h. Although the latter situation, driven speeds of 80 km/h (50mph) in a highway are unusual, also the CPT system is limited for a power transfer output of up to 200 kW.

5.7.1. Distribution and length of the CPT segments

Given the maximum length of the primary winding, as it has been shown in the previous section, a CPT system along the highway must be created. Firstly, the system depends on the total highway distance to be covered with the inductive charging on the go system. Also a second important factor is the numbers of cars to be powered with the systems. As more prolonged and more electric cars on the highway bigger will be the energy need to be transferred to the electric cars. For the battery of the electric vehicles, small shallow cycles are better than deep cycles. Therefore, smaller segments are more beneficial for the battery life cycle (Jasprit S.Gill, 2014). On this basis, short segments of the primary winding are better than longer ones. Also, it would be more beneficial a fortiori if the segments are well distributed. If the CPT segments are well-distributed over the road, the usability of the system from the car drivers will be better. Assuming that the CPT system is just installed in one lane of the highway and the electric car driver will drive on that lane. Besides that, a more excellent distribution of the CPT system segments will require more extended cabling that adds losses to the system.

With that in mind, in this thesis have been considered 300 m length primary windings segments, densely placed over the highway and with the same power transferred, coverage and distribution along the highway.

5.7.2. Driving Range extension

As it has been seen before in Figure 12: Energy consumption value is given for the vehicle manufacturers, the average driving range for the pure electric vehicles is 140 mi. (225 km), and the average energy consumption is 260 Wh/km (78Wh/300m), the total consumption of the power if it consumes all the battery, leaving a gap for safety conditions of 2 kWh, will be 57 kWh. If a CPT system is installed along the highway, additional energy will be provided to the vehicle while it is driving. Therefore, the range will be increased.

Considering the Table 15 values of transferred power coming from the primary winding and 300m length, the following Figure 19: Driven range extension depending of the percentage of road covered by CPT Systems shows the range extension that could be achieved depending on the percentage of the highway covered by a CPT system. Considering as a calculation example a highway length of 80 km, where the horizontal axis shows the percentage of highway covered by a CPT system and the vertical axis shows the total range covered including the battery size capacity.

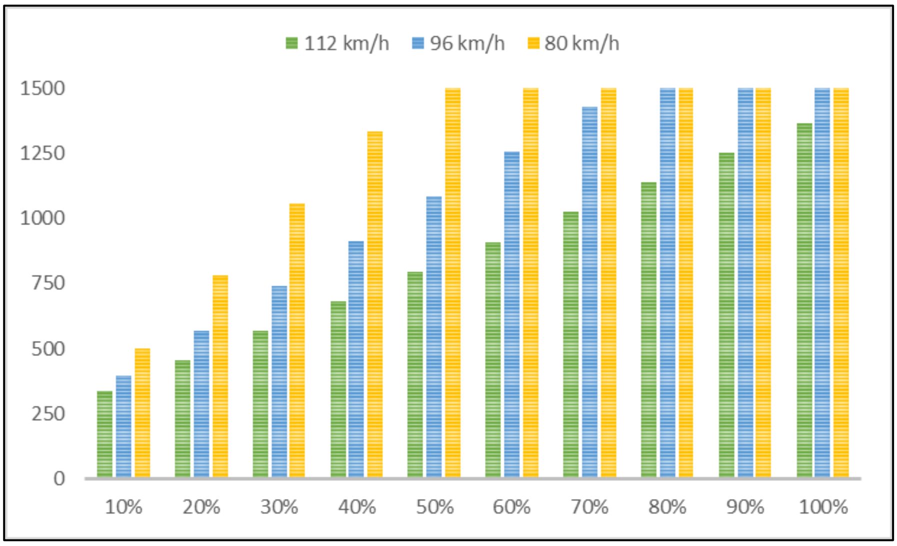


Figure 18: Driven range extension depending of the percentage of road covered by CPT Systems

As it can be seen in the above figure, for a 50% highway covering the driving range extension will increase until 750 km maintaining a constant driven speed of 112km/h, or 1250 km for a driven speed of 96 km/h. Also, is can be seen that for a more significant percentage the driving range will higher than 1500 km, nowadays unattainable for any petrol or diesel car.

5.7.3. Battery size decrease

Moreover, taking into consideration the battery range for the driven range extension as have been seen before, the battery size of the electric vehicles can also be reduced. Borrowed from the values seen before Figure 12: Energy consumption value is given for the vehicle manufacturers, the battery size of the most common pure electric vehicles (removing 2 kWh for safety reason) are: (38 kWh, Nissan Leaf), (42 kWh Renault Zoe), and considering a driving range of 225 km. The battery percentage that will be used for a driving distance of 80 km, if the CPT system will cover 10% of the total length of the highway is 51% for a Nissan Leaf and 46% for a Renault Zoe, as the Figure 20, shows. On the other hand, for a total CPT system covered with 50% of the highway total distance, the battery of the electric car would not be necessary to be used. Otherwise, the CPT system will transfer more power to the car that which is needed to drive all the 80 km highway length.

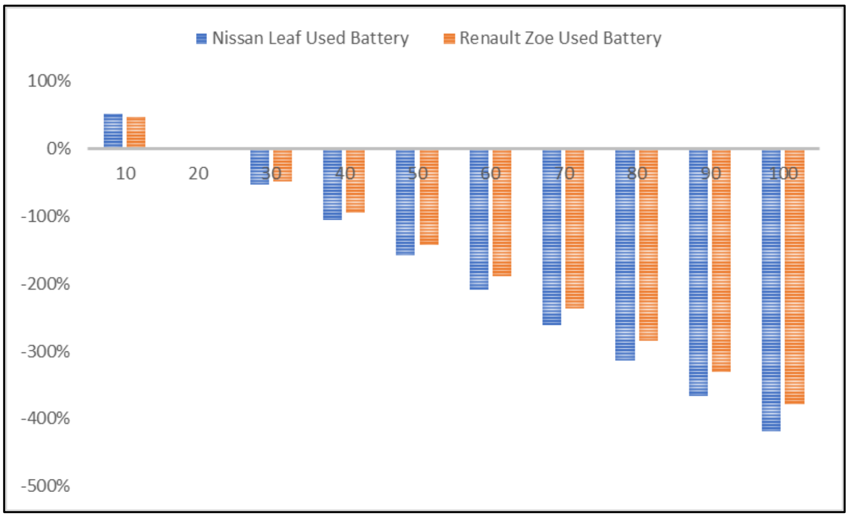


Figure 19: Percentage of electric car battery used depending to the CPT system % covered along the highway

Therefore, as the above figure shows, the electric car battery reduction is feasible, as a consequence, the price of the car and the environmental impact will be lower. For a smaller CPT system covered, the battery size will have a significant impact on the amount of power needed. Since the distance not covered by the CPT system needs to be covered by the battery. With that in mind, for a 50% of the highway length covered with CPT system, the battery size will not be even reduced to the minimum, but the system will provide 150% of the energy that the electric car will need to cover that highway distance. Even though, it should be taken into account the total flow of cars on the highway as well as the highway distance to be covered with CPT system, as it will be seen in section *8. Case of Studies*.

6. Daily and Monthly Global Solar Radiation on an Inclined Surface

6.1. Methodology

To get the daily and monthly Global Solar Radiation on an inclined surface, a set of inputs has been inserted in order to develop a mathematical method to predict the global solar radiation for any given place on the world. These set of inputs are as follows (*Table 15: Input example for getting the total irradiance value for a given location.)*:

- Latitude (Lat)
- Longitude (Lng)
- Location, City and Country (even when would not be relevant for the data deliverable)
- Altitude (m)
- Date (dd/mm/yyyy)
- Hour (hh:mm:ss)
- Time to Zone (± to E), (e.g., UK Time +0, Los Angeles Time -7)
- Surface Azimuth, (e.g., 180° South, 270° West, 90° E, 0° N)
- Ground reflectivity, (e.g., 0.25,0.20)

Surface Azimuth (º)	-180/+180	***South***	***Latitude***	º
Ground reflectivity	0.25/1.25		***Longitude***	º
Date	dd/mm/hhhh		***Location***	City
Time to Zone (+to E)	+0		***Country***	Name
			Altitude	m

Table 15: Input example for getting the total irradiance value for a given location

Once the data input is inserted, the excel spreadsheet will calculate automatically a set of outputs needed to get the final global radiation data. Therefore, it will be calculated the following:

- Day of the week, month and day of the year
- Solar Time form the Location
- Solar Data from the Location
- Collector Plane Orientation
- Total, Hourly Solar Irradiance at the surface of the Earth (kWh/m^2)

6.1.1. *Day of the week, month and day of the year*

To get all the final data consecutively ordered from the input date from now on, a couple of formulas must be settled to get the exact day of the week, month and day of the year for the given data, to this effect the following formulas have been established in the excel spreadsheet:

- Exact day of the week (DoW):

$$* \ CHOOSE(WEEKDAY(Date),\text{Sunday,Monday,Tuesday,Wednesday},$$
$$= \text{Thursday,Friday,Saturday}) \quad (Equation\ 1)$$

- Exact month of the year (MoY):

$$* \ CHOOSE(MONTH(Date),"Jan","Feb","Mar","Apr","May","Jun",$$
$$"Jul","Aug","Sep","Oct","Nov","Dec") \ (Equation\ 2)$$

- Day of the year (DoY):

$$* \ (Date) - DATE(YEAR(Date), 1{,}0) \quad (Equation\ 3)$$

6.1.2. Solar Time

The solar time is a crucial factor to get the global irradiance, that is variable depending on the latitude, longitude and zone time of the given place. Following the doctrines highlighted in ("NOAA Solar Position Calculator," n.d.).Therefore, a set of data must be calculated:

- Hour Angle (w, deg)

For describing the rotation of the earth around its polar axis, which is equivalent to +15° per hour during the morning and -15° per hour during the afternoon. Also, it is described as the angular distance between the observer´s meridian and the meridian whose plane contains the sun. At noon the hour angle is always 0°. The following equation has been used to calculate the hour angle in degrees.

$$\begin{aligned} * \, DEGREES(ACOS(COS(RADIANS(90.833))/(COS(RADIANS(Lat)) \\ * \, COS(RADIANS(Sd) - TAN(RADIANS(Lat)) \\ * \, TAN(RADIANS(Sd) \quad (Equation\ 4) \end{aligned}$$

- Solar noon (SN, hh:mm: ss)

For getting the exact hour in which, the Sun passes a location´s and reaches its highest position in the sky, except at the poles.

$$\begin{aligned} * \ (720 - 4 * (Lng) - (\mathrm{EoT}) + (Time\_to\_Zone) \\ * \, 60)/1440 \quad (Equation\ 5) \end{aligned}$$

- Sunrise Time (ST, hh:mm: ss)

For getting the moment when the upper limb of the Sun appears on the horizon in the morning.

$$* \left((SN) - (w) * \frac{4}{1440} \right) (Equation\ 6)$$

- Sunset Time (St, hh:mm: ss)

For getting the moment when the lower limb of the Sun disappears below the horizon in the afternoon.

$$* \left((SN) + (w) * \frac{4}{1440} \right) (Equation\ 7)$$

- Sunlight duration (Sd, min, h)

For knowing how many hours per day a PV installation will be able to produce electricity.

$$* \ \big(8 * (w)\big)/60) \ \ (Equation\ 8)$$

6.1.3. Solar Data from the location

Depending on the latitude, longitude, and the zone time of the given data, the following factors will be calculated:

- Solar Declination angle (Ɣ, º)

The solar declination angle is the angular distance from the sun north or south to the earth´s equator. The maximum and minimum declination angle values of the earth´s orbit is variable with the season. The declination angles fluctuate between 23.45º north and 23.45º south. In the northern hemisphere, the earth is declined -23.45º from the sun around 21 December, and the is declined 23.45º from the sun around 21 June.

Meanwhile, during the fall and spring equinoxes, the sun passes directly over the equator, which begins 21 September and 21 March — being the opposite on the southern hemisphere as the below picture shows.

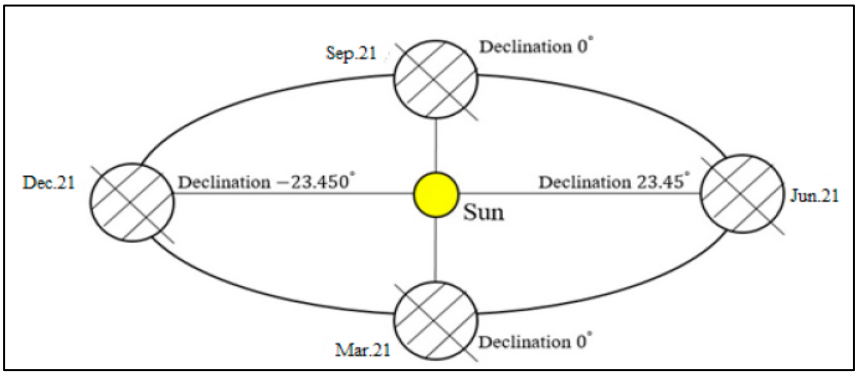


Figure 20: Maximum and Minimum value of declination angle. (H. Hizam, 2017)

Being the declination formula as follows:

$$* \; 23.45 * SIN(RADIANS(280.1 + 0.9863 * DoY))(Equation\ 9)$$

- Equation of Time (EoT)

For describing the discrepancy between time kept by an ordinary electrical or mechanical clock, keeping civil time, and the time kept by the sun, such as what a sundial would read (usno.navy, 2017), given by the following equation:

$$\begin{aligned} * \; 9.87 * SIN(RADIANS((1.978 * DoY) - 160.22)) - 7.53 \\ * COS(RADIANS((0.989 * DoY) - 80.11)) - (1.5 \\ * SIN(RADIANS(0.989 * DoY - 80.11)))(Equation\ 10) \end{aligned}$$

- Solar time (Sm, min)

For measuring the Earth´s rotation relative to the Sun. It is measured by direct observation if the Sun travelled apparent uniform speed throughout the year, instead of, at a slightly varying apparent speed that depends on the seasons, given by the following equation:

$$\begin{aligned} * \; MOD(Hour * 1440 + EoT + 4 * Lng - 60 \\ * Time\_to\_Zone, 1440) \; (Equation\ 11) \end{aligned}$$

- Hour angle (w, º)

For getting the angle between an observer´s meridian and the hour circle on which some celestial bodies lie, the number of degrees the earth must turn before the sun is directly over the local meridian must be calculated. All the calculations have been made taking the hour angle in degrees, cause 15º of arc being equal to one hour (Encyclopedia Britannica, 2019), given by the following equation:

$$* \; MIF(Sm/4 < 0, Sm/4 + 180, Sm/4 - 180) \; (Equation\ 12)$$

6.1.4. Collector Plane Orientation

Once the Solar time and Solar data from the given location have been calculated, the excel spreadsheet will calculate the solar, azimuth and collector tilt angles that will affect the power output of the Solar PV installation; these angles are the followings:

- Solar Altitude (β_s,º)

For getting the angular displacement to form the south of the beam radiation projection on the horizontal plane, as it is shown in Figure 22: Solar Azimuth (º), (H. Hizam, 2017).

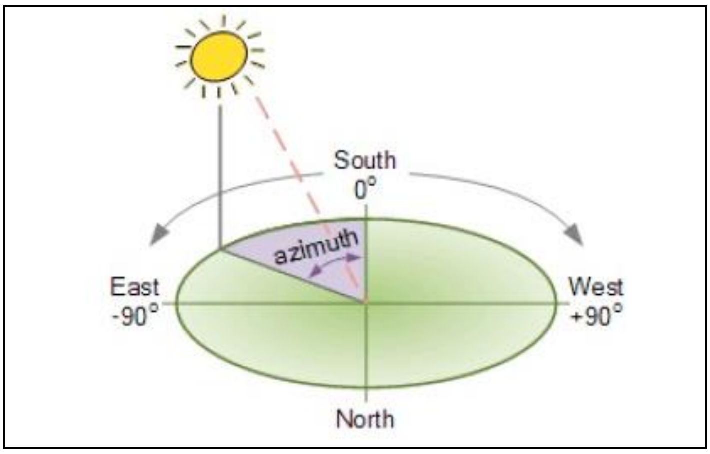


Figure 21: Solar Azimuth (º), (H. Hizam, 2017)

Therefore, the following equation has been deployed:

$$\begin{aligned}
&\ast\ DEGREESDEGREES((ASIN((SIN(RADIANS(Lat))\\
&\quad \ast SIN(RADIANS(\text{Ɣ}))) + COS(RADIANS(Lat))\\
&\quad \ast COS(RADIANS(\text{Ɣ}))\\
&\quad \ast COS(RADIANS(Ha)))))(\mathit{Equation}\ 13)
\end{aligned}$$

- Solar Zenith Angle (α_s,°)

For getting the angle between the local zenith (i.e. directly above the point on the ground) and the line of sight from that point to the sun. Meaning as higher is the Solar Zenith Angle; lower is the high of the Sun in the sky. Elaborating the ensuing equation:

$$\begin{aligned}
&\ast\ DEGREES\Big(ACOS\Big(SIN\big(RADIANS(\$L\$at)\big) \ast SIN\big(RADIANS(\text{Ɣ})\big)\\
&\qquad + COS\big(RADIANS(\$L\$at)\big) \ast COS\big(RADIANS(\text{Ɣ})\big)\\
&\qquad \ast COS\big(RADIANS(Ha)\big)\Big)\Big)\ (\mathit{Equation}\ 14)
\end{aligned}$$

The values provide for equation 13, had given not precise data from the Northern Hemisphere. Therefore another Solar Zenith Angle equation was deployed in order to get more precise values, following as follows:

$$\begin{aligned}
&\ast IF(Ha > 0, MOD(DEGREES(ACOS(((SIN(RADIANS(\$L\$at))\\
&\qquad \ast COS(RADIANS(Sz))\\
&\qquad - SIN(RADIANS(\text{Ɣ})))/(COS(RADIANS(\$L\$at))\\
&\qquad \ast SIN(RADIANS(Sz))))) + 180{,}360), MOD(540\\
&\qquad - DEGREES(ACOS(((SIN(RADIANS(\$L\$at))\\
&\qquad \ast COS(RADIANS(Sz))\\
&\qquad - SIN(RADIANS(\text{Ɣ})/(COS(RADIANS(\$L\$at)\\
&\qquad \ast SIN(RADIANS(Sz),360))\ (\mathit{Equation}\ 15)
\end{aligned}$$

- Surface Solar-Azimuth (α_f,º)

For getting the angular displacement to the sun position and the angles that define the PV module position, through the following equation:

$$* \; ABS(Sa - Sz) \; (Equation\ 16)$$

- The optimal angle of the PV module (β_f,º)

For receiving the maximum possible irradiance in a tilted surface, an optimal angle of inclination must be calculated, considering it variable during the year, by the use of the following equation:

$$* \; 90 - (90 + ɣ - Lat)(Equation\ 17)$$

For standardise the calculations, a fixed average angle of the PV module has been calculated (β_{ff}), taking the average of the optimal daily angle for every single day of the year for the location given. As could be seen in the chapters *0 Table 16:* Example of the Input data to get the hourly energy production for a given PV Panel

6.2. Temperature data

One of the most essential factor to get the hourly energy production for a given PV Panel, is the PV Panel temperature, as higher the PV Panel temperature is as lower will be its efficiency output. In this thesis has been considered the PV Panel Temperature on the PV panel is calculated as follows (“Forecasting the Cell Temperature of PV Modules with an Adaptive System,” 2018):

$$* \, T_{PV=} \, T_{air} + (T_{nor} - 20) * \left(\frac{I_T}{800}\right), (°\mathrm{C})(Equation\ 31)$$

$$-T_{air} = Air\ temperature$$

$$-T_{nor} = PV\ Panel, Normal\ Temperature. Given\ for\ the\ manufacturer$$

$$-I_T = Total\ hourly\ irradiance\ (W/m^2)$$

6.3. Calculation method

For getting the hourly energy production for a given PV Panel, in this thesis had been an asset the following equation:

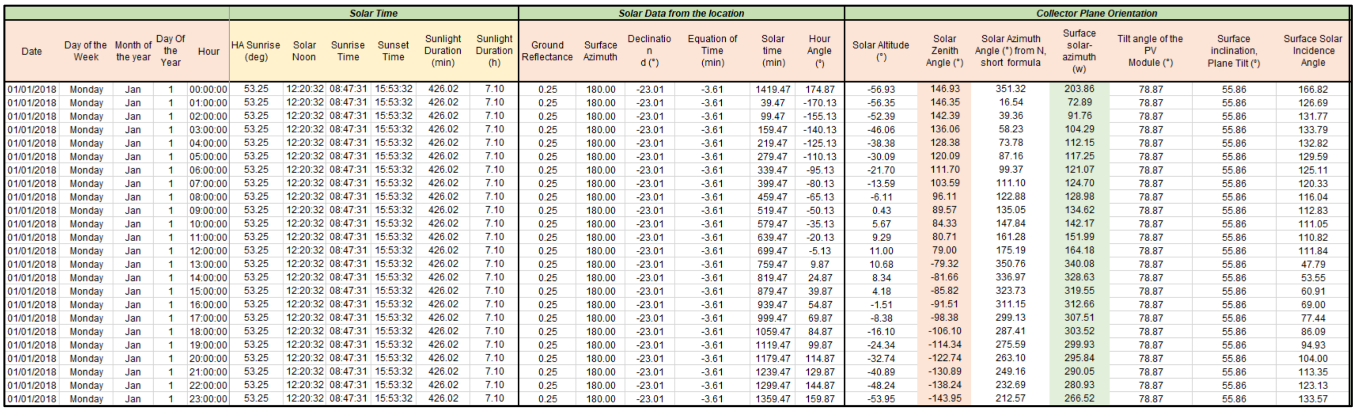
$$* IF(I_T < 0{,}0, (\$Poutput\$ * I_T/\$Reference\_condition\$) * ((1 - ((T_{PV} - \$T_{nor}\$) * \$\Omega\$)) * \$\eta\$)) * \$Area\$) (Equation\ 32)$$

The harmful irradiance data are ruled out, cause this value is produced during the night where it is not any kind of irradiance.

- P output (W): Maximum power output for ideal conditions, given by the PV Panel manufacturer
- Reference Conditions (W/m^2) = 1000 W/m^2, constant value considered as the optimal power production per square meter
- Ω $(\frac{W}{K})$: Constant value, also given for the PV Panel manufacturer
- η: PV panel efficiency, given for the manufacturer
- Area (m^2): Total size area of each PV Panel

and *7.5.2 Tracking PV Panel*, the monthly irradiance data change prominently if the inclination of the PV Panel can change automatically applying a dynamic sun tracker.

- Surface Solar Incidence Angle (i_b,º)



					Solar Time						Solar Data from the location						Collector Plane Orientation						
Date	Day of the Week	Month of the year	Day Of the Year	Hour	HA Sunrise (deg)	Solar Noon	Sunrise Time	Sunset Time	Sunlight Duration (min)	Sunlight Duration (h)	Ground Reflectance	Surface Azimuth	Declination d (°)	Equation of Time (min)	Solar time (min)	Hour Angle (°)	Solar Altitude (°)	Solar Zenith Angle (°)	Solar Azimuth Angle (°) from N, short formula	Surface solar-azimuth (w)	Tilt angle of the PV Module (°)	Surface inclination, Plane Tilt (°)	Surface Solar Incidence Angle
01/01/2018	Monday	Jan	1	00:00:00	53.25	12:20:32	08:47:31	15:53:32	426.02	7.10	0.25	180.00	-23.01	-3.61	1419.47	174.87	-56.93	146.93	351.32	203.86	78.87	55.86	166.82
01/01/2018	Monday	Jan	1	01:00:00	53.25	12:20:32	08:47:31	15:53:32	426.02	7.10	0.25	180.00	-23.01	-3.61	39.47	-170.13	-56.35	146.35	16.54	72.89	78.87	55.86	126.69
01/01/2018	Monday	Jan	1	02:00:00	53.25	12:20:32	08:47:31	15:53:32	426.02	7.10	0.25	180.00	-23.01	-3.61	99.47	-155.13	-52.39	142.39	39.36	91.76	78.87	55.86	131.77
01/01/2018	Monday	Jan	1	03:00:00	53.25	12:20:32	08:47:31	15:53:32	426.02	7.10	0.25	180.00	-23.01	-3.61	159.47	-140.13	-46.06	136.06	58.23	104.29	78.87	55.86	133.79
01/01/2018	Monday	Jan	1	04:00:00	53.25	12:20:32	08:47:31	15:53:32	426.02	7.10	0.25	180.00	-23.01	-3.61	219.47	-125.13	-38.38	128.38	73.78	112.15	78.87	55.86	132.82
01/01/2018	Monday	Jan	1	05:00:00	53.25	12:20:32	08:47:31	15:53:32	426.02	7.10	0.25	180.00	-23.01	-3.61	279.47	-110.13	-30.09	120.09	87.16	117.25	78.87	55.86	129.59
01/01/2018	Monday	Jan	1	06:00:00	53.25	12:20:32	08:47:31	15:53:32	426.02	7.10	0.25	180.00	-23.01	-3.61	339.47	-95.13	-21.70	111.70	99.37	121.07	78.87	55.86	125.11
01/01/2018	Monday	Jan	1	07:00:00	53.25	12:20:32	08:47:31	15:53:32	426.02	7.10	0.25	180.00	-23.01	-3.61	399.47	-80.13	-13.59	103.59	111.10	124.70	78.87	55.86	120.33
01/01/2018	Monday	Jan	1	08:00:00	53.25	12:20:32	08:47:31	15:53:32	426.02	7.10	0.25	180.00	-23.01	-3.61	459.47	-65.13	-6.11	96.11	122.88	128.98	78.87	55.86	116.04
01/01/2018	Monday	Jan	1	09:00:00	53.25	12:20:32	08:47:31	15:53:32	426.02	7.10	0.25	180.00	-23.01	-3.61	519.47	-50.13	0.43	89.57	135.05	134.62	78.87	55.86	112.83
01/01/2018	Monday	Jan	1	10:00:00	53.25	12:20:32	08:47:31	15:53:32	426.02	7.10	0.25	180.00	-23.01	-3.61	579.47	-35.13	5.67	84.33	147.84	142.17	78.87	55.86	111.05
01/01/2018	Monday	Jan	1	11:00:00	53.25	12:20:32	08:47:31	15:53:32	426.02	7.10	0.25	180.00	-23.01	-3.61	639.47	-20.13	9.29	80.71	161.28	151.99	78.87	55.86	110.82
01/01/2018	Monday	Jan	1	12:00:00	53.25	12:20:32	08:47:31	15:53:32	426.02	7.10	0.25	180.00	-23.01	-3.61	699.47	-5.13	11.00	79.00	175.19	164.18	78.87	55.86	111.84
01/01/2018	Monday	Jan	1	13:00:00	53.25	12:20:32	08:47:31	15:53:32	426.02	7.10	0.25	180.00	-23.01	-3.61	759.47	9.87	10.68	-79.32	350.76	340.08	78.87	55.86	47.79
01/01/2018	Monday	Jan	1	14:00:00	53.25	12:20:32	08:47:31	15:53:32	426.02	7.10	0.25	180.00	-23.01	-3.61	819.47	24.87	8.34	-81.66	336.97	328.63	78.87	55.86	53.55
01/01/2018	Monday	Jan	1	15:00:00	53.25	12:20:32	08:47:31	15:53:32	426.02	7.10	0.25	180.00	-23.01	-3.61	879.47	39.87	4.18	-85.82	323.73	319.55	78.87	55.86	60.91
01/01/2018	Monday	Jan	1	16:00:00	53.25	12:20:32	08:47:31	15:53:32	426.02	7.10	0.25	180.00	-23.01	-3.61	939.47	54.87	-1.51	-91.51	311.15	312.66	78.87	55.86	69.00
01/01/2018	Monday	Jan	1	17:00:00	53.25	12:20:32	08:47:31	15:53:32	426.02	7.10	0.25	180.00	-23.01	-3.61	999.47	69.87	-8.38	-98.38	299.13	307.51	78.87	55.86	77.44
01/01/2018	Monday	Jan	1	18:00:00	53.25	12:20:32	08:47:31	15:53:32	426.02	7.10	0.25	180.00	-23.01	-3.61	1059.47	84.87	-16.10	-106.10	287.41	303.52	78.87	55.86	86.09
01/01/2018	Monday	Jan	1	19:00:00	53.25	12:20:32	08:47:31	15:53:32	426.02	7.10	0.25	180.00	-23.01	-3.61	1119.47	99.87	-24.34	-114.34	275.59	299.93	78.87	55.86	94.93
01/01/2018	Monday	Jan	1	20:00:00	53.25	12:20:32	08:47:31	15:53:32	426.02	7.10	0.25	180.00	-23.01	-3.61	1179.47	114.87	-32.74	-122.74	263.10	295.84	78.87	55.86	104.00
01/01/2018	Monday	Jan	1	21:00:00	53.25	12:20:32	08:47:31	15:53:32	426.02	7.10	0.25	180.00	-23.01	-3.61	1239.47	129.87	-40.89	-130.89	249.16	290.05	78.87	55.86	113.35
01/01/2018	Monday	Jan	1	22:00:00	53.25	12:20:32	08:47:31	15:53:32	426.02	7.10	0.25	180.00	-23.01	-3.61	1299.47	144.87	-48.24	-138.24	232.69	280.93	78.87	55.86	123.13
01/01/2018	Monday	Jan	1	23:00:00	53.25	12:20:32	08:47:31	15:53:32	426.02	7.10	0.25	180.00	-23.01	-3.61	1359.47	159.87	-53.95	-143.95	212.57	266.52	78.87	55.86	133.57

Figure 22: Example of the excel spreadsheet results for Solar time, Solar Data and Collector Plane Orientation for a given

- For getting the angle between the sun´s rays and the normal on a surface. For a horizontal plane, the incidence angle (i_b), and the zenith angle (α_s) are the same. On the excel spreadsheet Figure 23, is calculated, trough the following equation:

$$* DEGREES(ACOS(COS(RADIANS(90-\beta_{ff})*SIN(RADIANS(\beta_s)) + COS(RADIANS(\beta_s)*COS(RADIANS(\alpha_f)) * SIN(RADIANS(90-\beta_{ff})(Equation\ 18)$$

6.3.1. Hourly Solar Irradiance at the surface of the Earth (kWh/m^2)

For getting the total Solar Radiation striking a tilt PV Panel on a clear sky, the American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE) (Masters, 2005) model has been used to deploy the next equations. Firstly, the Hourly

Solar irradiance striking at the surface of the Earth must be calculated, where the direct, diffuse and reflected irradiance are calculated, for that purpose the following equations are needed:

- Beam portion of solar radiation, normal to the rays (I_{BN}) passes through the atmosphere and arrives at the earth´s surface on a clear day (See *6.4.1 below Solar data assumptions and not considerations*), bearing in mind the incoming equation:

$$* \text{IBN} = (A) * (EXP(m * k * -1))(Equation\ 19)$$

- A= Apparent Extra-terrestrial Flux (W/m^2)

$$- A = \ 1160 + 75 * SIN(RADIANS((360/365) * (DoY - 275)\ (Equation\ 20)$$

- m= Air Mass Ratio

$$- m = \ 1/SIN(RADIANS(\beta_s))\ (Equation\ 21)$$

- K= Optical Depth

$$- k = \ 0.174 + 0.035 * SIN(RADIANS((360/365) * (DoY - 100)))\ (Equation\ 22)$$

- Direct-Beam radiation striking a tilt PV Panel (I_{BS}), is an equation depending on the angle between a line drawn normal to the collector's face and the incoming bean radiation, as it is shown in the following equation:

$$* \text{IBS} = \text{IBN} * \cos \emptyset, (\frac{\text{W}}{m^2})(Equation\ 23)$$

$- \theta$ = Angle of incidence of an equator facing surface in degrees

$$-\cos\emptyset = \cos(\beta_s) * \cos(\alpha_s - \alpha_f) * \sin\ (\beta_f) + \sin\ (\beta_s) * \cos\ (\beta_f)\ (Equation\ 25)$$

- Diffuse radiation striking a tilt PV Panel (I_D), this radiation is much more difficult to calculate than the direct radiation, since the radiation can be scattered from atmospheric particles and moisture. Also, it can be reflected by clouds. Some of them are reflected from the surface back into the sky and scattered again to the surface. Due to the complexity to estimate the diffuse radiation in this thesis accurately, have been assumed that the diffuse radiation I_D is proportional to the direct beam portion of solar radiation normal to the rays (I_{BN}), as it is used by the (ASHRAE). Therefore the equation is as follows:

$$* 0.5 * \mathrm{C} * \mathrm{IBN} * \left(\left(1 + \mathrm{COS}\left(\mathrm{RADIANS}(\beta_f)\right)\right)\right), (\mathrm{W}/m^2)(Equation\ 27)$$

$$-C = Diffuse\ factor =$$

$$= 0.095 + 0.04 * \mathrm{SIN}(\mathrm{RADIANS}((360/365) * (\mathrm{DoY} - 100)(Equation\ 28)$$

- Reflected radiation striking a tilt PV Panel (I_R), this radiation is the result of the reflected radiation by surface in front of the PV Panel. The ground reflectance is an input data, but an estimation of ground reflectance ranges from about 0.8 for fresh snow to about 0.1 for a bituminous-and gravel roof, which the most typical default value for common ground or grass is taken around 0.20/0.25. The amount reflected is calculated as follows:

$$* 0.5 * \mathrm{Gr} * \mathrm{IBN} * \left(\mathrm{SIN}\left(\mathrm{RADIANS}(\beta_s)\right) + \mathrm{C}\right) * \left(1 - \mathrm{COS}\left(\mathrm{RADIANS}(\beta_s)\right)\right), (\mathrm{W}/m^2)(Equation\ 29)$$

Once calculated, each of the radiation individually, the total hourly radiation at the surface of the earth is the summation of the Direct, Diffuse and Reflected radiation. Therefore the equation is as follows:

$$* I_{T=} I_{BS} + I_D + I_R , (\mathrm{W}/m^2) (Equation\ 30)$$

6.4. Results

As being the solar irradiance a value dependent on multiple different factors, such as cloudiness, pollution level on the atmosphere, rain, snow, wind, dust and dirtiness. Modelling an accurate solar mathematical model to predict the hourly irradiance value in every single place around the earth, it is nearly unattainable. For that, in this thesis had been developed a mathematical model that consider the smooth factors that affect the total irradiance value for an input data. Henceforth, is thesis is mentioned the direct irradiance in a tilt panel, the diffuse irradiance in a tilt panel, but just considering a bright sky landscape as well as the irradiance due to the reflection, where the most critical value is the input value of Ground reflected (Gr). Consequently, in the following subsection, *6.4.1. Solar data assumptions and not considerations*, all the factors that should be taken into consideration to develop a highly precise mathematical method to predict the total irradiance value for a given point are aforementioned.

6.4.1. Solar data assumptions and not considerations

To predict the diffuse radiation in an inclined surface, several mathematical models have been defined to estimate it. That model can be classified is two different types as follows:

- Isotropic models

This model needs information about the environmental conditions about the given place, such as atmospheric turbidity, partial sunshine, cloud cover, and perceptible water content (Gueymard, 1993). Therefore, for making it more straightforward is this thesis, the ASHRAE method has been chosen to an estimate the diffuse radiation on inclined surfaces. So, this model assumes there is uniformity in the distribution of diffuse radiation over the sky.

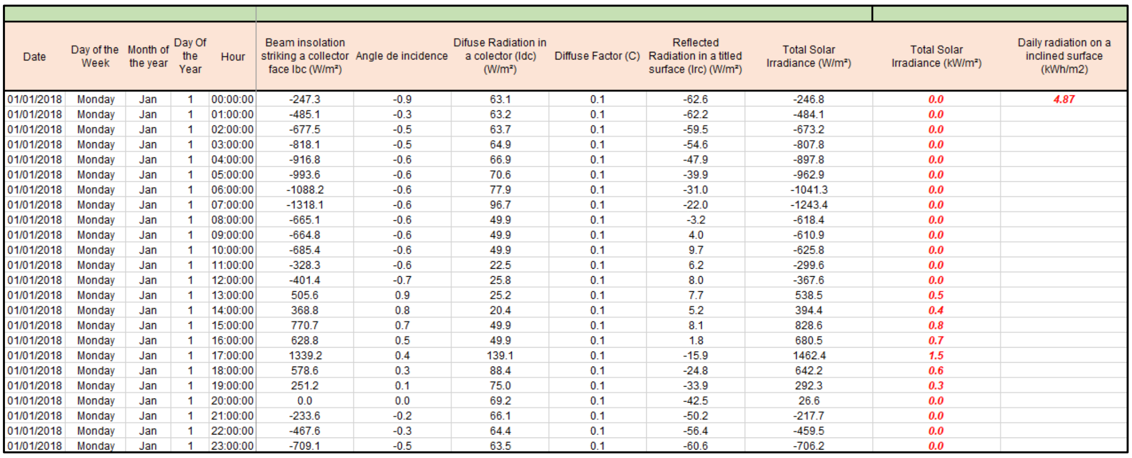
- Anisotropic models

  This model is much precise than the isotropic model because it uses data from global radiation to estimate diffuse radiation. Comparing the total diffuse radiation for a horizontal surface, having a clearness index factor, to determinate the atmospheric effects in an isolated place. As a random parameter, it changes with the time of the year, season, climatic conditions and geographical situation of the given location. This mathematical method has a high level of complexity, taking a lot of different factors to estimate with, for that, this method has been ruled out.

6.4.2. Data Outputs

The ultimate aim of the excel spreadsheet is to get an hourly data radiance output by the data inputs value presented before ***Error! Reference source not found.*****.** ***Error! Reference source not found.***, to this, affect each of the different irradiance reaching a tilted surface, Direct, Diffuse and Reflected are combined together to get the total irradiance hourly value for a given location, as it is shown on the next ***Error! Reference source not found.***.

The excel spreadsheet will calculate the daily total irradiance (Daily/kWh/m^2), for all year round. Then, on the following sheet, the total monthly irradiance (Monthly/kWh/m^2) will be calculated as well, summing all the daily irradiance date depending on the days that have every single month on the year. As can be seen in section *8. Case of Studies.*



Date	Day of the Week	Month of the year	Day Of the Year	Hour	Beam insolation striking a collector face Ibc (W/m²)	Angle de incidence	Difuse Radiation in a colector (Idc) (W/m²)	Diffuse Factor (C)	Reflected Radiation in a titled surface (Irc) (W/m²)	Total Solar Irradiance (W/m²)	Total Solar Irradiance (kW/m²)	Daily radiation on a inclined surface (kWh/m2)
01/01/2018	Monday	Jan	1	00:00:00	-247.3	-0.9	63.1	0.1	-62.6	-246.8	*0.0*	*4.87*
01/01/2018	Monday	Jan	1	01:00:00	-485.1	-0.3	63.2	0.1	-62.2	-484.1	*0.0*	
01/01/2018	Monday	Jan	1	02:00:00	-677.5	-0.5	63.7	0.1	-59.5	-673.2	*0.0*	
01/01/2018	Monday	Jan	1	03:00:00	-818.1	-0.5	64.9	0.1	-54.6	-807.8	*0.0*	
01/01/2018	Monday	Jan	1	04:00:00	-916.8	-0.6	66.9	0.1	-47.9	-897.8	*0.0*	
01/01/2018	Monday	Jan	1	05:00:00	-993.6	-0.6	70.6	0.1	-39.9	-962.9	*0.0*	
01/01/2018	Monday	Jan	1	06:00:00	-1088.2	-0.6	77.9	0.1	-31.0	-1041.3	*0.0*	
01/01/2018	Monday	Jan	1	07:00:00	-1318.1	-0.6	96.7	0.1	-22.0	-1243.4	*0.0*	
01/01/2018	Monday	Jan	1	08:00:00	-665.1	-0.6	49.9	0.1	-3.2	-618.4	*0.0*	
01/01/2018	Monday	Jan	1	09:00:00	-664.8	-0.6	49.9	0.1	4.0	-610.9	*0.0*	
01/01/2018	Monday	Jan	1	10:00:00	-685.4	-0.6	49.9	0.1	9.7	-625.8	*0.0*	
01/01/2018	Monday	Jan	1	11:00:00	-328.3	-0.6	22.5	0.1	6.2	-299.6	*0.0*	
01/01/2018	Monday	Jan	1	12:00:00	-401.4	-0.7	25.8	0.1	8.0	-367.6	*0.0*	
01/01/2018	Monday	Jan	1	13:00:00	505.6	0.9	25.2	0.1	7.7	538.5	*0.5*	
01/01/2018	Monday	Jan	1	14:00:00	368.8	0.8	20.4	0.1	5.2	394.4	*0.4*	
01/01/2018	Monday	Jan	1	15:00:00	770.7	0.7	49.9	0.1	8.1	828.6	*0.8*	
01/01/2018	Monday	Jan	1	16:00:00	628.8	0.5	49.9	0.1	1.8	680.5	*0.7*	
01/01/2018	Monday	Jan	1	17:00:00	1339.2	0.4	139.1	0.1	-15.9	1462.4	*1.5*	
01/01/2018	Monday	Jan	1	18:00:00	578.6	0.3	88.4	0.1	-24.8	642.2	*0.6*	
01/01/2018	Monday	Jan	1	19:00:00	251.2	0.1	75.0	0.1	-33.9	292.3	*0.3*	
01/01/2018	Monday	Jan	1	20:00:00	0.0	0.0	69.2	0.1	-42.5	26.6	*0.0*	
01/01/2018	Monday	Jan	1	21:00:00	-233.6	-0.2	66.1	0.1	-50.2	-217.7	*0.0*	
01/01/2018	Monday	Jan	1	22:00:00	-467.6	-0.3	64.4	0.1	-56.4	-459.5	*0.0*	
01/01/2018	Monday	Jan	1	23:00:00	-709.1	-0.5	63.5	0.1	-60.6	-706.2	*0.0*	

Figure 23: Output example of the total hourly irradiance for a given point (W/m2)

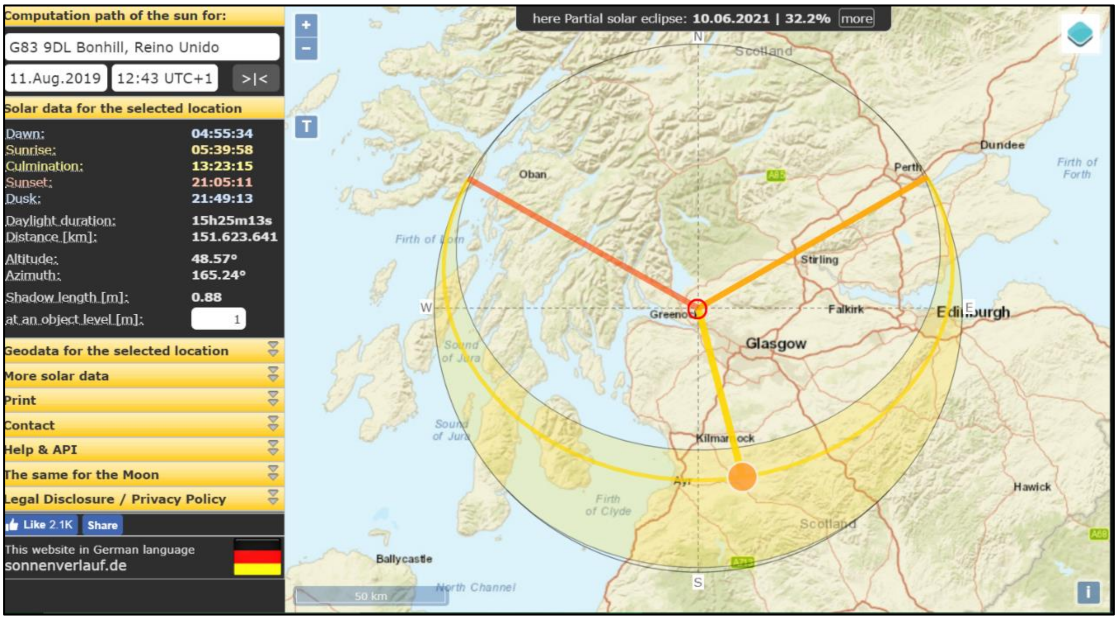
6.5. Solar Data Validation

6.5.1. Solar Time and Solar Data Validation

In order to validate the data given by the equation showed above (*Equation 10*, *Equation 11, Equation 12, Equation 13, Equation 14, Equation 15, Equation 16, Equation 17*), has been used a free software webpage (https://www.suncalc.org), where once the input data has been added (Date, Latitude, Longitude, Hour) the software automatically will calculated the following values to compare with (:

- Sunrise Time: ST
- Sunset Time: St

- Solar declination: Ɣ
- Solar noon: SN
- Sunlight duration: Sd
- Solar Altitude: β_s
- Solar Zenith Angle: α_s



Computation path of the sun for:

G83 9DL Bonhill, Reino Unido

11.Aug.2019 | 12:43 UTC+1

Solar data for the selected location

Dawn:	04:55:34
Sunrise:	05:39:58
Culmination:	13:23:15
Sunset:	21:05:11
Dusk:	21:49:13
Daylight duration:	15h25m13s
Distance [km]:	151.623.641
Altitude:	48.57°
Azimuth:	165.24°
Shadow length [m]:	0.88
at an object level [m]:	1

here Partial solar eclipse: 10.06.2021 | 32.2%

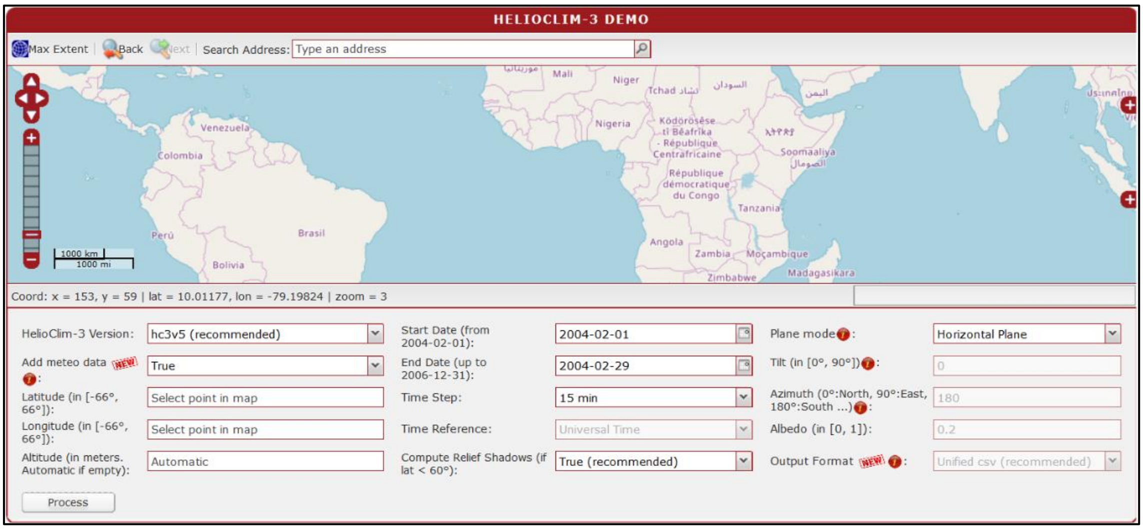
Figure 24:Example taken from the suncal.org, webpage in Glasgow

6.5.2. Solar Irradiation Data Validation

For the solar irradiation data validation, the results given for the mathematical model followed in the thesis have been compared with the hourly irradiation value given for an official solar irradiation data centre, among the many different official data centre, in this thesis have been compared with the data given for the Helioclim-3 Archives, having data from 2004 to 2006. Also, the satellite-derived HC3 Archives Web service provides time series of all components of the radiation over a horizontal, fix-titled and normal plane for the weather conditions by the date and location input data (“HelioClim-3 Archives for Free - www.soda-pro.com,” 2004).

As the diffuse irradiation has been considered in a clear sky day, the solar irradiation data centre also considered a clear sky day. Therefore the result validation can be compared with the same sky conditions.

To get the hourly irradiance data, it is necessary first to sign-in on the Solar Radiation webpage (SODA) (*http://www.soda-pro.com/web-services/radiation/helioclim-3-archives-for-free*) and makes a free account, once it has been done. The SODA webpage shows the following dialogue window, *Figure 26: SODA webpage, dialog window.*.



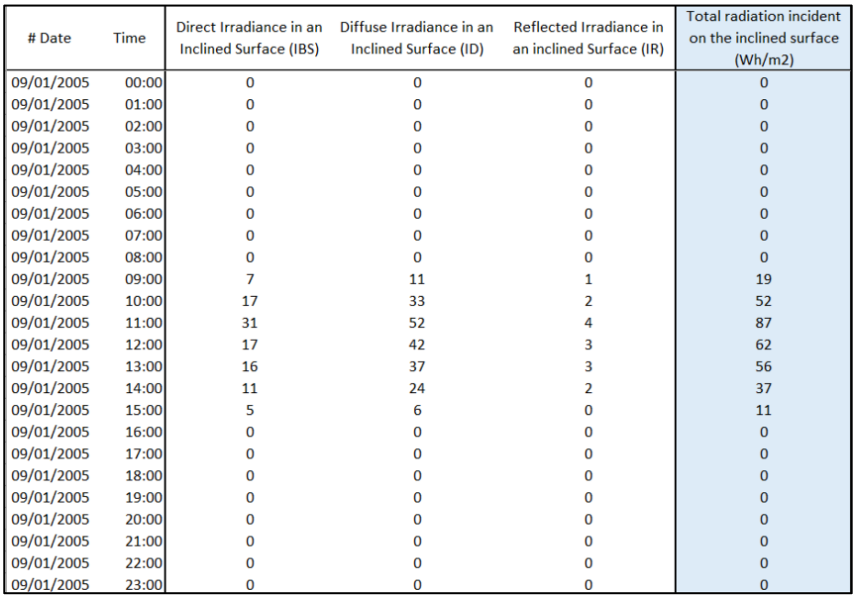
Coord: x = 153, y = 59 | lat = 10.01177, lon = -79.19824 | zoom = 3

HelioClim-3 Version: hc3v5 (recommended)
Add meteo data: True
Latitude (in [-66°, 66°]): Select point in map
Longitude (in [-66°, 66°]): Select point in map
Altitude (in meters. Automatic if empty): Automatic
Start Date (from 2004-02-01): 2004-02-01
End Date (up to 2006-12-31): 2004-02-29
Time Step: 15 min
Time Reference: Universal Time
Compute Relief Shadows (if lat < 60°): True (recommended)
Plane mode: Horizontal Plane
Tilt (in [0°, 90°]): 0
Azimuth (0°:North, 90°:East, 180°:South ...): 180
Albedo (in [0, 1]): 0.2
Output Format: Unified csv (recommended)

Figure 25: SODA webpage, dialog window.

The following endeavour, is the data insertion, for that it is necessary to insert the Latitude, Longitude, Altitude, Start Date from, End Data from and time step (in this case 1 hour), the plane mode (in this case Fixed tilted plane), the plane tilt at it has been calculated with the (*Equation* 17), the azimuth surface angle as an input, and the ground reflectance as input data as well, also it has to be chosen, in which format the output data are given (in this case in .csv), to be easier to compare this data with the data that it has been already calculated on the thesis mathematical spreadsheet model. Once, all the data have been inserted in the dialogue window, click on the process button the software automatically will give the output data in .csv format, as it is shown in *Figure 27: SODA Software output in .csv format*.

From the data output given, just three spreadsheet files will be taken. The ones that show the Direct Irradiance in an Inclined Surface (I_{BS}), Diffuse Irradiance in an Inclined Surface (I_D), Reflected Irradiance in an inclined Surface (I_R).



# Date	Time	Direct Irradiance in an Inclined Surface (IBS)	Diffuse Irradiance in an Inclined Surface (ID)	Reflected Irradiance in an inclined Surface (IR)	Total radiation incident on the inclined surface (Wh/m2)
09/01/2005	00:00	0	0	0	0
09/01/2005	01:00	0	0	0	0
09/01/2005	02:00	0	0	0	0
09/01/2005	03:00	0	0	0	0
09/01/2005	04:00	0	0	0	0
09/01/2005	05:00	0	0	0	0
09/01/2005	06:00	0	0	0	0
09/01/2005	07:00	0	0	0	0
09/01/2005	08:00	0	0	0	0
09/01/2005	09:00	7	11	1	19
09/01/2005	10:00	17	33	2	52
09/01/2005	11:00	31	52	4	87
09/01/2005	12:00	17	42	3	62
09/01/2005	13:00	16	37	3	56
09/01/2005	14:00	11	24	2	37
09/01/2005	15:00	5	6	0	11
09/01/2005	16:00	0	0	0	0
09/01/2005	17:00	0	0	0	0
09/01/2005	18:00	0	0	0	0
09/01/2005	19:00	0	0	0	0
09/01/2005	20:00	0	0	0	0
09/01/2005	21:00	0	0	0	0
09/01/2005	22:00	0	0	0	0
09/01/2005	23:00	0	0	0	0

Figure 26: SODA Software output in .csv format

Further down, on the *8. Case of Studies* section, both methods of calculation have been compared.

7. Solar Photovoltaic installations design

Once the daily irradiance data has been calculated, the following step is knowing how much energy production it is possible to generate for a specific Photovoltaic Solar Panel (kWh/m^2).

7.1. Input data

All the input data are highlighted in red as it is shown in *Table 16: Example of the Input data to get the hourly energy production for a given PV Panel*.

Manufactured: *Sun Power*		***Technology:***	*Silicon-Monocrystalline*	
Model: *SPR-X22-360*		***Efficiency (%):***	*22.1*	
Reference condition (W/m2)	*1000*	***Size:***	***Length (mm)***	*1559*
Operation temperature (°C)	*25*		***Width (mm)***	*1046*
P output (W)	*360*		***Thickness (mm)***	*46*
β:	*0.04*		***Weight (kg)***	*18.6*
			Area (m^2)	*1.631*

Table 16: Example of the Input data to get the hourly energy production for a given PV Panel

7.2. Temperature data

One of the most essential factor to get the hourly energy production for a given PV Panel, is the PV Panel temperature, as higher the PV Panel temperature is as lower will be its efficiency output. In this thesis has been considered the PV Panel Temperature on the PV panel is calculated as follows ("Forecasting the Cell Temperature of PV Modules with an Adaptive System," 2018):

$$* T_{PV=} T_{air} + (T_{nor} - 20) * \left(\frac{I_T}{800}\right), (°\mathrm{C}) (Equation\ 31)$$

$$-T_{air} = Air\ temperature$$

$$-T_{nor} = PV\ Panel, Normal\ Temperature. Given\ for\ the\ manufacturer$$

$$-I_T = Total\ hourly\ irradiance\ (W/m^2)$$

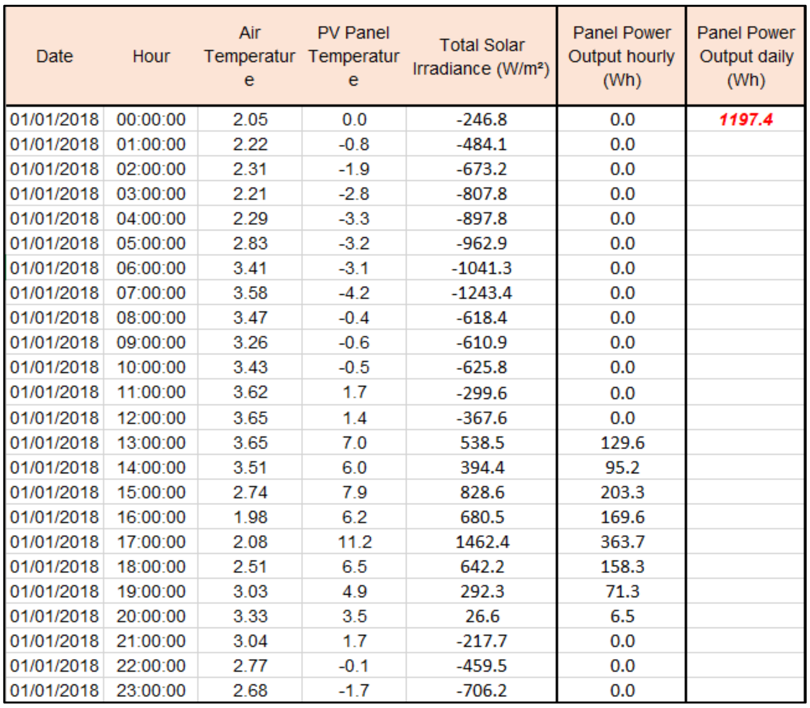
7.3. Calculation method

For getting the hourly energy production for a given PV Panel, in this thesis had been an asset the following equation:

$$* IF(I_T < 0{,}0, (\$\text{Poutput}\$ * I_T/\$\text{Reference\_condition}\$) * ((1 - ((T_{PV} - \$T_{nor}\$) * \$\Omega\$)) * \$ŋ\$)) * \$\text{Area}\$) \quad (Equation\ 32)$$

The harmful irradiance data are ruled out, cause this value is produced during the night where it is not any kind of irradiance.

- P output (W): Maximum power output for ideal conditions, given by the PV Panel manufacturer
- Reference Conditions (W/m^2) = 1000 W/m^2, constant value considered as the optimal power production per square meter
- Ω ($\frac{W}{K}$): Constant value, also given for the PV Panel manufacturer
- ŋ: PV panel efficiency, given for the manufacturer
- Area (m^2): Total size area of each PV Panel



Date	Hour	Air Temperature	PV Panel Temperature	Total Solar Irradiance (W/m^2)	Panel Power Output hourly (Wh)	Panel Power Output daily (Wh)
01/01/2018	00:00:00	2.05	0.0	-246.8	0.0	*1197.4*
01/01/2018	01:00:00	2.22	-0.8	-484.1	0.0	
01/01/2018	02:00:00	2.31	-1.9	-673.2	0.0	
01/01/2018	03:00:00	2.21	-2.8	-807.8	0.0	
01/01/2018	04:00:00	2.29	-3.3	-897.8	0.0	
01/01/2018	05:00:00	2.83	-3.2	-962.9	0.0	
01/01/2018	06:00:00	3.41	-3.1	-1041.3	0.0	
01/01/2018	07:00:00	3.58	-4.2	-1243.4	0.0	
01/01/2018	08:00:00	3.47	-0.4	-618.4	0.0	
01/01/2018	09:00:00	3.26	-0.6	-610.9	0.0	
01/01/2018	10:00:00	3.43	-0.5	-625.8	0.0	
01/01/2018	11:00:00	3.62	1.7	-299.6	0.0	
01/01/2018	12:00:00	3.65	1.4	-367.6	0.0	
01/01/2018	13:00:00	3.65	7.0	538.5	129.6	
01/01/2018	14:00:00	3.51	6.0	394.4	95.2	
01/01/2018	15:00:00	2.74	7.9	828.6	203.3	
01/01/2018	16:00:00	1.98	6.2	680.5	169.6	
01/01/2018	17:00:00	2.08	11.2	1462.4	363.7	
01/01/2018	18:00:00	2.51	6.5	642.2	158.3	
01/01/2018	19:00:00	3.03	4.9	292.3	71.3	
01/01/2018	20:00:00	3.33	3.5	26.6	6.5	
01/01/2018	21:00:00	3.04	1.7	-217.7	0.0	
01/01/2018	22:00:00	2.77	-0.1	-459.5	0.0	
01/01/2018	23:00:00	2.68	-1.7	-706.2	0.0	

Figure 27: Example of an Hourly PV Panel Power output (Wh)

7.4. PV power output validation

A software (PV Sol) has been used at the background of the project, to compare the results obtained by the mathematical procedure developed for the thesis, and real data provided for the data given by the software, processing the settings to estimate the power production for a given place on earth and selecting a PV panel characteristics.

7.5. PV Panel Inclination

A PV installation can be designed to have a fixed inclination throughout the year where the collector is permanently attached to a surface that does not move, or on the contrary, enable the collector with the mobile help rack that follows the sun moves throughout the day. Being more effective than the fixed PV panels, but thus having a substantial price increase.

7.5.1. Fixed PV Panel

In this thesis, a fixed PV panel with an average angle of inclination has been considered. Even though when a daily angle of inclination is calculated in the excel spreadsheet, an average yearly incidence angle has been used as a model for all the year energy production outputs.

7.5.2. Tracking PV Panel

The most effective technique to improve solar panel tilt is to apply a dynamic sun tracker. Dynamic sun trackers are electromechanical or mechanical devices that continually change the tilt of a solar panel array periodically during the day. Although changing the tilt angle from daily to monthly for a PV panel may be more attainable than applying a dynamic sun tracker. Estimating the solar radiation on inclined surfaces is a compulsory aspect in the tilt angle selection, which consequently determines the amount of solar radiation received by the PV module surfaces.

8. Case of Studies

8.1. Glasgow

8.1.1. Input data

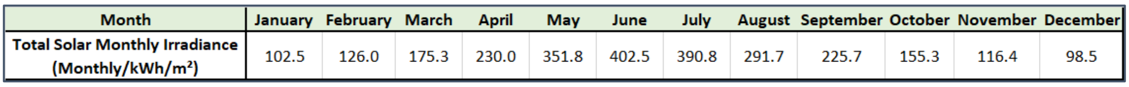
As it has been explained before in chapter *6.1. Methodology of* the inputs data are displayed as follows:

Surface Azimuth	*180*	***South***	***Latitude***	*55.8626*
Ground reflectivity	*0.25*		***Longitude***	*-4.2306*
Date	*01/01/2018*		***Location***	*Glasgow*
Time to Zone (+to E)	*1*		***Country***	*UK*
			Altitude	*187*

Table 17: Input example for getting the total irradiance value for Glasgow

8.2. Sun Irradiance data output

Using the equation already explained and detailed in section *6.4 Results*, the total solar monthly irradiance for Glasgow are as follows:



Month	January	February	March	April	May	June	July	August	September	October	November	December
Total Solar Monthly Irradiance (Monthly/kWh/m^2)	102.5	126.0	175.3	230.0	351.8	402.5	390.8	291.7	225.7	155.3	116.4	98.5

Table 18: Example of the Monthly Irradiance in a table

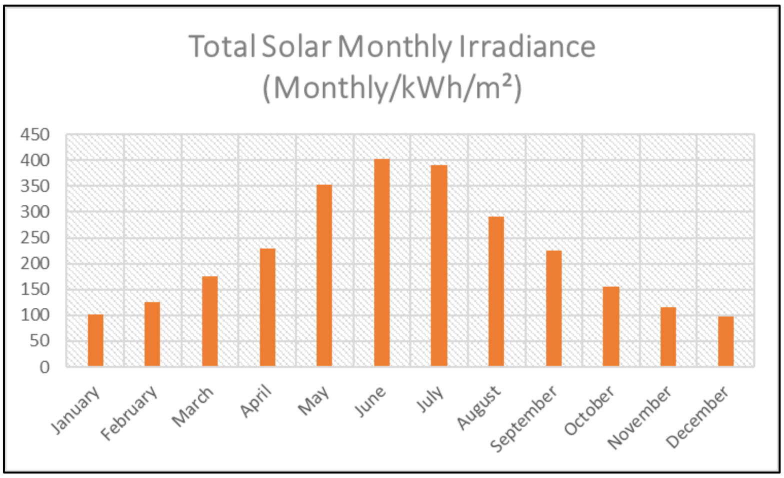


Figure 28: Example of the Monthly Irradiance in a Graph

8.3. Power Output for the PV Installations

As well as it has been done in the previous section, and following the equations already deployed in section *7. Solar Photovoltaic installations design*, considering the modelled PV Solar installation technical specifications displayed in section *7.1 Input data*. The power output data for a Glasgow is as follows:

Month	January	February	March	April	May	June	July	August	September	October	November	December
Average Solar Power Production Monthly per PV panel (kWh/panel/month)	*24.20*	*25.54*	*29.76*	*52.88*	*72.74*	*78.01*	*71.26*	*55.05*	*35.45*	*29.42*	*23.25*	*21.20*

Table 19: Monthly Power Output Table (kWh) for PV Panel in Glasgow

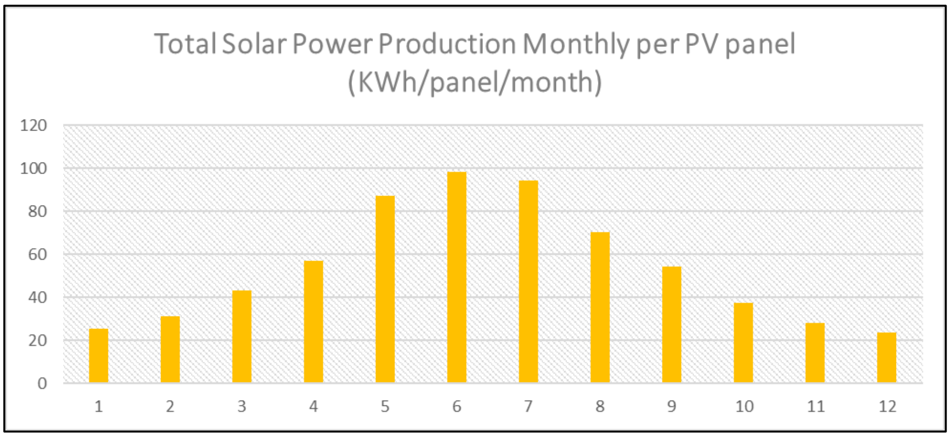
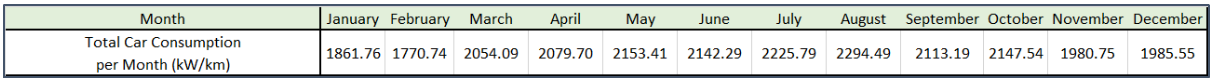


Figure 29: Monthly Power Output Graph (kWh) for PV Panel in Glasgow

8.4. Energy Consumption Requirements

Following what has been already displayed in section *4.3. Monthly power consumption requirements*, and considering this data valid to extrapolate for a Highway in Glasgow, as could be the M8 Highway between Glasgow and Edinburgh, with a high-density daily flow traffic, the total power requirements for the electric vehicles driven on the electric road will be as follows:



Month	January	February	March	April	May	June	July	August	September	October	November	December
Total Car Consumption per Month (kW/km)	1861.76	1770.74	2054.09	2079.70	2153.41	2142.29	2225.79	2294.49	2113.19	2147.54	1980.75	1985.55

Figure 30: Total power consumption for all the electric vehicles passing by (kW/km)

As the Figure 31: Total power consumption for all the electric vehicles passing by (kW/km) shows, the total power electric car consumption is the summary of every single electric vehicle driving on the Highways, an energy consumption is indicated in (kW/km). Therefore, it means that in January, the total consumption for the total month electric cars flow will be 1861.76 kW/km. Extrapolating that result in the total highway length the overall e-Highway will be more prominent.

For a more realistic case, a potential route has been chosen 49 miles (78.89 km), between the University of Strathclyde in Glasgow, and the University of Edinburgh in Edinburgh, of the which 39.2 miles (63.12 km) are travelled in the M8 Highway. Therefore, this route (**Error! Reference source not found.**) is a suitable election for a future installation of an electric road system as it has been explained throughout the thesis, due to its two lines lengthwise the highway, with some points with three lines per direction.

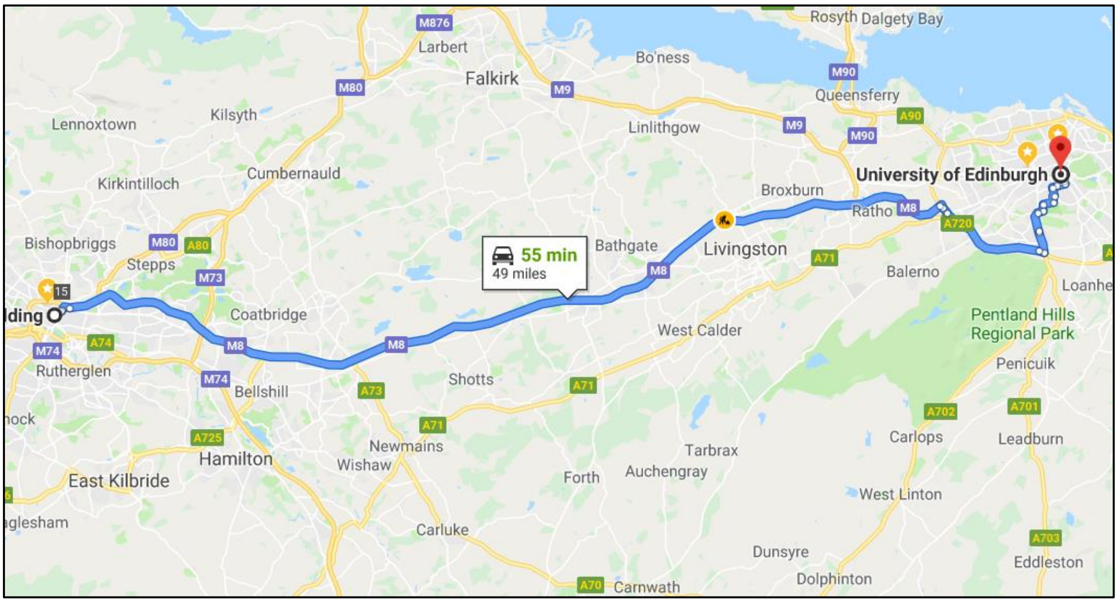


Figure 31: Suitable location for an ERS System in the M8 highway

Consequently, the total power consumption for the electric vehicles driving by the M8 Highway in both directions will be as follows:

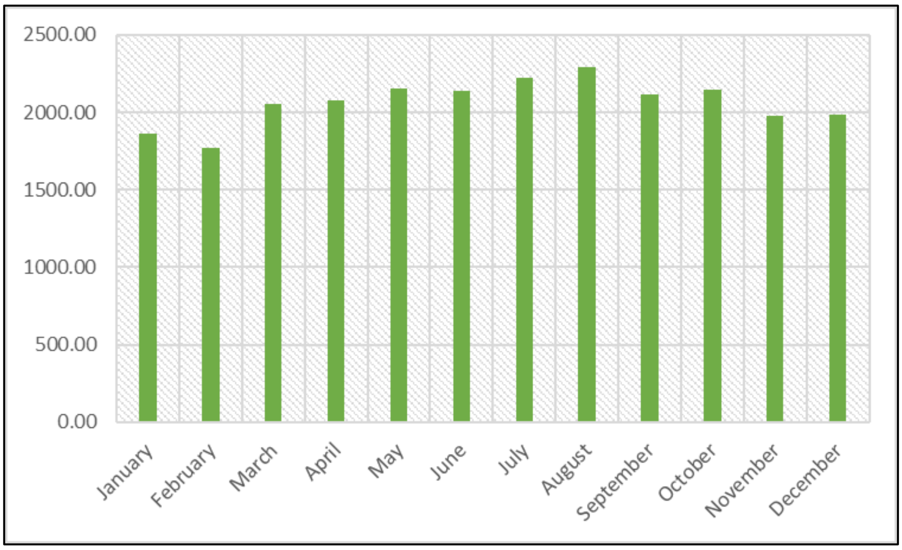


Figure 32: Total Car Consumption per Month in the M8 Highway (kW/month)

Then, as Figure 33: Total Car Consumption per Month in the M8 Highway (kW/month), shows, the total power consumption per month is almost steady through the year. It should be noted, that considerable amount of assumption has been taken to get this final number, also, abundant of improvements and further investigations should be made to get a better and accurate final power consumption, as it has been said in the *9.2. Improvements*.

One of the most important goals of this thesis is to show it it is possible to produce all the energy requirements that a CPT system will require for all the electrics vehicles driven on it. For that purpose, a PV installation installed alongside the road has been designed, to figure out depending the location and sun irradiation on the place where the CPT system is installed, which will be the demand/supply match throughout the year. On it behalf and taking into account the data shown in Figure 30 and Figure 31. Considering the average number of PV panels that would be needed to provide 100% of the energy power demand of every single month throughout the year (3374 PV panels, with a total surface area of 6155 m^2, the demand-supply match per month in the M8 between Glasgow and Edinburgh, will be as follows:

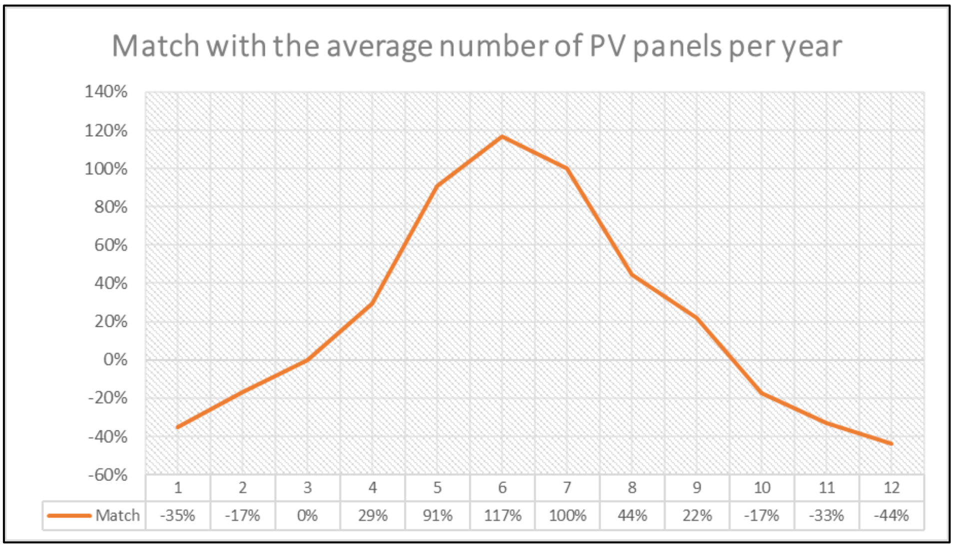


Figure 33: Demand/Supply match throughout the year in Glasgow

As the Figure 34 shows, the average numbers of PV Panels would be able to provide enough energy to cover the requirements of the electric vehicles driving on the CPT system during the summer months, where more irradiance hits the earth surface. Being June the month with a higher match demand/supply with 117% of overproduction. On the contrary, the Winter months are the ones with less supply, being December the lower match demand/supply with an energy production deficit of 44% of the energy consumption requirements.

8.4.1. CPT system design on the M8 Highway

Taking into consideration which it the maximum power supply that the Electric Road System (ERS), as it has been described in chapter *5. Inductive Charging on the go system* can transfer per car and by CPT system. Moreover, the maximum power demand for the electric cars driving on the highway that it is on Fridays during August with a total power consumption of 77,198 kW/km. The CPT system on the M8 Highway would be designed as follows:

- Power requirements: $77{,}198\ \mathrm{kW/km}$
- Power requirements for the total Highway distance: $80\ km\ x\ 77{,}198\,\frac{\mathrm{kW}}{\mathrm{km}} = 6{,}175.84\ kW$
- Considering an average, driven speed of 112 km/h (70mph), each of the primary winding will transfer 148 $\mathrm{kW/300m}$
- So, the number of primary winding system of 300m each will be: $\frac{6{,}175.84\ kW}{191\ kW} = 42$
- Therefore, a total CPT system along the road will be $42x300m = 12{,}600\ m$
- Meaning that with a total of the 16% of the highway length covered with the CPT system the energy transferred for the system will be enough to transfer enough energy for moving all the electric vehicles passing by

9. Conclusion

9.1. Key Project Findings

- A Contactless Power Transfer system is feasible for a real application in a big scale (Highways) in a short period, if the current technology is still developing and it becomes a mature and reliable breakthrough technology.
- The battery size of the electric cars can be minimised up until a minimum backup for safety reason (2kWh), as higher the percentage of the highway will be covered by a CPT system smaller the battery size will be.
- A power transfer system of 300 m length and output power of 200 kW are technically feasible and already tested.

- Further developments can be extrapolated for other electric vehicles such as buses, trucks or vans.

- Better performance can be made with more precise flow traffic data.

- Driven test in different driving conditions may be taken as an accurate data for the average power electric car consumption.

- Greater details on electric car consumption can be taken, getting more precise data from the manufacturers.

- Higher supply/demand percentage will happen in countries with high sun irradiance values.

9.2. Improvements

- In the thesis, it has been considered that the energy consumption started from 0, that is, assuming that the electric car has no battery and starts its journey consuming energy from the CPT system. In reality, the latter could never happen, since, apart from the percentage of batteries that cars have as security (2kWh), there is the fact that cars always have energy stored in their batteries. However, developing a model that considers the amount of energy stored in the battery of each of the cars that circulate on the highway would be very complex and extremely difficult to develop.

- In this thesis, it has also been considered that all the electric cars will drive all the highway distance, and this is far from reality. Because, maybe several cars will drive all the distance, but the majority of them will drive less than the length of the highway, for example, the average travel distance per car in the UK (13.59 mi/car/day). Therefore, if in this thesis the average daily travel distance in the

UK would be considered as the average driving distance per electric car in the highway the M8 power consumption will considerably less, the total power consumption for all the highway will pass from the previous power calculated $6{,}175.84\ kW$to $1{,}689\ kW$. Consequently, the power consumption will drop almost 73% of the overall results presented on the thesis.

- More electric car consumption patrons could be detailed; such as, electric consumption during traffic jumps, heavy weather conditions also considered the recovery energy for the brake system, analysed all of these patrons will be closer to which the reality is.
- Non fixed driven speed values could be considered because during the thesis, just three different driven speed values have been considered (50,60,70 mph). So, to have an accurate and authentic average driven speed of an electric car during it drives in a highway, a meticulous mathematical model must be developed.
- More detail of the CPT system design could be elaborated, more in-depth dynamic analysis of the power transfer between the grid or the PV installation and the CPT system should be given. Losses on the system have not been considered.
- Taking into account the different world location where a CPT system can be installed, a better study of the primary renewable resource existing on the place should be made. Studying, for example, the possibility of producing energy for another renewable energy source different than the sun, such as Wind, Biomass, or Tidal or Wave energy if the CPT system is located in see areas.

- Future developments of the electric car industry, will bring as a consequence better battery range performance, and less power consumption for the same amount of distance coverage. Therefore, less power production will be required coming from the PV installation alongside the highways, also a higher efficiency rate performance will be achieved for the PV panels. So, in coming years with a better technology and higher knowledge of the a contactless power system for charging electric vehicles on the go, will be even more feasible and easier to install that nowadays is.

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