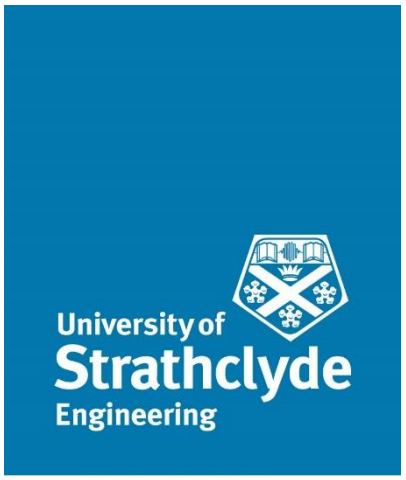


Department of Mechanical and Aerospace Engineering

Modelling and Analysis of a Photovoltaic System on a Car park as Energy Source for Electric Vehicle Charging

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A thesis submitted in partial fulfilment for the requirement of the degree

Master of Science

Sustainable Engineering: Renewable Energy Systems and the Environment

2017

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Abstract

Electric vehicles (EVs) have the potential of reducing countries dependence on fossil fuels, greenhouse gas emissions and improve urban air quality. Consequently, the use of EVs is being encouraged by many governments.

A global transition to EV use will have an increase in the total electrical consumption, which if not provided partly by renewable energy sources will be counterproductive to the reasons that prompt such shift.

The central goal of this dissertation is to study the energy efficiency of an urban photovoltaic (PV) installation as a source of energy for EV charging. An Excel based tool was constructed and utilised for this investigation. The analysed installation space was a car park in Glasgow, Scotland. A series of charging opportunity scenarios with different EV charging demands derived from a literature review were assessed. The energy efficiency of these were measured, by derivation of the renewable energy share of the total energy required.

It was found that the idea of utilising a PV installation to charge EVs with renewable energy share had the potential of being energy efficient with today's EV fleet share for day time charging. During night time charging, the use of today's batteries, can only help contribute with little renewable energy. As for an extensive EV use, a higher renewable energy generation penetration will be needed than that able to be provided by an urban PV installation, in order to make a widespread use of EVs sustainable.

Acknowledgements

Thanks to my supervisor, Professor Joseph Clarke, who gave me advice and assistance throughout the duration of this project.

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List of Abbreviations

AGM	Absorbed Glass Mat
AC	Alternate Current
AHP	Analytical Hierarchy Process
BEV	Battery Electric Vehicle
CT	Clock Time
DC	Direct Current
EVSE	Electric Vehicle Supply Equipment
EV	Electric Vehicles
GHG	Greenhouse Gas
HEV	Hybrid Electric Vehicle
LST	Local Solar Time
PV	Photovolatic
PHEV	Plug-in Hybrid Electric Vehicle
STC	Standard Test Conditions

1 Introduction

Currently the global transport sector consumes about 27% of the total global energy demand, and is roughly responsible for 14% of greenhouse gas emissions (World Energy Council, 2016). In developed countries, such as the UK, the transport sector accounts for the largest share of its final energy consumption at 40 per cent as of 2016 (World Energy Council, 2016). Due to the rapid development of countries and a steady rise in global population, energy demand is predicted to increase at a yearly rate of 1.4% from 2012 to 2040 (U.S. Energy. Information Administration, 2016).

As a result, authorities are under pressure to promote cleaner air quality in urban areas, and one obvious target is vehicle use. This has prompted countries like France and the UK, to ban the sale of diesel and petrol cars beyond the year 2040. Such decisions, along with financial incentives have aided in the increase of electric vehicles (EVs) share in the transport sector. New registrations of electric cars (including both battery electric and plug-in hybrids) increased by 70% between 2015 and 2016, with over 550 000 vehicles being sold worldwide in 2015 (International Energy Agency, 2016). A global transition to EVs use, will have an increase in the total electrical consumption, but this does not mean that the energy supplied must come from conventional energy sources. Such demand could be met by introducing an increased amount of renewable power production such as urban photovoltaic (PV) installations in the electrical systems i.e. Building integrated PV installations.

A factor that is positively correlated to EV market shares growth, is the availability of charging infrastructure (International Energy Agency, 2016). Taking into account that on average the car use represents only 4% of the total daily time (RAC Foundation, 2012), an opportunity window is open to use the resting time of the vehicle as a charging

occasion. An example of a suitable charging opportunity are workers EVs, since most parking (28%) that takes place during the working week is related to work (RAC Foundation, 2012).

According to a study carried by the Office for National Statistics, the average UK weekly hours for full-time workers are 37.6, meaning an average of 7.6 hours per day (Office for National Statistics, 2017). This daily time frame for example, gives enough margin to charge a standard EV at a 7 kWh rate, charging from 20% to full charge.

1.1 Project Scope, Aim and Objectives

The scope of this project is restricted to assess the energy efficiency of the installation in car parks. The case study addressed in this thesis is Duke Street car park, Glasgow. However, this tool has been developed in a way that can be implemented to other building sizes and locations.

Since this study is limited to addressing the energy efficiency of using urban PV installations for EV charging, no coverage of the economic aspects has been made. It was also considered outside the scope of this study to consider stochastic individual user charging behaviours given its modelling complexity.

The primary aim of this project is to examine the energy efficiency of an urban PV rooftop installation as an energy source for EV charging.

The project had the following objectives:

- Construct a modelling tool that calculates the amount of energy produced by the PV installation, and the percentage of renewable energy share for different EV charging demands.

- Model the behavioural pattern of car use
- Analyse potential EV charging scenarios
- Validate the tool, using verified programmes
- Assess energy efficiency of installation and make associated recommendations

The scenarios analysed were:

- daytime charging during the average working hours with an evaluation of its potential with current EV share and a futuristic case of only EVs circulating on the roads
- night time fast charging for taxis

1.2 Project Methodology

The project was carried out according to Figure 1-1:

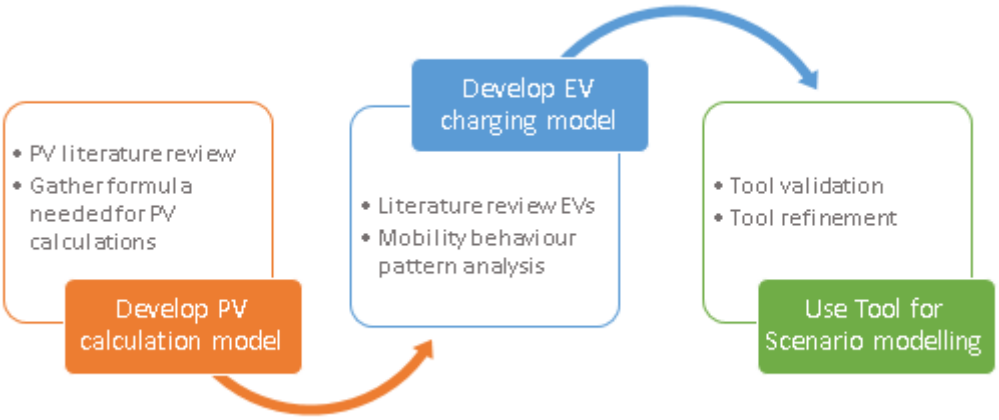


Figure 1-1 Project Methodology

The initial stage of the project was to undertake a thorough literature review to develop an in-depth understanding of how PVs work and their necessary infrastructure. A key

step was to gather the formulae required for the modelling of the energy output of a PV installation, as well as addressing the optimum layout of the PVs.

When proceeding to develop the car use behavioural pattern it was sought to identify possible charging scenarios. For this, a thorough understanding of car use patterns and the necessary EV charging requirements was needed.

Following the literature review, the formulae and knowledge gathered were utilised to build the modelling tool used in this project. To fulfill this thesis, the tool was implemented to assess a set of two different scenarios. This allowed an energy efficiency analysis of the installation to be obtained under different charging scenarios. The energy efficiency will be assessed by comparing the amount of renewable energy to grid import required for the different charging demands.

2 Literature Review

An initial literature review was conducted to be able to understand and model in the tool:

1. How PVs work and how solar energy in converted into electricity
2. Model the behavioural patterns of car usage to analyse charging opportunities
3. Understand the EV charging requirements and options

2.1 Photovoltaic (PV) cells

The photoelectric effect is the basic process by which PV cells convert sunlight into electricity. The top layer of the cell is dotted with an excess of electrons (negative charge) whilst the bottom layer has an electron deficiency (positive charge). The use of an intermediate semi-conductor material prohibits the free electron flow between top and bottom layers. When a photon collides with the negatively charged layer, an electron is knocked loose, this electron flows through the metal layer to the bottom layer, creating a current. The charges on the layers are obtained by doping the silicon with boron and phosphorous.

There are three main types of silicon based PVs: monocrystalline, polycrystalline and thin-film. The module efficiencies of crystalline silicon and thin film PV modules are generally measured under standard test conditions (STC) which are:

- Cell temperature of 25°C
- Irradiance of 1000 W/m^2

Table 2-1 PV module types comparison

Cell material	Module efficiency	Surface area needed for 1 Kilowatt peak (kWp)
Mono-Si	14-25%	c.7 m2
Poly-Si	12-16%	c.8 m2
Thin-film	6-11%	c.10 m2

Given that the aim of this project is to generate as much renewable energy as possible in a restricted area, the use of monocrystalline panels will be desired.

The PV modules are oriented in a specific way to obtain the maximum power output, the azimuth angle, φ, and the elevation angle at solar noon are the two key angles which are used to orient them.

Solar geometry

Solar geometry is a well understood topic covered in many publications such as in Solar Geometry by Szokolay, 1996.

Declination (δ)

Declination, δ, is the angular distance of the sun, north (positive) or south (negative) of the equator. Declination is a sine function, which is zero at the equinoxes and has a yearly cycle range of: $-23.5° < \delta < +23.5°$.

To calculate the yearly variation in declination, the distance from the March equinox to the end of the year (284 days) is added to the number of day of the year (*NDY*) i.e. being NDY=1 January the 1st. Since the number of days in one year (365) must correspond to a full circle (360 degrees), the ratio 360/365 is applied:

$$\delta = 23.45° \sin[\frac{NDY + 284}{365}\ x\ 360°] \quad (1)$$

Where declination, δ, is measured in degrees.

Local solar time (LST)

Calculation of sun position must be made in terms of local solar time (*LST*), since solar and local clock time (*CT*) do not necessarily correspond. The conversion between solar time and clock time requires knowledge of the location, the day of the year, and the standards to which local clocks are set (Chun-Sheng, et al., 2008). The conversion between *LST* and *CT* (in 24- hour) is as follows (when using this formula, time must be converted from decimal format to 24h):

$$LST = CT + E_t + \frac{L_{std} + L_{loc}}{15} - DT \quad (2)$$

Where:

LST = Local Solar Time [h]

CT = Clock Time [h]

L_{std} = Standard Meridian for the local time zone [degrees]

L_{loc} = Longitude of actual location [degrees]

E_t = Equation of Time [h]

DT = Daylight Savings Time correction (DT = 0 if not on Daylight Savings Time, otherwise DT is equal to the number of hours that the time is advanced for Daylight Savings Time)

Each degree difference in longitude amounts to 1/15 hour (4 minutes) of time.

Equation of Time (Et)

The Equation of Time, E_t, is the difference in hours between mean time and solar time. Calculated by:

$$E_t = 0.165 \sin(2B) - 0.126 \cos(B) - 0.025 \sin(B) \quad (3)$$

Where:

$$B = \frac{360\ (NDY - 81)}{365} \quad (4)$$

A negative value for the equation of time means that the sun-dial time is behind the clock time and a positive value means sun-dial time is ahead of clock time.

Hour angle (h)

Hour angle, *h*, expresses the time of day with respect to the solar noon. As hour angle varies by 15 degrees per hour and as it is zero at solar noon, and negative before solar noon, the equation for the solar hour angle in degrees can be given by:

$$h = 15 * (LST - 12) \quad (5)$$

Derived Solar angles

Besides the three basic angles (latitude, hour angle, and sun's declination), several other angles are useful in solar radiation calculations. Such angles include the sun's zenith angle (θ_H), elevation angle (β), and azimuth angle (φ). For a particular surface

orientation, the sun's incidence angle (θ), and surface-solar azimuth angle (γ), may be defined.

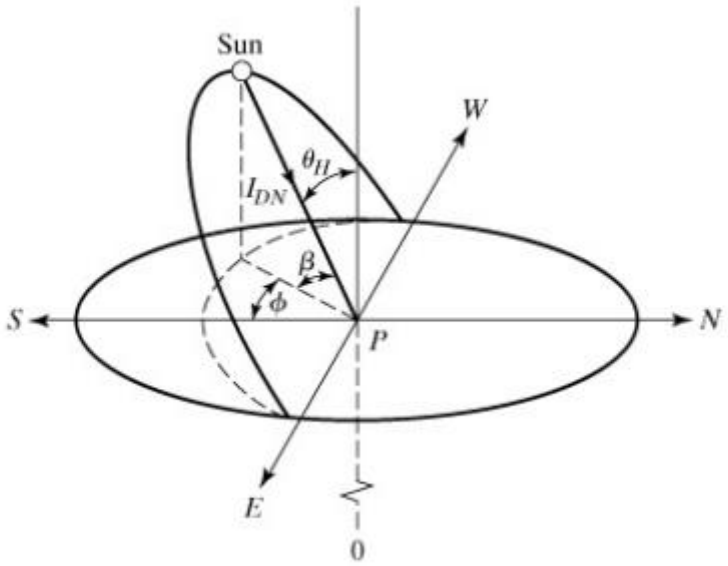


Figure 2-1 Definition of sun's zenith, altitude and azimuth angles (Kuehn & Ramsey, 2009)

The following equations can be derived:

$$\cos\theta_H = \cos(L)\cos(h)\cos(\delta) + \sin(L)sin(\delta) \tag{6}$$

Since

$$\beta = 90 - \theta_H \tag{7}$$

$$\sin\beta = \cos\theta_H = \cos(L)\cos(h)\cos(\delta) + \sin(L)sin(\delta) \tag{8}$$

The Sun’s azimuth, φ, in degrees given by:

$$\cos\varphi = \frac{1}{\cos\beta}\left(\cos(\delta)\sin(L)\cos(h) - sin(\delta)\cos(L)\right) \tag{9}$$

In calculations involving non horizontal surfaces, it is convenient to express the sun's position relative to the surface in terms of the incidence angle, θ. The sun's angle of incidence is the angle between the solar rays and the surface normal.

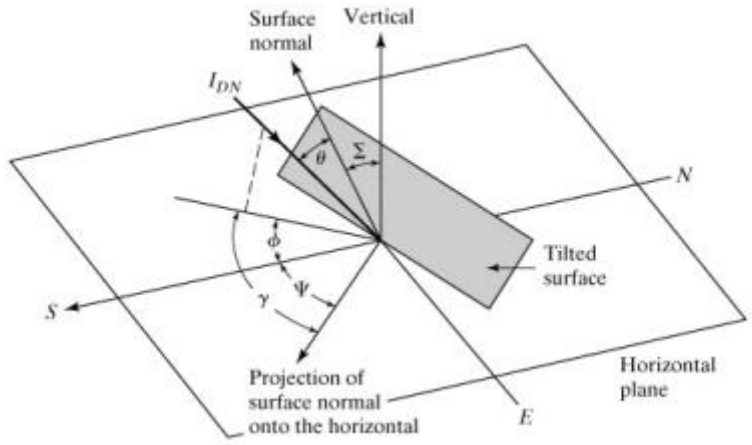


Figure 2-2 Representation of surface azimuth, surface tilt, and surface-solar azimuth angles and the relation of the sun's rays to a tilted surface (Kuehn & Ramsey, 2009)

In order to evaluate the angle of incidence we need to specify the direction of the surface normal. This is done in terms of the surface tilt angle, Σ, and is the azimuth angle of the panel, Ψ. Since the surface-solar azimuth angle, γ, is the angle between the horizontal projection of the solar rays and the horizontal projection of the surface normal, it can be derived that:

$$\gamma = \varphi - \psi \tag{10}$$

Where:

φ = the Sun's azimuth [degrees]

ψ = azimuth angle of the panel [degrees]

The following test must be done to determine whether the azimuth angle of the sun is greater or less than 90◦ away from the south. If:

$$\cos h \geq \frac{\tan \delta}{\tan L} \tag{11}$$

Then $|\varphi| \leq 90°$; otherwise $|\varphi| > 90°$ (Masters, 2004)

So for a tilted surface, the Sun incidence angle,θ, can be calculated by:

$$\cos \theta = \cos \beta \cos \gamma \sin \Sigma + \sin \beta \cos \Sigma \tag{12}$$

Where $\Sigma = 90°$ if surface is vertical and $\Sigma = 0°$

Solar radiation striking an inclined surface

Direct radiation ($I_{d\beta}$), ground-reflected radiation (I_r), and diffuse radiation ($I_{b\beta}$) are the three components of the total solar radiation incident on an inclined surface (I_β).

$$I_\beta = I_{d\beta} + I_{s\beta} + I_r \tag{13}$$

Diffuse radiation (Isβ)

Generally, diffuse radiation models for inclined surfaces can be classified into two groups: isotropic and anisotropic models. They differ in the division of the sky into regions with normal and elevated diffuse radiation intensities. Isotropic models assume there is uniformity in the distribution of diffuse radiation intensity over the sky. Anisotropic models include appropriate modules for representing areas of elevated diffuse radiation.

For diffuse radiation calculations, Klucher's Anisotropic Model (Klucher, 1978) which states as follows has been chosen:

$$I_{s\beta} = I_{fh}\left[\frac{1}{2}\left(1+\cos\left(\frac{\Sigma}{2}\right)\right)\right]\left[1+\left(1-\left(\frac{I_{fh}}{I_{gh}}\right)^2\right)\sin^3\left(\frac{\Sigma}{2}\right)\right]\left[1 + \left(1-\left(\frac{I_{fh}}{I_{gh}}\right)^2\right)\cos^2\theta\,\sin^3(90-\beta)\right] \quad (14)$$

Where:

I_{fh} = hourly diffuse horizontal solar radiation

I_{gh} = hourly global horizontal solar radiation

When the sky is completely overcast, $\frac{I_{fh}}{I_{gh}} = 1$and the expression reduces to the isotropic sky case.

The hourly global diffuse solar radiation can be measured with a pyranometer and the hourly global horizontal solar radiation by:

$$I_{gh} = I_{dh} + I_{fh} \quad (15)$$

Where:

I_{dh} = the direct horizontal irradiance; calculated by:

$$I_{dh} = I_{dn}\sin\beta \quad (16)$$

Where:

I_{dn}= the direct normal irradiance; measured by a pyrheliometer.

Direct radiation (Idβ)

The direct irradiance is determined by:

$$I_{d\beta} = I_{dn} \cos\theta \tag{17}$$

Where:

I_{dn} = the solar direct normal radiation

Ground-reflected radiation (Ir)

The part of the global solar radiation that is reflected by the earth's surface and any other intercepting object is called ground-reflected radiation. If the ground is horizontal and if the reflection is diffuse, an approximation for the reflected solar flux striking a surface, I_r, is given by:

$$I_r = \rho_g (I_{dh} + I_{fh}) \frac{(1 - \cos\Sigma)}{2} \tag{18}$$

Where:

ρ_g = the ground reflectivity

Grid Tied Solar Systems

A solar system is a system composed of mechanic, electric and electronic components which helps convert and transfer the solar energy into electricity. Grid tied means that it can import and/or export electricity from the main grid.

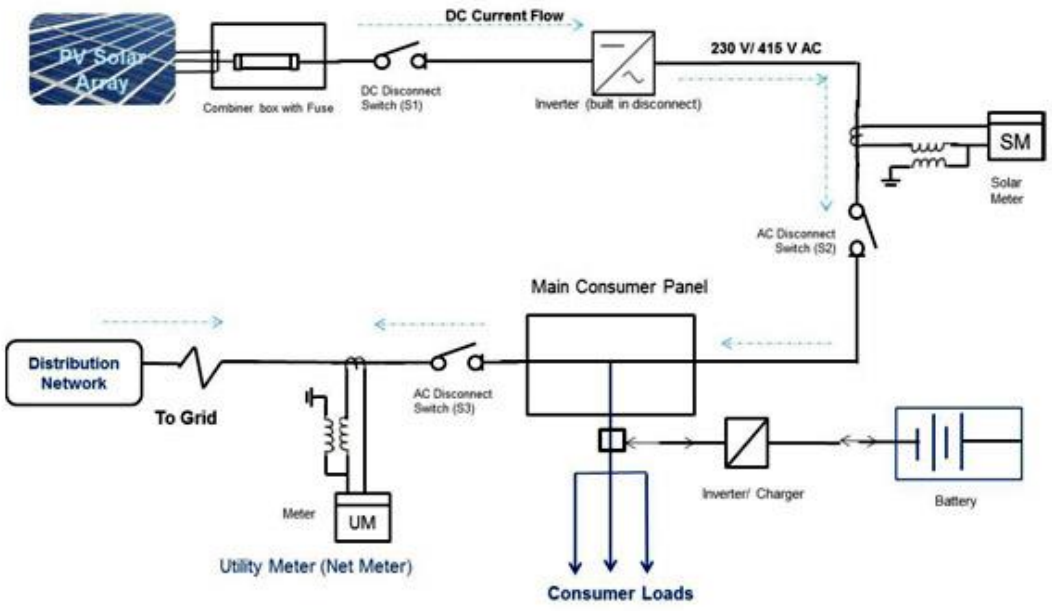


Figure 2-3 Grid Tied Solar System Schematics (RERC, 2015)

The main components are:

Charge controllers - manage the flow of electricity between the solar modules (arrays), energy storage, and loads. The main purposes of a charge controller is to protect batteries from damage and to prevent overcharging or excessive discharging.

Inverters - devices that convert direct current (DC) power coming from the solar modules to alternate current (AC) power.

Batteries - are used in many types of PV systems to supply power at low sun conditions (night or low irradiance). Additionally, batteries are required in solar systems because of the fluctuating nature of the PV output.

Batteries

A battery is a device that stores electrical energy by electrochemical procedures and, depending on the technology used returns it almost in its entirety. There are currently

three types of photovoltaic batteries: lead-acid batteries, gel batteries and absorbed glass mat (AGM).

- Lead-acid batteries: most common. It is characterized by being a battery that must be kept upright and in need of maintenance.
- Gel batteries: they are batteries, in theory, without maintenance, although in practice they have to be filled with distilled water
- AGM: maintenance free, used with normal chargers, and almost no gas when recharged.

The three characteristics that define a battery are:

1. The amount of energy it can store (Wh).
2. The maximum current that it can deliver (discharge).
3. The depth of discharge that it can sustain (%).

In addition to these three characteristics, other aspects such as battery capacity, life cycles, self-discharge should be taken into account when choosing the right battery. Based on information gathered throughout the literature review a comparison table, Table 2-2, of the three battery types based on the parameters discussed was constructed:

Table 2-2 Comparison of the three types of batteries

	Lead-acid	**Gel**	**AGM**
Depth of discharge (%)	55-60	80-90	80-90
Energy density (Wh/kg)	50-60	40-60	40
Self-discharge (%/month)	3	< 2	< 2
Life Cycles	1500-2000	1500-3000	1500-2000
Life (years)	3 - 8	5 - 15	7 - 12

For this study the use of a gel battery was found the most ideal, due to its greater life cycles.

In order to calculate the number of batteries need to be installed, the total nominal capacity, C_n (Ah), required by the batteries is to be calculated using the following formula.

$$C_n = \frac{E_r * N}{DOD + V_{bat}} \tag{19}$$

Where:

E_r = the energy consumed by the installation (Wh)

N = the number of autonomy of installation (days)

DOD = depth of discharge (%)

V_{bat} = voltage of the selected battery (V)

Once the total nominal capacity is worked the number of batteries needed can be calculated by the following:

$$N_{bat} = \frac{C_n}{C_{bat}} \tag{20}$$

2.2 EVs

Types of EVs

There are three types of EV: Battery Electric Vehicle (BEV), Plug-in Hybrid Electric Vehicle (PHEV) and Hybrid Electric Vehicle (HEV).

BEVs

Run entirely using an electric motor. The energy needed to function is provided by the energy stored in the vehicle battery which is charged by being plugged into an external source of electricity. This type of vehicles need a bigger battery than the ones mentioned below.

PHEVs

This type of EV runs using a combination of electric motor and/ or internal combustion engine in parallel or series configuration. They make use of a battery to run the electric motor, and use the internal combustion engine as a support system that may be used to recharge the vehicle's battery and/or to replace the electric motor when the battery is low. The internal combustion engine is smaller than that found in conventional and hybrid vehicles. The battery can be charged by plug-in to a power grid, the internal combustion engine or by regenerative braking.

HEVs

Own two complementary drive systems: a gasoline engine with a fuel tank; and an electric motor with a battery. HEVs cannot be recharged from the electricity grid – all their energy comes from gasoline and from regenerative braking.

Since this study will focus on the energy efficiency of the installation, we will study the worst case load scenario. Therefore we will focus on BEVs, the EVs that require the highest electrical demands out of all EVs.

Electric Vehicle Supply Equipment (EVSE) Technology

EVSE units are commonly referred to as EV charging stations, they are responsible of delivering electrical energy to the EV to charge the car battery. With the basic components being:

EVSE

Equipment connected to an electrical power source that provides the AC or DC supply to the electric vehicle that is needed to charge the vehicle's traction batteries. EVSE charging capacity options have a direct effect on how fast the batteries can be recharged.

Connectors

Five types of EV sockets with connectors for the pilot wire can be used for charging EVs.

SAE J1772 / Type 1 connector: has five pins for the 2 AC wires, earth, and 2 signal pins compatible with IEC 61851-2001 / SAE J1772-2001 for proximity detection and for the control pilot function.

Type 2 / Mennekes: European standard, 7 pins and can withstand a maximum of 63 A.

Type 3: 7 pins and can withstand a maximum of 32 A.

Type 4 / CHAdeMO: designed specifically for fast DC charging, 10 pins, and can withstand up to 200 A.

Combined Charging System (CCS): 5 pins, can stand both fast, DC, and slow charge, AC.

EV Inlet

Device on the EV that provides the physical connection between itself and the EVSE connector. The number and location of inlets varies from vehicle to vehicle.

Battery

Where the electrical charge is stored, similar to the fuel tank of a conventional car.

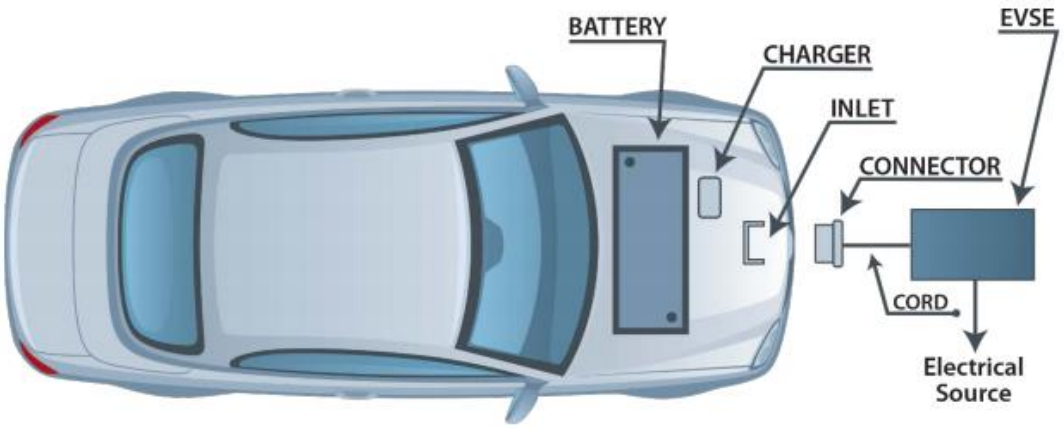


Figure 2-4 Schematic EVSE Components (Kettles, 2015)

Types of Charge

The types of charge are defined by the charging speed, in other words, how long it takes them to recharge the battery which is directly proportional to the amount of power available. The types of charging available and the number of hours needed to charge an average 25kWh capacity BEV are:

Table 2-3 Approximate BEV 25kWh charging times (SAE International, 2012)

Charge Power (kW)	Charging Time	State of Charge	Maximum Current (A)
1.4	17 -18 hours	20% - 100%	12
1.9	12 - 13 hours	20% - 100%	16
3.3	6 - 8 hours	20% - 100%	16
7	3 - 4 hours	20% - 100%	32
10	2 - 3 hours	20% - 100%	16
22	1 - 2 hours	20% - 100%	32
43	20 - 30 min	20%- 80%	63
50	20-30 min	20% - 80%	100-125

Charging Modes

The standard IEC61851-1 defines general requirements for conductive EV charging systems (Automotive Research Association of India, 2016).

Mode 1: slow AC charging, can withstand currents up to 16 A. The installation must be protected with circuit breakers and earth leakage protection elements. (Bossche, et al., 2015)



Figure 2-5 Mode 1 type connection (Ricaud & Vollet, n.d.)

Mode 2: slow AC charging consists special cable with an intermediate electronic device, with a control and protection pilot function (maximum 32 A per phase). Generally proposed for domestic charging.

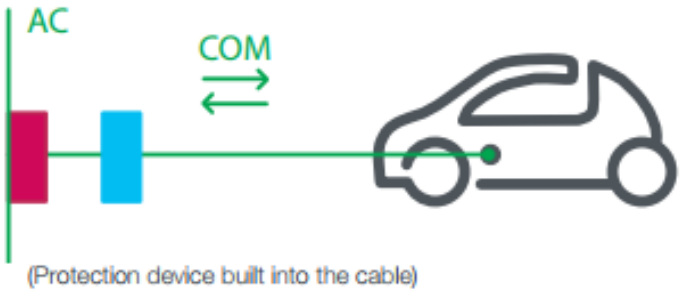


Figure 2-6 Mode 2 type connection (Ricaud & Vollet, n.d.)

Mode 3: involves the direct connection of the EV to the charging unit. The control standard IEC61851-1 mandates control pilot protection, the protection elements are included inside the charging EVSE. Maximum 63 A per phase.

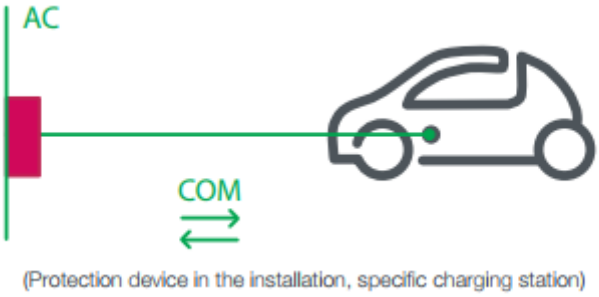


Figure 2-7 Mode 3 type connection (Ricaud & Vollet, n.d.)

Mode 3 has been selected as the ideal charging mode for the study, as due to its safety features alongside its potential for smart grid integration, make it the preferred solution for public EVSE as well as for home charging (CENELEC, 2011) .

Mode 4: consists of connection of the EV to an external charger delivering DC with a specific cable. The charger incorporates the control function and electrical protection (Cazals & Vidalenche, 2011). Even though Mode 4 charging capability is presently

available only on some vehicles in the market, there is a strong interest of the automotive industry to establish DC charging (CENELEC, 2011).

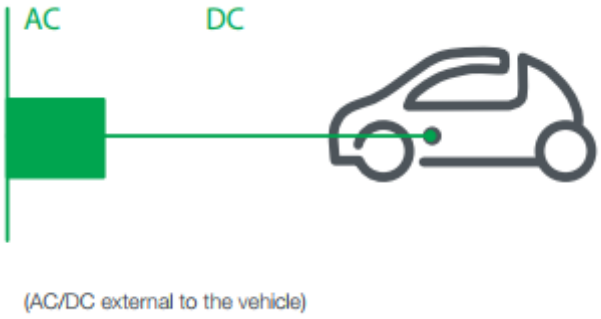


Figure 2-8 Mode 4 type connection (Ricaud & Vollet, n.d.)

3 Tool Construction

After initial literature review the modelling for a tool which had the ability to the following was constructed:

1. Calculate the amount of energy generated by a PV system on a given location
2. Model the behavioural patterns of car usage to analyse charging opportunities
3. Calculate the energy share that came from renewables upon different EV charging demands

3.1 Tool Requirements and Selection

In order to perform an analysis with regards to the energy efficiency of charging EV with the use of a PV system, a modelling tool was required to be designed for this purpose.

The majority of the models available were either online tools - very restrictive in their scope and/or with a limited trial period.

For example, although the HOMER Pro tool could have been used for simulation purposes in this project, it has a 21-day free trial which limits the possible modelling and availability of the tool for further analysis and alterations. Also, the focus of HOMER is more towards the economic aspects of the installation modelled, rather than the energy efficiency.

In the case of Merit modelling tool, the nominal power of the PVs were restricted to those available on the model. Which for the purpose of this project were considered low.

These tools, whilst excellent aides to the validation of this study did not cover the requirements. It was decided that for this specific study the creation of a simulation tool by the author would provide a better understanding of both technologies.

3.2 Description of Tool

The aim of the tool, aside from aiding in calculating results for this thesis, was to support in the decision making for the energy efficiency of urban PV installations as energy sources for EV charging. However due to time restraints, the tool was not complete in terms of optimal EV charging times.

The tool developed for this study consists of a set of Excel spreadsheets with Welcome, Climate Data, PV System Dimensioning, Optimum Tilt and demand sheets. The Welcome sheet has no particular use other than to introduce users to the tool. The climate data sheet is vital for any user as it is the main input page where aspects of the location, solar and PV data can be entered. In the PV System Dimensioning sheet, more in depth site selections can be made, for example space available for the PV installation. As this is a site dependent variable it cannot be pre assumed by the tool. Based on the surface area available and dimensions of the PV panels entered by the user, the number of PV modules able to be installed are sized by the tool.

The Optimum Tilt Worksheet contains the calculations regarding the optimum tilt the panels will be set at, taking into account total solar irradiance, area and distance needed between modules to avoid shading. No inputs are required in this page.

The demand sheets presents the results of the energy efficiency of the defined PV installation in both graphical and tabular form. The individual EV demand sheets can be altered to the users' preference.

The average percentage of renewables is obtained by calculating the average monthly percentage of energy stored form renewables form the total energy needed for the charging (renewable stored + import from the grid) when EV charging occurred, and calculating the yearly average.

For guidance purposes to new users the model was colour coded, with the following meaning:

- inputs needed to be included by the user are highlighted in yellow
- outputs in green

Tool Assumptions

- Climate data: The project does not consider any daylight-saving time modifications throughout the year in its solar calculations.
- PV losses: The model did not consider any specific losses but a performance ratio that included an estimate of all PV losses.
- Panel Array: An inclination of 0 degrees has been supposed for the installation surface.
- Costs: Since this is an energy efficiency study, no cost will be taken into account.

Tool Inputs

The tool inputs include:

- PV characteristics:
    1. Length

2. Width
3. Temperature coefficient of power (% / K)
4. Rated Power

Table 3-1 PV tool Inputs

Panel Data	
No. panels:	2180
α	0.0038
PSTC (W)	320
PR	0.9
Panel inclination (degrees) Σ	0

- Installation Area (i.e. Car park rooftop area):
    1. Length of PV installation surface area
    2. Width of PV installation surface area
    3. Number of total parking spaces
    4. Occupancy Rate of Car park
    5. Percentage of cars in car park that are EVs

Table 3-2 Car Park Data Input

Installation Space	
Width (m)	
Length (m)	
Nº of parking spaces	
Occupancy Rate (%)	
Percentage of EV (%)	
Number of EV in car park	

- Climate Data:
    1. Direct normal irradiance (W/m^2) per hour for 365 days
    2. Diffuse horizontal irradiance (W/m^2) per hour for 365 days
    3. Ambient Temperature (°C)

4. Longitude of installation location (degrees)
5. Latitude of installation location (degrees)
6. Ground reflectance
7. Surface Azimuth (degrees)

Table 3-3 Location Inputs

Location	Latitude (degrees)	Longitude (degrees)

Ground reflectance	
Surface azimuth Ψ	
Reference longitude	

- EVs:

1. Rate of charging (kWh)
2. Time needed to complete charge at specified charging rate (h)
3. Desired start time of charging (h in 24h format)

Table 3-4 EV Charging Demand Inputs

Charging Demands per car	
Power (kWh)	
Time needed complete charge (h)	
Start time of charging (h)	
Finish charging time (h)	
Number of cars	

The option of adding a suppletory battery with extra capacity is included.

Tool Outputs

The tool outputs include:

- Total maximum energy generated per year (kWh/ year)
- Distance between modules to avoid inter-panel shading (m)
- Total area of installation covered by PVs (m^2)

- Monthly % of renewable share of total energy required by charging scenarios

Applicability study

A user evaluation test of the tool was carried out by several people to analyse the status of the tool. The test consisted of two tasks, where the participants had to model different scenarios and report their experience. Both tasks can be seen in the Appendix A, under the Decision Support Tool Exercise. The participants selected had to possess a technical background and have experience within renewable energy sector. This was deemed necessary to give an accurate representation of the public the tool is focused to. Their feedback was considered and included as future work areas in Chapter 6.

An advantage the tool presented was its replication potential and easiness in doing so. This provides a window for future research on the topic and further tool refinement.

3.3 Development of PV model system

To model an accurate PV system, a literature review was conducted regarding the solar geometry calculations, as previously shown in the Solar geometry section.

To model the optimum layout, as per energy generation, a link between the installation space available, the distance needed between panels to avoid shading and optimum panel tilt was made. This was reflected with the interlinking between the climate data, optimal angle inclination and PV system dimensioning sheets.

Climate Data sheet

The equations found within the literature review, as seen on Chapter 2.1, were analysed and modelled in the Excel spreadsheet.

Table 3-5 Parameters modelled for PV calculations

Declination δ	Equation of time Et	Local solar time LST	Hour angle h	Solar elevation β	Solar azimuth φ	Azimuth angle test
(degrees)	(hour)	(hour)	(degrees)	(degrees)	(degrees)	

Surface-Solar azimuth	Solar incidence angle θ	Direct solar irradiance (Idβ)	Diffuse solar irradiance (Isβ)	Ground reflected irradiance (Ir)	Total solar radiation
γ	(degrees)	(W/m^2)	(W/m^2)	(W/m^2)	(W/m^2)

Table 3-5 summarises the parameters modelled using the equations extracted from the literature review, which correspond to the following equations explained before.

Declination (δ): Equation 1

Local solar time (LST): Equation 2

Equation of Time (Et): Equation 3 and Equation 4

Hour angle (h): Equation 5

Elevation angle (β): Equation 8

Solar azimuth (φ): Equation 9

*Azimuth angle tes*t: Equation 11

Surface-solar azimuth angle (γ): Equation 10

Solar incidence angle (θ): Equation 12

Diffuse radiation (Isβ): Equation 14, Equation 15 and Equation 16

Direct radiation (Idβ): Equation 17

Ground-reflected radiation (Ir): Equation 18

Total solar radiation (Iβ): Equation 13

With the energy output of the photovoltaic system being calculated as in the following formulae:

$$E = P_{STC} * \frac{I_\beta}{I_{\beta,STC}} * \left(1 - \propto \left[T_c - T_{c,STC}\right]\right) * p * PR \quad (21)$$

Where:

E = Energy output of PV array per hour (kWh)

P_{STC} = rated capacity of PV module under STC (kW)

I_β = solar radiation incident on the PV array in the current time step (kW/m^2)

$I_{\beta,STC}$ = solar radiation incident under STC (1 kW/m^2)

$\propto$ = temperature coefficient of power (% / °C)

T_c = the PV cell temperature in the current time step (°C)

$T_{c,STC}$ = the PV cell temperature under STC (°C)

p = number of panels

PR = Performance ratio (%)

The performance ratio (range between 0.5 and 0.9) gives the performance of the installation independently of the orientation, inclination of the panel. It includes all losses i.e. Inverter losses, temperature losses, DC and AC cables losses…

Although to be able to receive the maximum total panel energy output, the optimal panel tilt angle must be used. For clearance purposes, the modelling of such was carried out in a separate calculation sheet.

Optimal Angle Inclination Sheet

To find out the optimal panel tilt for the specified location, the total solar radiation (W/m^2) was calculated for the panel tilt ranges of 0-90 degrees. This was done with the use of an Excel spreadsheet, where the solar incidence angle, the direct, diffuse solar and ground reflected radiation and total radiation on panel where calculated per hour for 365 days for the angles ranges of 0-90 degrees based on the results for declination, equation of time, local solar time, hour angle, solar elevation, azimuth, azimuth angle test and surface-solar azimuth for a given location (as calculated on the Climate data sheet). The sum of the yearly total solar radiation for all degrees were compared, and the angle that gave the maximum total solar was found to be the optimum angle for the calculated location.

Table 3-6 Overview of Optimal Angle Inclination Calculation Sheet

Angle	0					90				
(Year Day)	Solar incidence angle	Direct solar on panel (Idβ)	Diffuse solar on panel (Isβ)	Ground reflected on panel (Ir)	Total solar on panel	Solar incidence angle	Direct solar on panel (Idβ)	Diffuse solar on panel (Isβ)	Ground reflected on panel (Ir)	Total solar on panel
1	146.6895	0	0	0	0	121.7214	0	0	0	0
1	142.6519	0	0	0	0	117.8079	0	0	0	0
1	136.22	0	0	0	0	111.1215	0	0	0	0
1	128.4471	0	0	0	0	102.3885	0	0	0	0
1	120.0769	0	0	0	0	92.23636	0	0	0	0
1	111.6129	0	0	0	0	81.12704	0	0	0	0
1	103.436	0	0	0	0	69.38492	0	0	0	0
365	89.29067	0	0	0	0	44.91254	0	0	0	0
365	84.00362	0	17	0	17	32.6299	0	12.96524	1.7	14.66524
365	80.35882	5.69423	58.26626	0	63.96049	20.95627	31.75103	59.18206	6.389423	97.30251
365	78.63137	53.22258	60.56313	0	113.7857	12.31629	263.7859	128.0314	11.22226	403.0396
365	78.96693	45.54736	75.58077	0	121.1281	14.39021	230.5329	141.1843	11.95474	383.672
365	81.33637	28.46969	68.75004	0	97.21973	24.58496	171.8663	109.2893	9.646969	290.8026
365	85.54532	10.64087	39.08924	0	49.73011	36.56476	110.0362	51.19254	4.964087	166.1928

PV system dimensioning sheet

The amount of electricity generated from the PV array, will be highly dependent on the amount of PV modules installed. This will be dependent on the size of the space available and the panels tilt. In order to calculate how many PVs can fit in a certain space, the following was considered, the minimum distance between arrays to avoid

shadowing (m) , the dimensions of the PV modules model used and the installation space available (m^2).

Shadowing between modules

To make sure the maximum amount of solar irradiance is captured by the installation, shading between the consecutive PV arrays should be avoided. To calculate the minimum distance needed between arrays to avoid shading, the use of triangle rules, sensitive to site latitude and panel tilt are used.

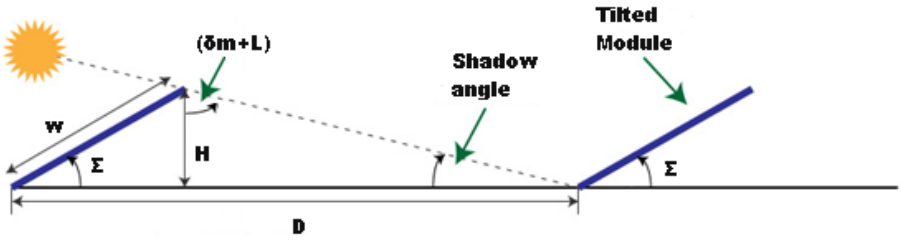


Figure 3-1 Schematic PV self –shading (Green Rhino Energy, 2013)

$$d_1 = w * \cos \Sigma \quad (22)$$

$$H = w * \sin \Sigma \quad (23)$$

$$d_2 = H * \tan(\delta_m + L) \quad (24)$$

$$D = d_1 + d_2 \quad (25)$$

Where:

Σ= the panel inclination (°)

w = the width (m) of the PV module

δ_m = the declination at the winter solstice (23.45 ° in December 21st)

L = the latitude of the site.

Maximum number of PV in a restricted area

Once the distance needed between the arrays of panels to avoid shading is known, the number of panels (n) is calculated by

$$n = \frac{A}{l * D} \quad (26)$$

Where:

A = the site area (m^2) available

l = the length of the panels

D = total distance between panels

Note that the equation notations are for a landscape orientation design, if the panels were to be portrait oriented the values for the length (l) and width (w) of the panel shall be interchanged in the above formulae (Cooper B-Line , 2010).

Installation Space

The installation space, is defined as the total space available that is destined to be covered in panels. In the case of this study a car park rooftop was selected as the installation area.

The optimal panel tilt is taken from the calculations on the previous Excel sheet.

Figure 3-2 summarises the input and output parameters for PV system dimensioning dependent on installation space and PV panel size

PV module characteristics	
Length (mm)	
Width (mm)	
Inclination angle (degrees)	
Area PV (m2)	

Installation Space	
Width (m)	
Length (m)	

Inter Panel Distance and Area Covered	
Number of Panels in Series	
Number of Panels in Parallel	
Distance between modules (m)	
D1	
H	
D2	
Total Area of PV (m2)	

Figure 3-2 Input and output parameters for PV system dimensioning dependent on installation space and PV panel size

3.4 Development of EV model

To ensure the charging demand alterations made in the model were a sensible approximation to today's behaviour car use, a detailed literature review was conducted to understand the charging requirements of an EV (covered in section 2.2) and to determine today's car mobility patterns in metropolitan areas.

The data gathered for mobility patterns was:

Average Workday Hours

According to the National Grid electricity non-residential demand typically peaks at approximately 8:30 am and maintains a constant demand till 5.30pm. On the other side residential demand suffers a peak at around 5:30pm.

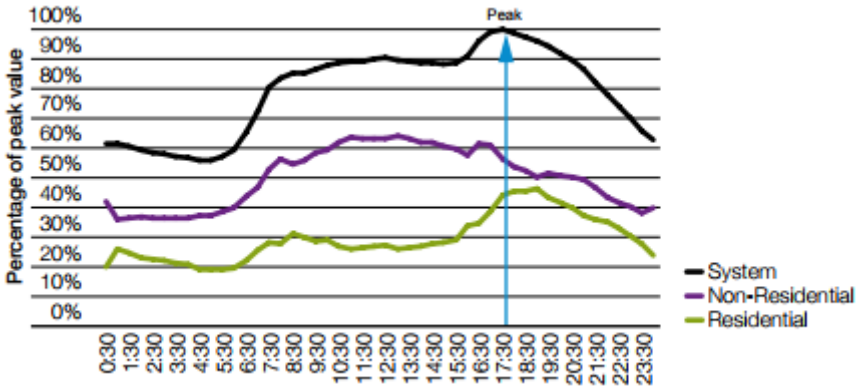


Figure 3-3 Typical hourly peak power demand (National Grid, 2015)

This electricity demand pattern along with the American Time Use Survey, which shows a demographic percentage of people working at a given hour by occupation, helped model the average working day as of 9 am to 5 pm.

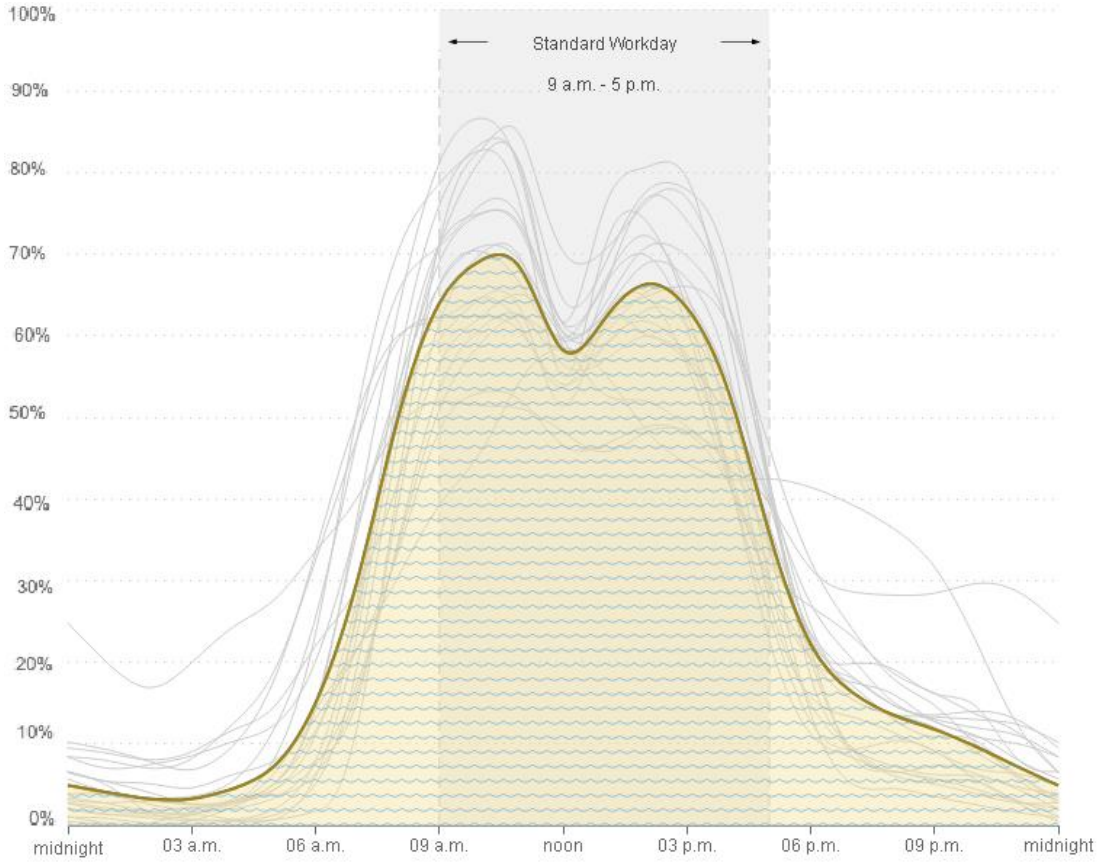


Figure 3-4 Percent of people working at a given hour by occupation (Bui, 2014)

Portion of people who commute by vehicle

Weekday work trips

Scotland was taken as a reference country of people's behaviour to model people's work transport mode. According to the Scottish Transport Statistics an average of 35.8% of the total population across all 4 most populated Scottish cities commute by private car or van to work, as seen in Figure 3-5.

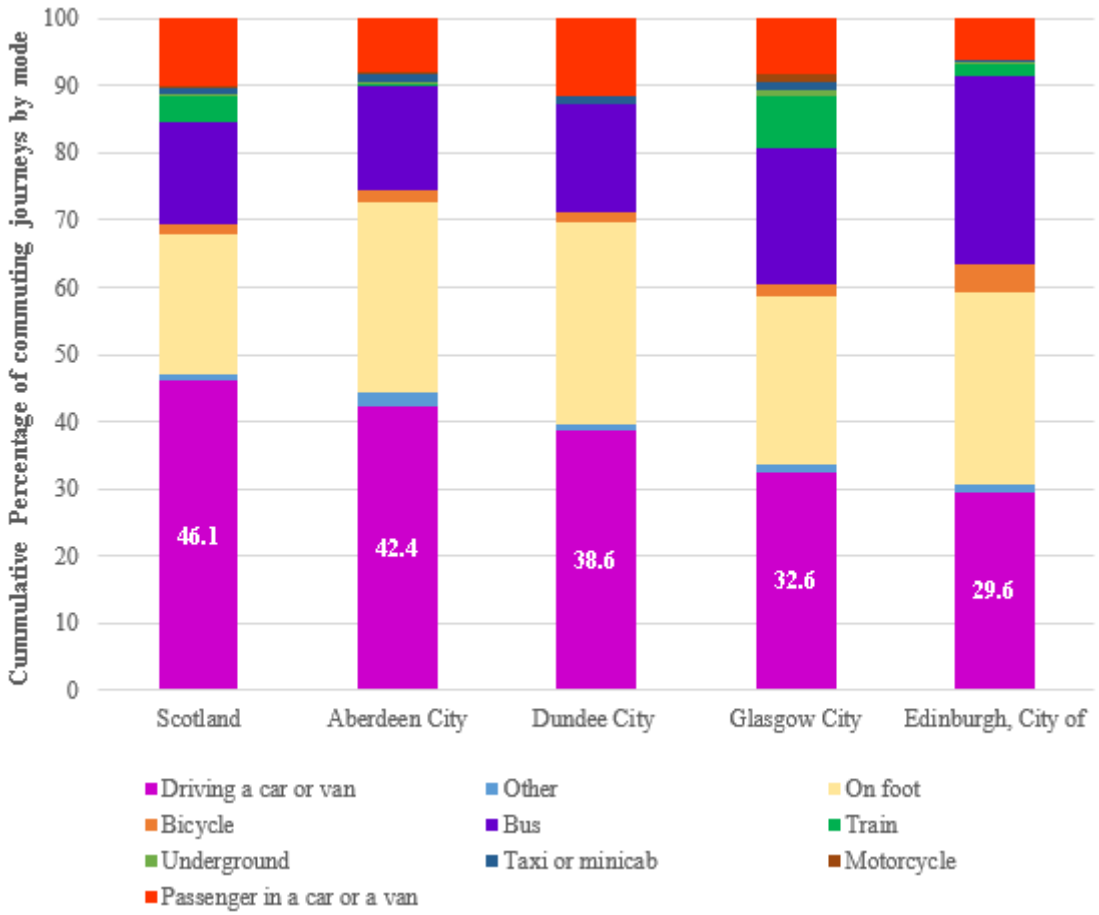


Figure 3-5 Travel to work commute profile, Scottish cities (The Glasgow Indicators Project, 2011)

As for parking patterns, a study regarding the driving and parking patterns of European car drivers carried by the European Commission, showed that 42% (24% in public parking areas, 18% in private parking areas as represented in Figure 3-6) of the people who travelled by car between Monday and Friday, parked either in a private or public parking area.

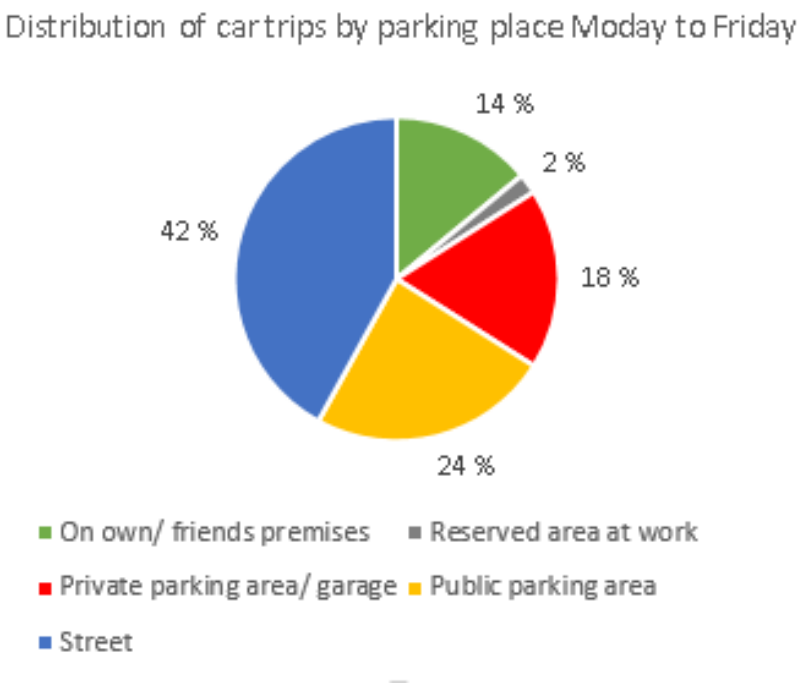


Figure 3-6 Distribution of car trips by parking place between Monday to Friday (UK) (European Comission, 2012)

Therefore, it is assumed that only 42% of that 38.5% share of the population that travel by car to work will park in a car park. Bearing in mind also the shortness of the average commuting distances (average 10 miles one way) and that the majority of EV charging will be carried out at home overnight, it is assumed that not all the EVs parked will need charging during the working day time, therefore the total percentage is of EVs parked that will require charging is said to be 12% of the total.

Weekends

During the weekend, there are fewer commuting trips. On average, the amount of time the car is parked before the first trip of the day or after the last trip of the day is greater than 16 hours during weekend days (European Comission, 2012). This means that during weekends the cars are parked in parking less amount of time, around 4 hours (European Comission, 2012).

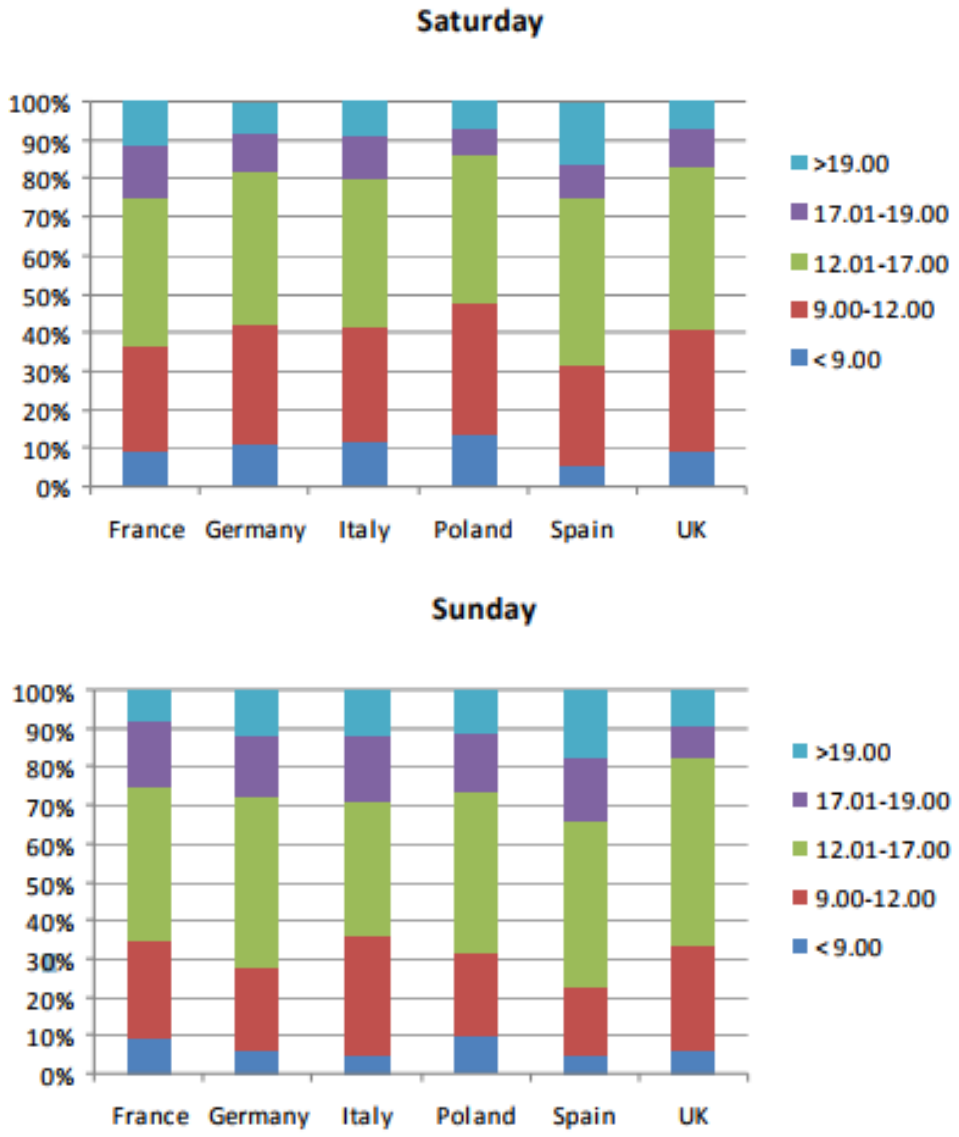


Figure 3-7 Car trips distribution by time of the day Weekend (European Comission, 2012)

It can be seen from Figure 3-7 that most of the trips during weekends are done later than 9 am and before 5 pm. This in contrast to the weekday behaviour statistics shows that people will tend to start their parking time later and finish it earlier than during weekdays. It is assumed that a lower percentage of people will use the car park, since there is a lower number of trips on average.

Behavioural Model

The following decision-making path was used to create the vehicle mobility behaviour pattern:

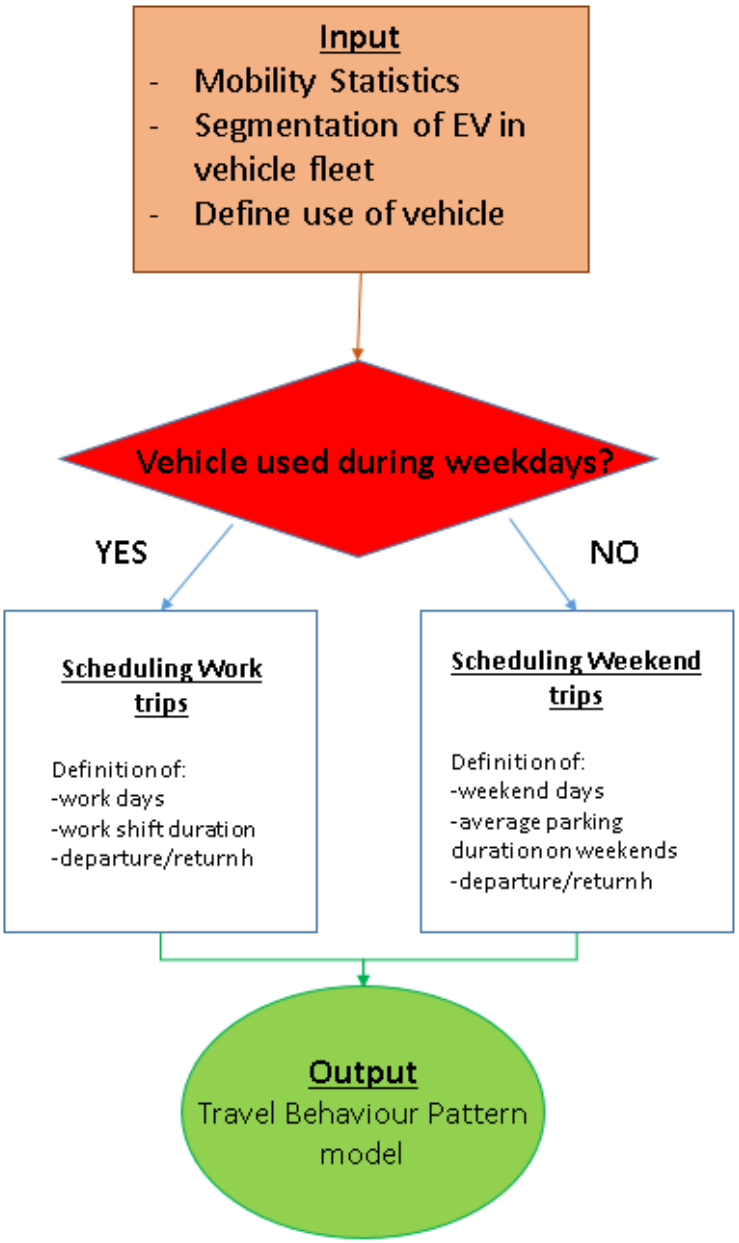


Figure 3-8 EV charging behaviour modelling methodology

These factors were then built into the tool, which allowed to integrate the charging demand variations of individual users from an average weekday job and average weekend car use.

Charging Demands per car Weekdays X am	
Power (kWh)	
Time needed complete charge (h)	
Start time of charging (h)	
Finish charging time (h)	
Number of cars	

Figure 3-9 Input and output parameters for EV charging system

The weekly behaviour pattern was assumed to be repetitive throughout the whole year for modelling simplicity.

Taxi Charging

The use of an alternate charging profile was thought to bring realism to the model, therefore a profile for rapid charging (higher charging demand per hour) was used. It was thought that one of the employment sectors that is car dependent on metropolitan areas and who could make use of this service, were taxis.

To construct the behavioural mobility model of taxis the same methodology as in Figure 3-8 was used. The behavioural patterns of taxi usage were modelled by consulting information regarding the usage of a private transport hire app in a metropolitan area: Uber usage in London. Which is corroborated by data gathered in a United Nations report, which states that 38.1% of the taxi journeys occur during night-time and weekends, when other forms of public transport are reduced or stopped (United Nations, 2011).

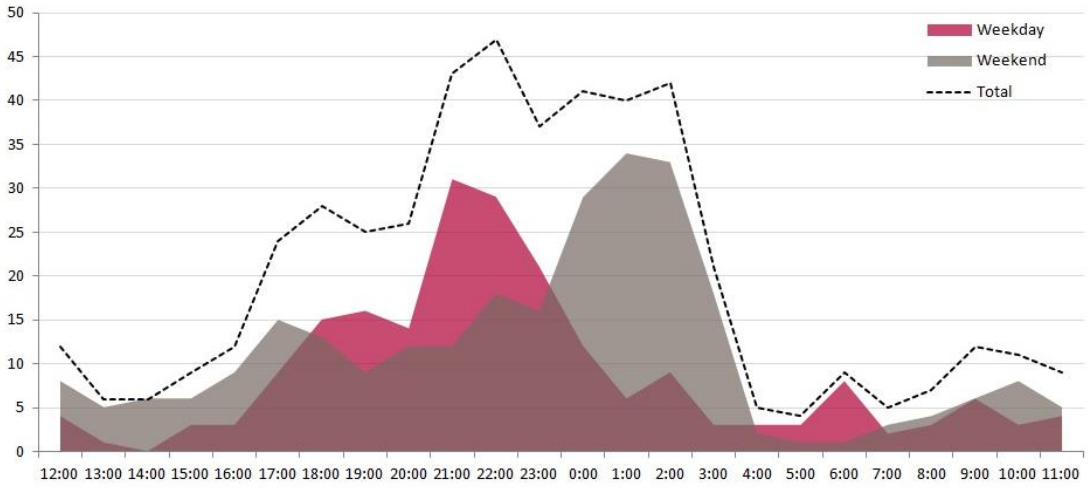


Figure 3-10 Uber App Usage London (Desai, 2016)

3.5 Tool Validation

In order to validate the tool, the following process posed by Schlesinger, et al., 1979 that is used for computer models was followed:

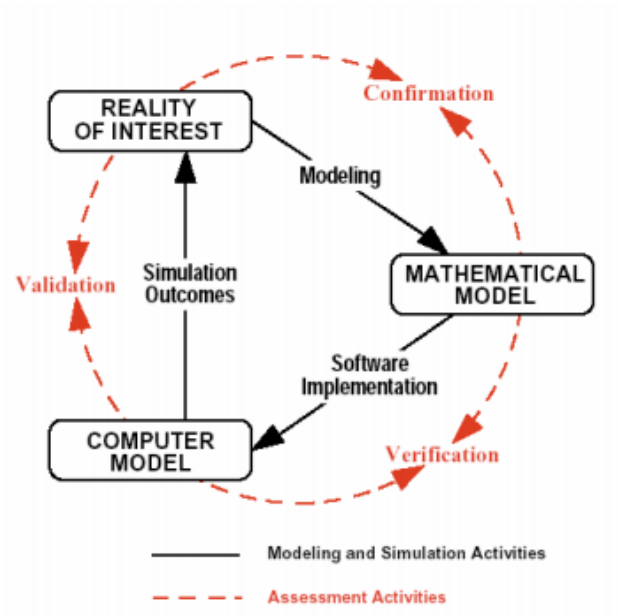


Figure 3-11 Simplified view of the model verification and validation process (Schlesinger, et al., 1979)

Where the Modelling and Simulation Activities carried out in this case were:

Reality of Interest: power generated by PVs in a restricted dimension at a certain location and determination of the % of total power needed for EV charging that comes from the PV system.

Modelling: Identification of modelling requirements i.e. solar geometry formulae, behavioural pattern models, charging requirements…

Mathematical Model: Gathering from the literature review carried out, the formulae and data needed for the tool modelling

Software Implementation: Construction in Excel of formulae and behaviour models

Computer Model: Linking set of Excel spreadsheets, to work jointly

Simulation Outcomes: Registration of data outcomes of different scenarios tested

And the Assessment activities as follows:

Confirmation: Making sure that following the formulae gathered in the literature review the reality of interest results are obtained. There is a path flow between input parameters, formulae and results.

Verification: Excel calculation results compared to manual calculation results, with a 5% discrepancy between results due to the inaccuracy of the manual calculations. The inaccuracy of the manual calculations was due to number round up during manual calculations. 10 random hours were taken throughout the year and verified against the CREST Integrated Electricity PV Demand Model (University of Loughborough).

Validation: Use of inter-model comparison with the use of HOMER programme for corroboration with tool designed.

Validation Study – HOMER

To perform a validation assessment of the tool used in this thesis, the modelling tool HOMER was used, although it should be noted that the validation of a mathematical model is a non-trivial exercise.

The following scenario was tested: An 85 kW PV system located in Glasgow, taking the solar resource data from Homer options of NASA Surface methodology and Solar Energy, which consists of the global horizontal radiation, monthly averaged values over 22-year period (July 1983 - June2005).

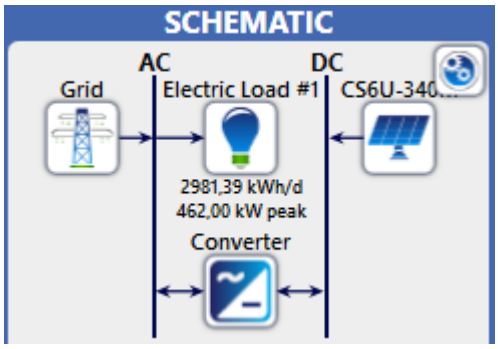


Figure 3-12 Schematic of system in HOMER

With the following components:

- 85 kW PV array rated capacity of the PV model CanadianSolar MaxPower CS6U-340M PV panel (Appendix B) with 0-degree inclination and Panel Azimuth (degrees West of South) equal to 0
- A generic converter
- Connection to the grid
- A load corresponding to the following energy demands:

Table 3-7 Load Data used for tool validation

Hour	Weekday Load (kW)	Weekend Load (kW)
1	0	0
2	0	0
3	0	0
4	0	0
5	0	0
6	0	0
7	0	0
8	231	0
9	462	396
10	462	396
11	462	396
12	462	0
13	462	0
14	462	0
15	462	0
16	231	0
17	0	0
18	0	0
19	0	0
20	0	0
21	0	0
22	0	0
23	0	0
24	0	0

After calculating it in HOMER the results obtained were the following

Table 3-8 HOMER simulation results

System/Ren Fraction (%)	CS6U-340M/Production (kWh/year)
5.94	72526

Where the System/Ren fraction is calculated by:

$$f_{ren} = 1 - \frac{E_{nonren} + H_{nonren}}{E_{served} + H_{served}} \quad (27)$$

Where:

E_{nonren} = non-renewable electrical production (kWh/yr)

H_{nonren} = non-renewable thermal production (kWh/yr)

E_{served} = total electrical load served (kWh/yr)

H_{served} = total thermal load served (kWh/yr)

Since the system modelled had no thermal loads, H_{nonren} and H_{served} can be accounted as zero.

When applying the same conditions to the tool created:

Table 3-9 Panel Data Validation

Panel Data	
No. panels:	250
α	0.004
PSTC (W)	340
PR	0.9
Panel inclination (deg)	
Σ	0

It was seen that the production a panel with the same rated capacity ($250 * \frac{340\ W}{1000} = 85kW$), as the CanadianSolar MaxPower CS6U-340M (Appendix B) gave a yearly Production of 70989.80 kWh. Comparing both PV production results the error difference is in the order of 2.1% in the PV calculations.

Charging Demands per car Weekdays 9 am	
Power (kWh)	3.3
Time needed complete charge (h)	7
Start time of charging (h)	9
Finish charging time (h)	16
Number of cars	70

Charging Demands per car Weekdays 10 am	
Power (kWh)	3.3
Time needed complete charge (h)	7
Start time of charging (h)	10
Finish charging time (h)	17
Number of cars	70

Charging Demands per car Weekends	
Power (kWh)	3.3
Time needed complete charge (h)	2
Start time of charging (h)	10
Finish charging time (h)	12
Max Number of cars possible to charge per hour	140
Number of cars	120

Figure 3-13 Charging Demand Profiles Validation

As for the system/renewable fraction, the one obtained using the Excel spreadsheets was calculated to be of the magnitude 6.5 % which is 0.6% higher than that calculated with HOMER.

Note that the renewable fraction results referred to in Chapter 4 are calculated differently to HOMER.

Conclusion on tool accuracy

The difference in results is noted to lie within a reasonable range of error due to assumptions made during the tool construction, as well as for the use of different solar data sources. Also, when modelling in HOMER, no temperature effects upon the panels were considered. This might be the reason why the PV model in HOMER gave a higher yearly energy production.

4 Evaluation of Future Potential

This project uses a car park as a case study for investigating the energy efficiency of EV charging stations powered by solar panels in an urban environment. A car park has been chosen because it is a good example of a medium sized urban building and a convenient place for cars to be charged. As seen on Figure 4-1 car parks are one of the most common places where people park their vehicles during the week.

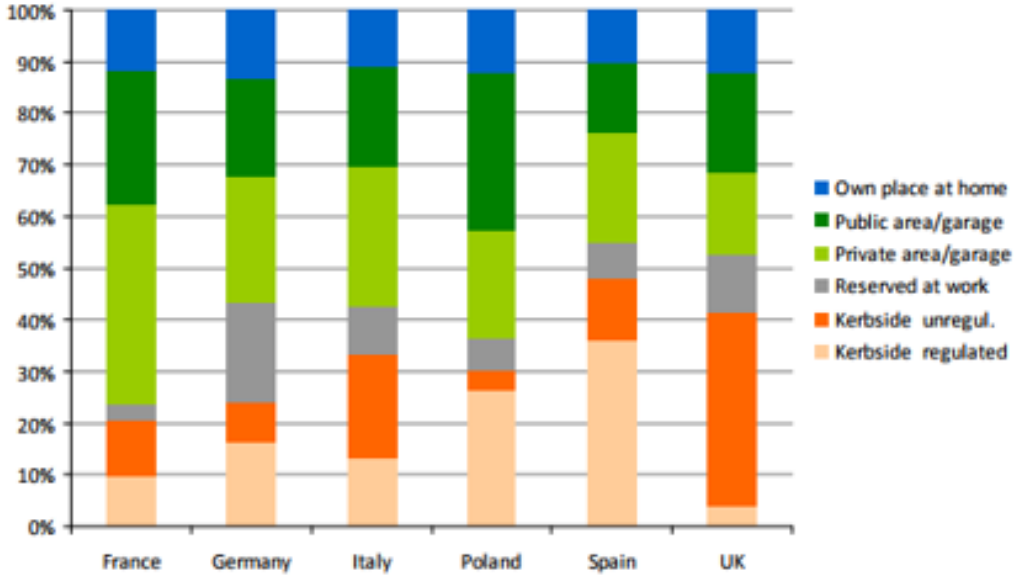


Figure 4-1 Distribution of parking places Monday to Friday (European Comission, 2012)

In order to dimension an average city car park area, a report on higher education institution parking was taken as source of information, as after having contacted parking city institutions no information was able to be provided, claiming commercially sensitive reasons.

The mean average number of car parking spaces was found to be around 1967 (British Parking Association, 2013) for higher education institutions parking facilities, which when extrapolated to a city like Glasgow, such parking spaces were close in parking spaces numbers to a car park which has a 3780 m^2 rooftop surface area. Place selected

for the PV installation, with the likelihood of adding a new floor for the PV installation, so no revenue is lost.



Figure 4-2 Aerial view of reference car park (Google, 2017)

The weather profile used for this study has been that of the city of Glasgow, Scotland with longitude -4.25 degrees and latitude 55.87 degrees.

The main function of our PV installation is to feed the EV charging points, therefore it is desirable that the installation achieves the highest possible power. The selection of the best solar panel for the photovoltaic system design was done following an Analytical Hierarchy Process (AHP). AHP is one of the most powerful and popular methods for efficient decision making (Balo & Şağbanşua, 2016). The main criteria priorities for this project are determined as electrical (50.5%), mechanic (23.5%).

Following this process, the photovoltaic modules SUN POWER E19/320 (Data sheet can be found in Appendix C) were found to be the most suitable. The panels have a peak power of 320 W, and are monocrystalline silicon panels. This type of panels was selected due to the high efficiency (19.6%) they provide compared to the other type of panels. The characteristics of the panel are: 1559 mm long and 1046 mm wide, with a temperature coefficient of -0.38 (%/ K).For the design of the PV layout the greatest possible PV dimensions have been used.

Regarding the panel inclination, the installation has been modelled as per a fixed tilt installation, accordingly it is sought that the installation has the maximum generation. They will be South-facing.

It is considered that the most suitable battery for this installation is the gel battery since it has a greater amount of life cycles. The batteries selected are the stationary batteries Sonnenschein A600 / 520 Solar (Data sheet can be found in Appendix D). These batteries are of gel and include 24 glasses of 2 V (48 V). In addition, they do not need any type of maintenance, its capacity is of 519 Ah (C100) and they have a useful life superior to 15 years with an 80% depth of discharge.

Regarding the inverter, the chosen inverter must allow an input voltage of 420 VDC and an output voltage of 400/230 VAC. It is necessary that the output is allowed both 400 V and 230 V because the slow recharge stations are fed with 230 Vac and those of rapid recharge are fed with 400 VAC.

Assumptions

- Car park: It is assumed that the parking will have a variation in occupancy rate, therefore for modelling purposes an average of 80% occupancy rate was taken.
- Type of EV: The project investigation only considers private vehicles and does not consider other user patterns such as public transport. The project only assesses a 25 kWh BEVs charge power consumptions and time frames, previously covered in Table 2-3.
- Demand: Behaviour patterns of EVs use are assumed as weekly constant throughout the year. There is two car slots for charging over the week, Weekday A and Weekday B, each with a 50% weight of the total EVs needed to be charged during the week.
- Time of Charging: for scenarios 1 and 2 the time when charging occurred varied upon the charging rate and time needed for charging selected but always within 9 am to 5 pm. The time was always selected to obtain the most efficiency.

4.1 Scenario 1 – Charging whilst Parked during Worktime

Current EV share

As discussed previously, under the Portion of people who commute by vehicle, it will be assumed that only 12% of the total cars parked in the car park are going to be EV needed of charge. It is accounted therefore that the number of EV needed to be charged for this scenario is 112 (number of parking spaces*occupancy rate*percentage of the total cars parked in the car park which are going to require charging). During the

weekends it is assumed a lower percentage of car affluence, therefore we will assume a 20% decrease of EV charging demands compared to the weekdays.

No conventional cars, all EVs

For a futuristic scenario of all EVs, the number of cars that will be needed to charge are as if 100% of the cars in the carpark are EVs, being in this case 936 cars.

Set 1:

Charge Rate: 3.3 kWh

Charging Time Required: 7 hours

Set 2:

Charge Rate: 7 kWh

Charging Time Required: 4 hours

Set 3:

Charge Rate: 10 kWh

Charging Time Required: 3 hours

Set 4:

Charge Rate: 22 kWh

Charging Time Required: 2 hours

Set 5:

Charge Rate: 43 kWh

Charging Time Required: 1 hours

4.2 Scenario 2 – Taxi charging

The purpose of this scenario is to assess with regards of energy efficiency, the number of taxis that could be charged, at high charging rates during the time where taxi demand is at its highest, 4 to 24 h during weekdays and from 21 to 4 h during the weekends, with the same battery size needed for charging for scenario 1 – Current EV share, 112 cars, at rates 3.3, 7, 10, 20 and 43 kWh. The charging rate chosen to charge the taxis, 43kWh, was one that could complete the EV charge within the shortest time possible, as contrary to the previous scenarios taxis benefit from being on the go, not parked.

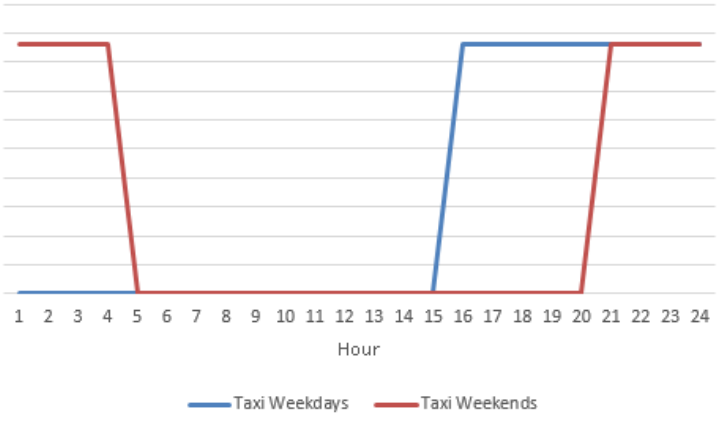


Figure 4-3 Taxi weekly charging profile hour

The average percentage of renewables is obtained by calculating the average monthly percentage of energy stored form renewables form the total energy needed for the charging (renewable stored + import from the grid) when EV charging occurred, and calculating the yearly average.

5 Project Outcome

Electricity generation from PV panels

The maximum number of SUN POWER E19/320 panels able to be installed in the specified area was 2180 modules. This installation meant a total installed power capacity of 698 (kW) and produced a total of 581(MW) yearly.

The average hourly energy production performance for the PV system described above is shown on Table 5-1.

Table 5-1 PV system performance (Average Hourly Energy)

Month	Jan	Feb	March	April	May	June	July	Aug	Sep	Oct	Nov	Dec
Average Energy Production (kWh)	11.81	27.84	53.62	97.86	129.89	132.88	115.94	103.21	61.91	33.84	16.54	8.56

Sensitivity Analysis of PV installation

The daily average performance of the PV installation for the original system, 100% of roof space covered with PV panels, and 50% of roof space used are shown in Figure 5-1, along with the total solar radiation received in that specific location for each month of the year.

When a smaller area was used for the installation, a decrease in the average and total energy production of the PV installation was recorded.

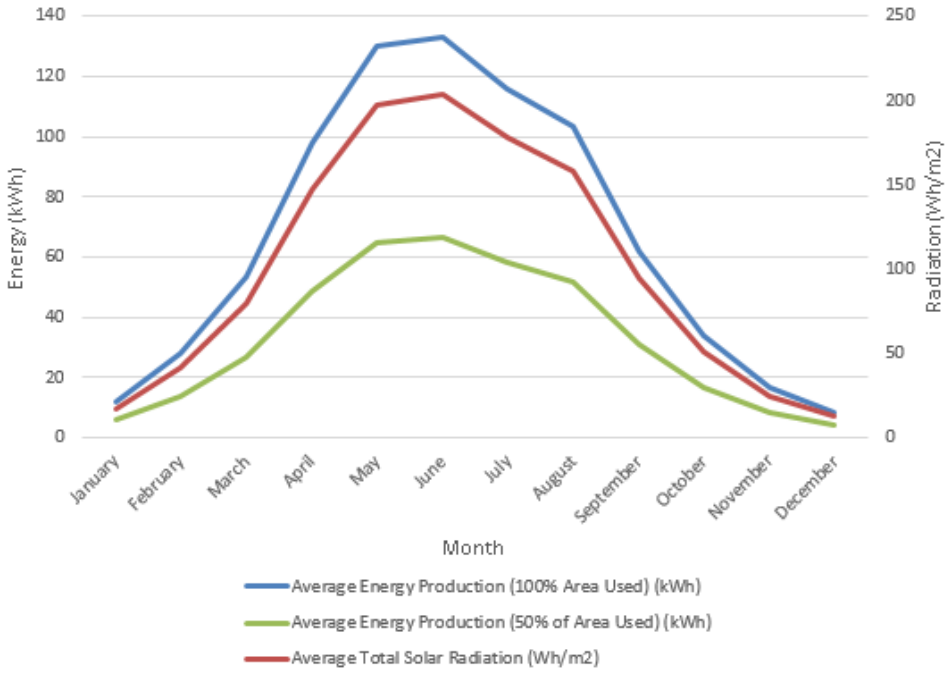


Figure 5-1 PV simulation results

The comparison of space available for fitting the installation, shows how the installation space available will be a determining factor in the amount of energy production from our PV array.

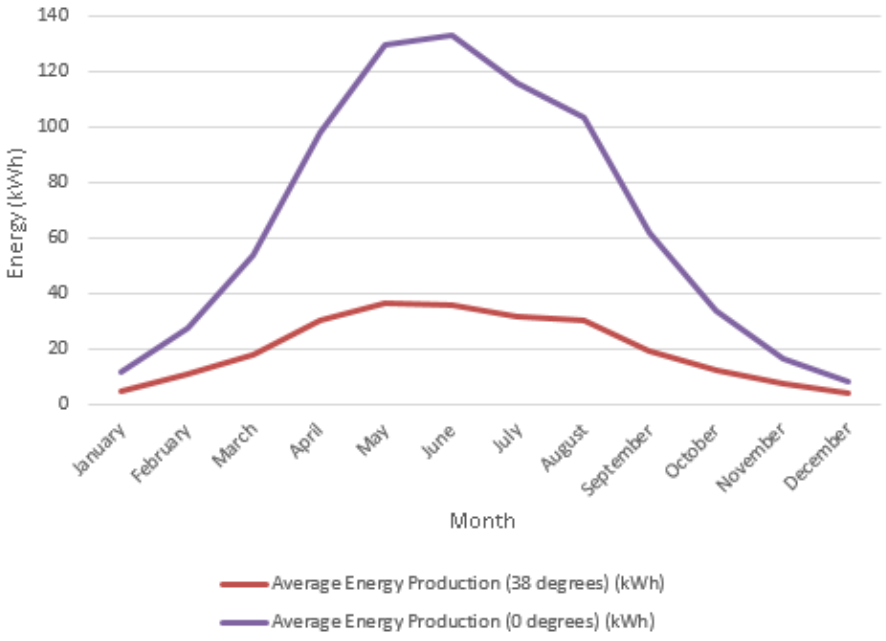


Figure 5-2 Variation in Energy Generation upon Tilt and Inter-panel Shading Avoidance

Another factor in the installation of panels on a restricted area, is whether to use the locations optimal angle or to occupy the maximum area possible. Figure 5-2 shows how when having a certain space, and seeking the maximum generation output possible, the use of an inclination angle of 0 degrees and lower inter-panel distance, was more energy efficient per area.

It was found that putting the panels at the optimal inclination angle, what in theory seemed would give an optimal power generation was not the optimal layout for restricted area. When using the optimum angle to size the number of panels that could be fitted in a restricted area it was found that the link between optimum generation and number of panels that could be fitted, was not optimum in energy generation means.

It would be more energy efficient to fit the panels at 0 degrees and have the minimum spacing between the panels to avoid shading since a greater number of panels could be fitted in the space.

For this reason, it was found to that in the case of restricted areas, such as dimensioning on a rooftop, there was a need of studying more in depth the optimum performance of panels per day regarding both optimum inclination and area available.

To do this not only the total irradiance for 0 to 90 degrees was calculated, but the number of panels that could be fitted in the same area was also calculated for the range of inclination angles 0 to 90 by considering the avoidance shading distance needed between the panels using Equation 22, Equation 23, Equation 24 and Equation 25. Knowing the total irradiance and surface area of PV modules, the energy generated for all tilt scenarios, 0 to 90, were calculated.

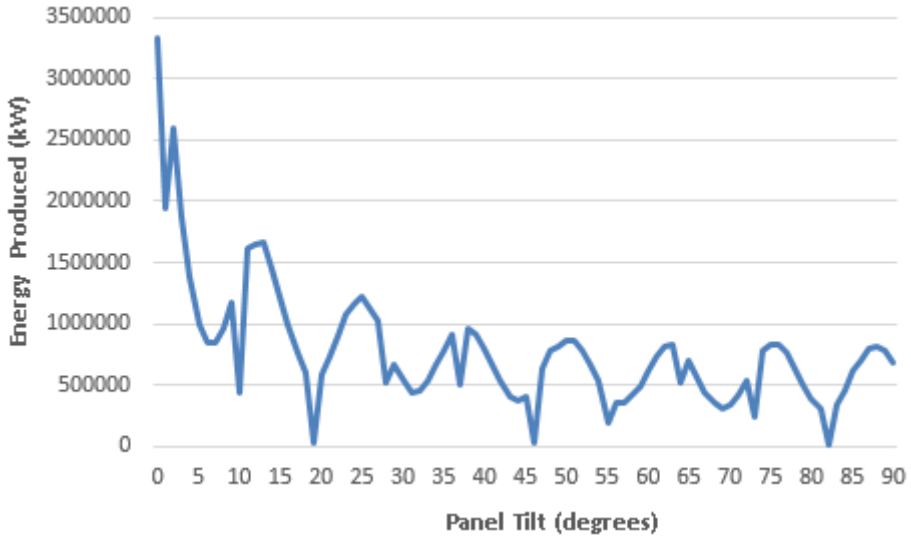


Figure 5-3 Energy production variation in a restricted area upon panel tilt variation

After the calculations, it was concluded that it would be more beneficial to install the panels at 0 degrees. Although this inclination, poses a greater energy loss per panel compared to having the panels inclined at their optimum tilt, especially during winter time, the loss is compensated by the number of panels that can be fitted, as seen on Figure 5-3.

Charging whilst Parked during Worktime

Current EV share

The performance for the different charging rates in Scenario 1 are shown in Table 5-2. When the charging rate increased, a reduction in the average renewable energy share was recorded, with the exception of charging at a rate of 43 kWh.

Table 5-2 Simulation Results Scenario 1

		Start Charging Time			Total Yearly Import from Grid (MWh)	Average % Renewables
		Weekday A	Weekday B	Weekend		
Charging Rate (kWh)	3.3	9	10	11	347	61.5
	7	9	13	12	462	57.3
	10	10	12	11	528	55.6
	22	10	15	11	836	51.3
	43	10	15	10	727	56.6

When the charging rate changed from 22 kWh to 43 kWh a decrease in the amount of yearly grid import was recorded, and a higher average of renewables was used in the car charging. Although when comparing the charges 10 kWh and 43 kWh, it can be seen that the import from the grid increased but so did the average percentage of renewables. The reason for this, can be explained by looking at the share of renewables between charging rates per month as shown in Figure 5-4.

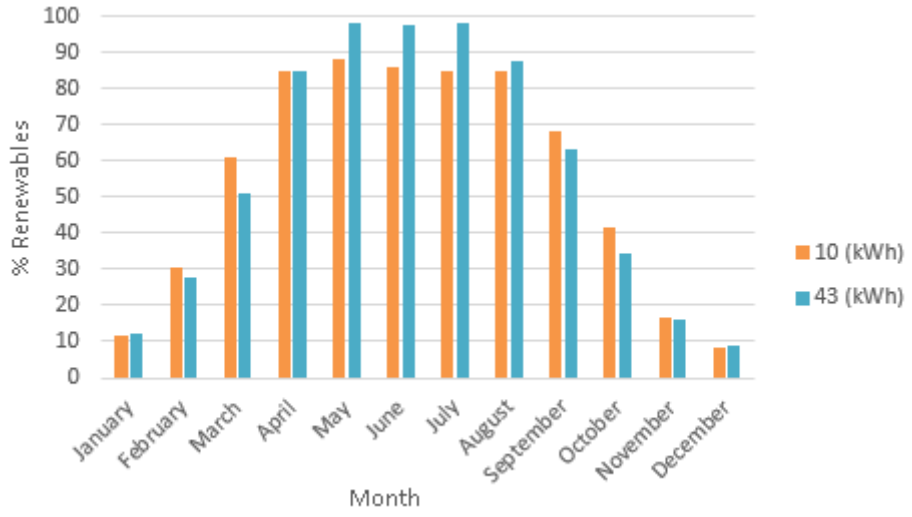


Figure 5-4 Comparison of renewable share between charging rates 10 and 43 kWh per month

Here it can be seen that in the winter months, the percentage of renewables is slightly higher when charging at a rate of 10 kWh. Nonetheless, during the summer months charging at a rate of 43 kWh has a greater benefit in regards of renewables share. This is explained by the fact that when dimensioning the size of our storage battery, when charging for the same amount of cars at different charging rates, a greater battery size will be need to charge at 43kWh. This battery can then be used to store the renewable energy generated. Therefore, a battery with a greater capacity will be able to store more energy, when it is created in great excess.

No conventional cars, all EVs

Error! Reference source not found. Table 5-3 shows the effect of shifting towards an all EV scenario, upon different charging rates will have on the energy mix.

Table 5-3 Simulation Results Scenario 2

		Start Charging Time			Total Yearly Import from Grid (MWh)	Average % Renewables
		Weekday A	Weekday B	Weekend		
Charging Rate (kWh)	3.3	9	10	11	6721	11
	7	12	13	12	8138	12.1
	10	13	14	11	8722	12.3
	22	9	10	11	13171	8.6
	43	9	16	11	12771	8.0

It was seen that for a futuristic scenario a high amount of cars meant a small amount of the energy required for charging would actually come from renewables.

It is worth noting that there is a decrease in renewables as the charging rate increase. Although there are two exceptions; when comparing the percentage of renewables needed between 7 kWh and 10 kWh, there exists a slight increase, 0.2%, in renewable penetration. This can be explained by the fact that charging at a rate of 10 kWh requires less time to complete the charge, therefore there is a greater opportunity to space the

charging sets, A and B during the weekdays and therefore be able to store more renewables during winter months, as seen on Figure 5-5.

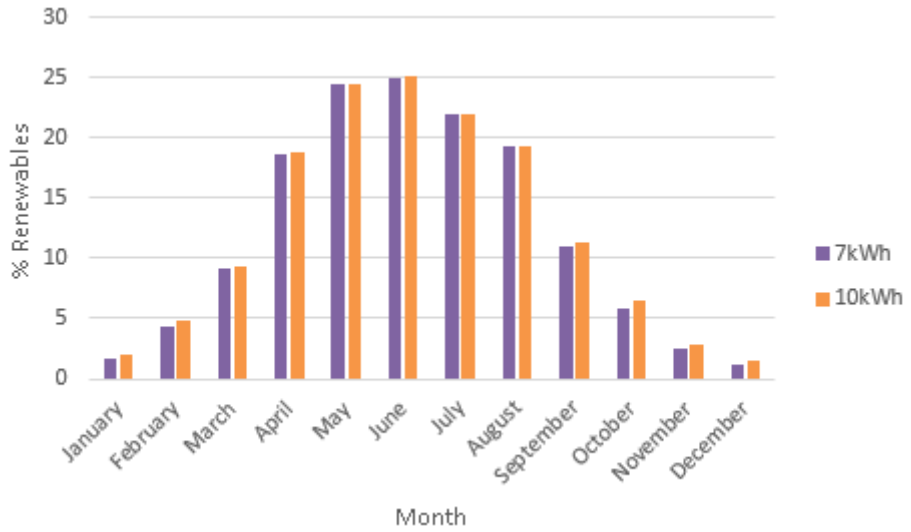


Figure 5-5 Monthly Percentage Renewables for charges 7 kWh and 10 kWh - Scenario 2

Taxi Charging

The performance for the different battery storage capacities at a high charging rate (43kWh) are shown in Table 5-4.

Table 5-4 Simulation results Scenario 3

Battery Storage Capacity (kWh)	Number of EV taxis powered per hour	Average % Renewables
370	8	8
784	18	10.93
1120	26	9.57
2464	57	6.45
4816	112	3.78

In scenario 3 it can be seen that using the same battery sizes as during the day charging for scenarios 1 and 2, with the highest charging rate (43 kWh) causes the efficiency of the installation to reach its lowest point.

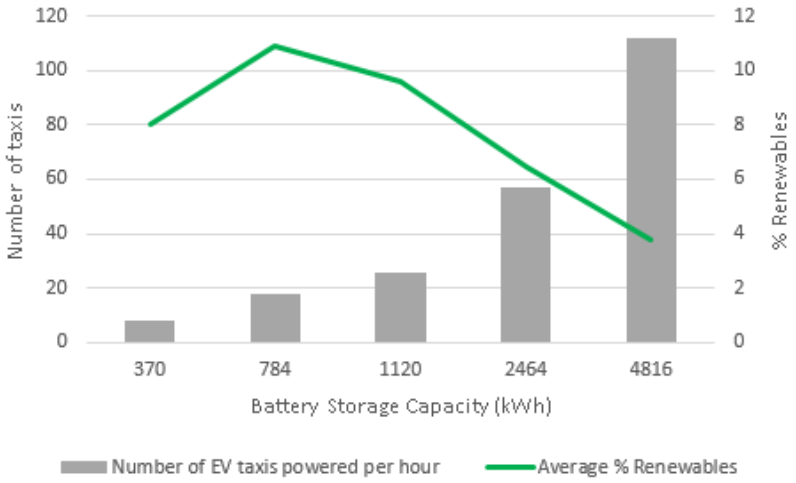


Figure 5-6 Number of taxis and average renewable percentage against battery storage capacity

In Figure 5-6 it can be seen that for all sets of battery sizes, the efficiency was very low as well as the number of taxis being able to be powered at a rate of 43 kWh. This showed that there would be a need of greater battery storage capacity to be able to store all renewable generated throughout the day and a limited number of cars that would be allowed to charge at high charging rate, so this system would become efficient.

Scenario Inter-comparison

From the two set of scenarios it can be withdrawn that a charging system as the one studied is only energy efficient, for medium during daytime hours, when the energy generated from the PV installation can be directly used to charge the EVs. As comparing scenarios 1 and 2, with a high charging rate, and different battery capacities, only a few amount of cars can be charged with a low input from renewables.

Comparing the results in scenario 1 between current EV share and all EVs it is clear to see that this concept when applied to great amount of charging loads, high number of EVs, reaches an inefficient point. The results for a large amount of EV, showed an average of circa 9 % renewable energy share for all charging rates.

5.1 Summary of Results

PV Layout

It was found that putting the panels at the optimal inclination angle in a restricted area, was not optimum in energy generation means.

It would be more energy efficient to fit more panels at 0 degrees and have minimum spacing between the panels to avoid shading.

Scenario 1 – Current EV share

As the charging rate was increased, an increase in the amount of energy need to be imported by the grid, and a lower average renewables share of the total energy needed to charge the EVs was noted. There was an exception regarding this pattern when charging at a rate of 43 kWh.

Scenario 1 – Non-Conventional cars, all EVs

A high demand of cars needing charging meant a very low percentage of renewables across all charging modalities, ranging from 8-11%. In this case the optimum charging rates for a huge demand was 7kWh and 10kWh.

Scenario 2 – Taxi Charging

Having a greater storage capacity increased the number of taxis that could be charge with a general decrease in renewables when charging at a high rate (43kWh). Charging more taxis meant that the average amount of renewable energy used in the car charging would be lower per car.

6 Conclusions

It was recognised that the idea of utilising a PV installation to charge EVs with renewable energy share had the potential of being energy efficient in a range of EV charging scenarios. The scenarios where the charging demands were of medium rate and occurred during the day time were proven to be when the PV installation became the most energy efficient.

In addition, it was seen how the use of a renewable energy source can help mitigate the impact of a widespread adoption of EVs. Although in the futuristic idea of only EVs circulating, a higher renewable energy generation penetration will be needed than that able to be provided by an urban PV installation, in order to make a widespread use of EVs sustainable.

It is clear that there is a global ambition to shift from conventional fossil fuelled vehicles to EVs, incentivised by the desire to improve urban air quality and GHG emission reduction. Nonetheless, the transition to a totally electrified vehicle fleet will mean an increase in the total electrical consumption which if not provided by renewable energy sources will be counterproductive to the reasons that prompt such shift.

For this project a Microsoft Excel based tool was constructed and used to provide an assessment of the energy efficiency of a PV installation against different EV charging scenarios. The tool also allowed adjustments to certain factors determining the charging loads and PV installation aspects for it to be used as a decision support tool for future studies.

The tool was constructed with the information gathered in the literature review regarding PV systems and EV charging systems and behavioural ca usage patterns. It

was validated by inter-model comparison with the software HOMER. The tool showed reasonable levels of accuracy in estimating the energy generation of a PV installation and the percentage of renewable energy such generation had upon a certain load.

The project used Duke Street Car Park in the city of Glasgow as the case study in which to base the scenario investigations. A car park was selected since it represents a suitable place for both a PV and an EVSE installation, with Duke Street car park being an approximate representation of a typical medium sized city car park.

The investigation consisted of an analysis of 3 different scenarios, which tested the efficiency installation for working hours charging, night time charging at high charge rate and a full electrified vehicle situation. From the three set of scenarios it was withdrawn that a charging system as the one studied is only energy efficient, with today's technology, if charging occurs when the energy generated from the PV installation can be directly used to charge the EVs.

Reviewing the results discussed, the following recommendations can be made:

- The use of urban PV installations are only worthwhile for daytime charging. For night time charging, the battery sizing to store all the renewable energy produced would be too big. It can become a viable option if the efficiency, capacity and price of batteries decreased.
- If installation of PVs is set to be on a restricted space area, the maximum energy generated would be obtained when the PV panels are inclined at 0 degrees rather than the optimum panel tilt.

- Concept of charging EVs during working hours with the use of energy generated by PVs, can help mitigate the effect of electrifying transport.
- Future scenario of all EV transport should look at higher generation forms of renewable energy. Urban installations, as with today's technologies (i.e. PV and batteries efficiencies) do not generate sufficient energy to withstand the charging demands of a high EV penetration.

The following areas became apparent as worthwhile and insightful research avenues for future work:

- It was acknowledged that the tool could have been more accurate by optimising mathematically the optimum times and cars to be charged per hour, rather than the user having to optimise the charging times by trial and improvement and with the charging of all cars done at the same time. This would also aid in reducing the battery size and capacity needed by the installation, telling the user the ideal battery sizing.
- The use of a combination of more demand profiles, such as combining charging cars during the day time working hours and taxi charging can help create a more realistic usage pattern of the EVSE.
- Additionally having the option of storing data from simulation results could be beneficial for those users using it as a decision support tool, as it would make it easier to compare results gathered and see what the advantages and disadvantages of slight changes.
- Regarding future research, it was uncovered the need of a more in depth study of the relation between optimum panel tilt against number of panels in generation means for a restricted area.

- Given that the major driver behind the acceptability of new infrastructure and installations is usually investment costs. An economic study of the installation for different scenarios, can help in aiding to decide in what cases it is economically viable.
- Assessment of power quality of renewable sources.
- Other sources that can be implemented in urban areas or in surroundings.

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Appendix A Decision Support Tool Exercise

The following information and guidelines were supplied to the participants in the tasks. The intention of the first test was to establish whether the tool was valid and the second to gather participant's opinions on the overall use of the tool. The participants had previously been briefly familiarised with the project background and the tools purpose.

Task 1

The first task is for you to use to use the tool to calculate the energy efficiency of a domestic PV installation and EV charging demand in Glasgow, Scotland with Latitude 55.87 degrees and Longitude -4.25 degrees.

The details of the PV model and house building are as detailed below:

Table 7-1 Exercise PV properties

PV	
Rated Power (PSTC)	80
PR	0.8
α (%/K)	0.004
Length(mm)	1559
Width (mm)	1046

Table 7-2 Exercise Installation Characteristics

Installation Space	
Width (m)	15
Length (m)	14
Nº of parking spaces	580
Occupancy Rate (%)	40
Percentage of EV (%)	30

The figure below is a snippet from the Excel Worksheet to illustrate where the transport demand selection should be inputted.

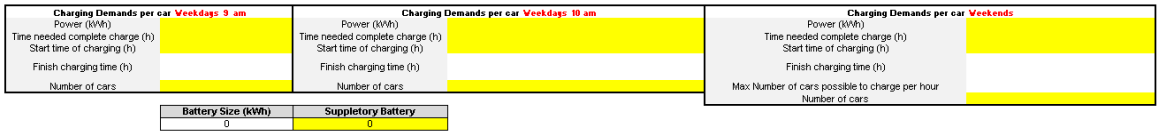


Figure 7-1 Snippet demand worksheet

Your EV cars should be charged at a rate of 22kWh for 3 hours, from 11 am to 2 pm.

Your results can then be viewed in the Result section under each demand sheet. Once the task has been completed, please return the excel sheet for evaluation.

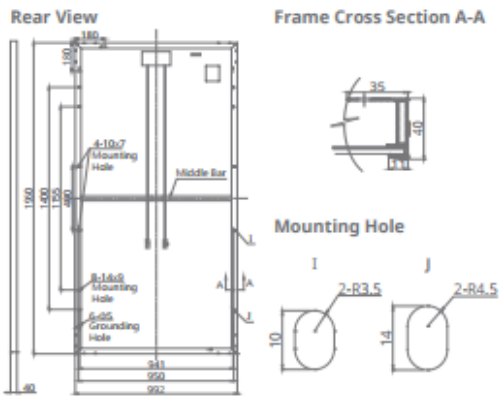
Task 2

The second task is for you to make slight PV installation and EV demand changes to those defined previously in task 1 and note down the impact of such on the Energy Efficiency results of the installation.

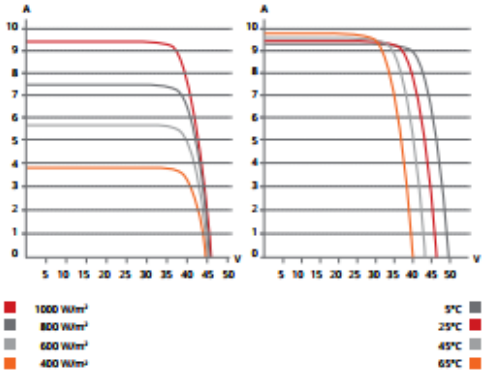
Comment on your experience with the tool, such as its user friendliness and any lack of features or possible further developments that may be needed.

Appendix B - CanadianSolar MaxPower CS6U-340M Data Sheet

ENGINEERING DRAWING (mm)



CS6U-335M / I-V CURVES



ELECTRICAL DATA / STC*

CS6U	330 M	335 M	340 M
Nominal Max. Power (Pmax)	330 W	335 W	340 W
Opt. Operating Voltage (Vmp)	37.5 V	37.8 V	37.9 V
Opt. Operating Current (Imp)	8.80 A	8.87 A	8.97 A
Open Circuit Voltage (Voc)	45.9 V	46.1 V	46.2 V
Short Circuit Current (Isc)	9.31 A	9.41 A	9.48 A
Module Efficiency	16.97 %	17.23 %	17.49%
Operating Temperature	-40°C ~ +85°C		
Max. System Voltage	1500 V (IEC) or 1500 V (UL)		
Module Fire Performance	TYPE 1 (UL 1703) or CLASS C (IEC 61730)		
Max. Series Fuse Rating	15 A		
Application Classification	Class A		
Power Tolerance	0 ~ + 5 W		

* Under Standard Test Conditions (STC) of irradiance of 1000 W/m², spectrum AM 1.5 and cell temperature of 25°C.

MECHANICAL DATA

Specification	Data
Cell Type	Mono-crystalline, 6 inch
Cell Arrangement	72 (6 × 12)
Dimensions	1960 × 992 × 40 mm (77.2 × 39.1 × 1.57 in)
Weight	22.4 kg (49.4 lbs)
Front Cover	3.2 mm tempered glass
Frame Material	Anodized aluminium alloy
J-Box	IP67, 3 diodes
Cable	PV1500DC-F1 4 mm2 (IEC) & 12 AWG 2000 V (UL), 1160 mm (45.7 in)
Connector	T4-1500V or PV2 series or H4-UTX
Per Pallet	26 pieces
Per container (40' HQ)	572 pieces

ELECTRICAL DATA / NOCT*

CS6U	330 M	335 M	340 M
Nominal Max. Power (Pmax)	238 W	242 W	245 W
Opt. Operating Voltage (Vmp)	34.2 V	34.5 V	34.6 V
Opt. Operating Current (Imp)	6.96 A	7.01 A	7.10 A
Open Circuit Voltage (Voc)	42.1 V	42.3 V	42.4 V
Short Circuit Current (Isc)	7.54 A	7.62 A	7.67 A

* Under Nominal Operating Cell Temperature (NOCT), irradiance of 800 W/m², spectrum AM 1.5, ambient temperature 20°C, wind speed 1 m/s.

TEMPERATURE CHARACTERISTICS

Specification	Data
Temperature Coefficient (Pmax)	-0.41 % / °C
Temperature Coefficient (Voc)	-0.31 % / °C
Temperature Coefficient (Isc)	0.053 % / °C
Nominal Operating Cell Temperature	45±2 °C

PERFORMANCE AT LOW IRRADIANCE

Outstanding performance at low irradiance, average relative efficiency of 96.5 % from an irradiance of 1000 W/m² to 200 W/m² (AM 1.5, 25°C).

PARTNER SECTION

The specification and key features described in this datasheet may deviate slightly and are not guaranteed. Due to on-going innovation, research and product enhancement, Canadian Solar Inc. reserves the right to make any adjustment to the information described herein at any time without notice. Please always obtain the most recent version of the datasheet which shall be duly incorporated into the binding contract made by the parties governing all transactions related to the purchase and sale of the products described herein.

Caution: For professional use only. The installation and handling of PV modules requires professional skills and should only be performed by qualified professionals. Please read the safety and installation instructions before using the modules.

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Appendix C - SUN POWER E19/320 Data Sheet

SUNPOWER

E19 / 320 SOLAR PANEL

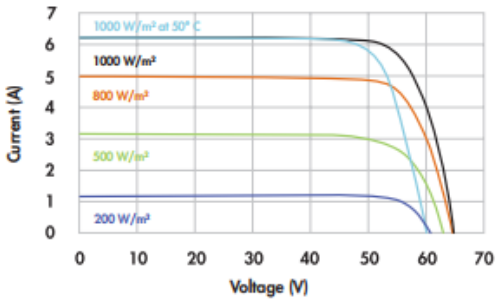
MAXIMUM EFFICIENCY AND PERFORMANCE

Electrical Data

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

Peak Power (+5/-3%)	P_{max}	320 W
Efficiency	η	19.6 %
Rated Voltage	V_{mpp}	54.7 V
Rated Current	I_{mpp}	5.86 A
Open Circuit Voltage	V_{oc}	64.8 V
Short Circuit Current	I_{sc}	6.24 A
Maximum System Voltage	UL	600 V
Temperature Coefficients	Power (P)	-0.38% / K
	Voltage (V_{oc})	-176.6mV / K
	Current (I_{sc})	3.5mA / K
NOCT		45° C +/-2° C
Series Fuse Rating		20 A

I-V Curve



Current/voltage characteristics with dependence on irradiance and module temperature.

Tested Operating Conditions

Temperature	-40° F to +185° F (-40° C to + 85° C)
Max load	113psf 550 kg/m² (5400 Pa), front (e.g. snow) w / specified mounting configurations 50 psf 245 kg/m² (2400 Pa) front and back – e.g. wind
Impact Resistance	Hail 1 in (25 mm) at 51mph (23 m/s)

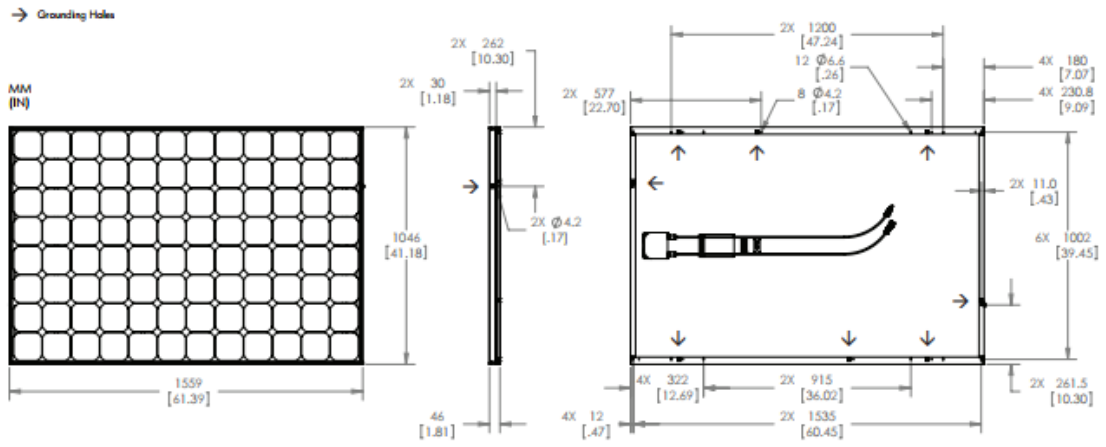
Mechanical Data

Solar Cells	96 SunPower all-back contact monocrystalline
Front Glass	High transmission tempered glass with anti-reflective (AR) coating
Junction Box	IP-65 rated with 3 bypass diodes Dimensions: 32 x 155 x 128 (mm)
Output Cables	1000mm length cables / MultiContact (MC4) connectors
Frame	Anodized aluminum alloy type 6063 (black)
Weight	41.0 lbs (18.6 kg)

Warranties and Certifications

Warranties	25 year limited power warranty
	10 year limited product warranty
Certifications	Tested to UL 1703. Class C Fire Rating

Dimensions



CAUTION: READ SAFETY AND INSTALLATION INSTRUCTIONS BEFORE USING THE PRODUCT.

Visit sunpowercorp.com for details

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Appendix D - Sonnenschein A600 / 520 Solar Data Sheet

Sonnenschein A600 SOLAR

Technical data

Technical characteristics and data

Type	Part number	Nom. voltage V	Nominal capacity C_{120} 1.85 Vpc 20 °C Ah	Discharge current I_{120} A	Length (l) max. mm	Width (b/w) max. mm	Height up to top of cover (h1) max. mm	Height incl. connectors (h2) max. mm	Weight approx. kg	Terminal	Pole pairs
A602/295 SOLAR	NGS6020295HS0FC	2	294	2.45	105	208	357	399	19.0	F-M8	1
A602/370 SOLAR	NGS6020370HS0FC	2	367	3.05	126	208	357	399	23.0	F-M8	1
A602/440 SOLAR	NGS6020440HS0FC	2	440	3.66	147	208	357	399	27.0	F-M8	1
A602/520 SOLAR	NGS6020520HS0FC	2	519	4.32	126	208	473	515	30.0	F-M8	1
A602/625 SOLAR	NGS6020625HS0FC	2	623	5.19	147	208	473	515	35.0	F-M8	1
A602/750 SOLAR	NGS6020750HS0FC	2	727	6.05	168	208	473	515	39.0	F-M8	1
A602/850 SOLAR	NGS6020850HS0FC	2	845	7.06	147	208	648	690	49.0	F-M8	1
A602/1130 SOLAR	NGS6021130HS0FC	2	1126	9.42	212	193	648	690	66.0	F-M8	2
A602/1415 SOLAR	NGS6021415HS0FC	2	1408	11.7	212	235	648	690	80.0	F-M8	2
A602/1695 SOLAR	NGS6021695HS0FC	2	1689	14.1	212	277	648	690	95.0	F-M8	2
A602/1960C SOLAR	NGS6021960HS0FC	2	1994	16.3	212	277	717	759	115	F-M8	2
A602/2600 SOLAR	NGS6022600HS0FC	2	2613	21.7	216	400	775	816	160	F-M8	3
A602/3270 SOLAR	NGS6023270HS0FC	2	3266	27.2	214	489	774	816	198	F-M8	4
A602/3920 SOLAR	NGS6023920HS0FC	2	3919	32.6	214	578	774	816	238	F-M8	4

Capacities C_1 - C_{120} (20 °C) in Ah

Type	C_1 1.67 Vpc	C_3 1.75 Vpc	C_5 1.77 Vpc	C_{10} 1.80 Vpc	C_{24} 1.80 Vpc	C_{48} 1.80 Vpc	C_{72} 1.80 Vpc	C_{100} 1.85 Vpc	C_{120} 1.85 Vpc
A602/295 SOLAR	124	167	193	217	248	273	289	285	294
A602/370 SOLAR	155	209	241	272	310	342	362	357	367
A602/440 SOLAR	186	251	289	326	372	410	434	428	440
A602/520 SOLAR	229	307	342	379	435	471	503	505	519
A602/625 SOLAR	275	369	410	455	523	565	604	606	623
A602/750 SOLAR	321	431	479	531	610	659	705	707	727
A602/850 SOLAR	368	520	614	681	729	782	827	822	845
A602/1130 SOLAR	491	694	818	908	973	1043	1102	1096	1126
A602/1415 SOLAR	614	867	1023	1135	1216	1304	1378	1370	1408
A602/1695 SOLAR	737	1041	1228	1362	1459	1565	1654	1644	1689
A602/1960C SOLAR	867	1222	1371	1593	1803	1942	2016	1957	1994
A602/2600 SOLAR	1047	1548	1782	2024	2276	2472	2599	2547	2613
A602/3270 SOLAR	1309	1935	2227	2530	2846	3090	3249	3184	3266
A602/3920 SOLAR	1571	2322	2673	3036	3415	3708	3899	3821	3919