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ESTUDIO DE VIABILIDAD DE UNA INSTALACIÓN SOLAR FOTOVOLTAICA EN UNA VIVIENDA PARTICULAR

Titulación: Ingeniería Técnica Industrial
Intensificación: Electricidad
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A Adri, por estar siempre ahí.

Abstract

The motivation for the work conducted within this paper was to asses if a common private property was capable of generate the energy it consumed. To evaluate this, a feasibility study was conducted based on research carried out throughout PV technology including components, system topologies and economic support schemes. The methodology employed for the study was PV software system simulation using PVSyst, where a 3D model of the property was developed to conduct performance simulations of the system. The study concluded that the property was effectively capable of generate more than the electrical energy needed. Nevertheless, the economic feasibility of the project, even though it resulted feasible, seemed discouraging because of the long payback period obtained due to the recent second review of feed-in tariffs in the UK. Finally, both preliminary electrical and structural designs were conducted.

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List of Abbreviations

AC	*Alternate Current*
a-Si	*Amorphous Silicon*
CdS	*Cadmium Selenide*
CdTe	*Cadmium Telluride*
CFC	*Chlorofluorocarbon*
CO2	*Carbon Dioxide*
DC	*Direct Current*
DCC	*Department of Climate Change*
DTI	*Department of Trade and Industry*
FiT	*Feed-in Tariff*
GaAs	*Gallium Arsenide*
Impp	*Current at Maximum Power Point*
Isc	*Short-circuit Current*
MPP	*Maximum Power Point*
MPPT	*Maximum Power Point Tracker*
NOx	*Nitrogen Oxide*
Pmax	*Maximum Power*
PV	*Photovoltaics*
RPI	*Retail Price Index*
STC	*Standard Test Conditions*
UV	*Ultra-Violet*
Vmpp	*Voltage at Maximum Power Point*
Voc	*Open-Circuit Voltage*

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1. Introduction

The aim of this paper is to determine the feasibility into the installation of a photovoltaic grid-connected power generation system in a private property. This chapter will present some necessary background information, as well as it will expose the main aims of the work conducted.

1.1 Background information

Energy requirements have elevated considerably with the fast development of global economy. Within this context, awareness of facts such as climate change and the progressive exhaustion of non-renewable energy sources have been raised. As a result of this, to protect the environment and to save energy has become tasks of high priority (Baños, et al., 2010). In order to develop these tasks, there are to main paths to be followed: to improve energy efficiency and to orientate the future of energy towards renewable energies.

Energy efficiency seeks to remove energy wasting so as to decrease energy requirements. It should be a stage process, i.e. it should encompass from small-scale actions such as actions taken by individuals at home, to large-scale actions, implemented in vast generation plants or great energy consumers.

On the other hand, the purpose of moving towards renewable energies is to satisfy the existing energy requirements without negative effects either on the environment or on the fossil fuel reserves. Renewable energy can be also implemented within a great span of magnitudes, from decentralized small-scale generator consisting of a small number of kilowatts of generation power to several megawatts systems.

1.1.1 Current global situation

Energy has been always considered as a main actor in wealth generation as well as a key aspect in economic development. It could be said that the 1970s supposed a division point regarding energy related concerns; to this point, all concerns were on the cost of energy, especially after the oil crisis which took place in the first years of this decade. Nevertheless, in the past three decades awareness of the environmental degradation, with its accompanying risks, has been incremented (Kalogirou, 2009).

Within the current global context, the internationally accepted as most vital problems are acid precipitation, ozone layer depletion and global climate change (Dincer, 1999). These topics are explained in the following subsections.

1.1.1.1 Acid rain

This phenomenon is described as the precipitation (as rain, snow, hail or fog) of acidic pollutants sulphur dioxide (SO_2) and nitrogen oxide (NO_x) when the pH level of the precipitation is lower than 5.6. Human life is affected by acid rain in several ways, for instance, it obstructs the forests growth as well as causes death to a significant span of animals such as fish, frogs and insects when the pH level is below 4.5. Apart from this, acid rain leads to the deterioration of buildings and is capable of corrode lead and copper (Nagase & Silva, 2006).

1.1.1.2 Ozone layer depletion

It is well known that the ozone in the stratosphere acts as a shield which protects the surface of the earth against the dangerous ultraviolet radiation from the sun (Winter-Sorkina, 2000). It also ensures the maintenance of the equilibrium by absorbing infrared radiation (Dincer, 1998). The major problem related to the ozone layer is the distortion, along with regional depletion of this ozone layer. This deterioration is believed to be caused by CFCs, halons and NO*x* emissions. This important issue can lead the increase of harmful UV radiation reaching the earth's surface, with consequences such as eye damage or skin cancer (Dincer, 1999).

1.1.1.3 Global climate change

Originally, the term *greenhouse effect* was used to encompass the whole process whereby the atmosphere keeps the surface of the earth warm. However, nowadays this term is gradually more related to the contribution of CO_2. It is estimated to add around 50% of the anthropogenic greenhouse effect. Apart from the mentioned CO_2, gases such as CFCs, halons, N_2O, ozone and CH_4 contribute to this effect. The growing accumulation of these gases (called *greenhouse gases*) makes the heat radiated from the earth's surface decrease (or raise the volume of heat retained). This phenomenon causes the raise of the earth's surface temperature (Kalogirou, 2009). The proportions of this repercussion have been calculated (Ramanathan & Feng, 2009; Colombo, 1992), for instance, Colonbo (1992) quantified the earth's surface temperature rise in 0.6°C throughout the last century, whereas the consequent rise of the sea level was estimated around 20 cm.

1.1.2 Introduction to renewable energies

Renewable energy technologies are those capable of generating profitable energy by transforming natural phenomena into useful types of energy. These sources produce energy from gravitational forces, the heat inside the earth and the energy of the sun with its direct and indirect effects on the earth. In spite of being inexhaustible energy sources, the main disadvantage of these sources is the fact that they use to be diffused and not as accessible as desired. Apart from this, they vary depending on the location and are extremely intermittent (Kalogirou, 2009).

The different renewable energy sources available will be presented in the next subsections.

1.1.2.1 Geothermal energy

Geothermal energy is those stored underneath the earth's surface. The different geothermal sources can be classified with regard to its temperature as low (<100°C), medium (100°C-150°C) and high temperature (>150°C) (Kalogirou, 2009).

Geothermal heat plants can operate with either one-hole or two-hole systems. The two-hole system is frequently discarded because of the high expense caused by drilling two holes. On the other hand, one-hole systems or even the use of an existing hole from a former system (gas or oil exploration) reduces significantly the cost of the system. In these systems a double-pipe heat exchanger is introduced into the hole, extracting the geothermal water by via the inside pipe (Kalogirou, 2009).

1.1.2.2 Ocean energy

Ocean energy is the least developed energy within renewable energies (Katofsky, 2008). It is an abundant energy source, but it uses to be available far from the consumer sites (Kalogirou, 2009).

The energy available in the ocean can be used in three basic ways:

- **Wave energy conversion:** they convert kinetic energy into electricity. This can be performed by either capturing waves' vertical oscillation or capturing waves' linear motion (Katofsky, 2008).
- **Tidal energy conversion:** this consists of trap tides behind dams when they come to the shore and, when the tide drops, the water trapped is allowed to flow, like in a regular hydro-electric power plant (Kalogirou, 2009).
- **Ocean thermal energy conversion:** this conversion uses ocean temperature gradients. These gradients must be greater than 20°C and no more than 1,000 metres deep (Katofsky, 2008).

1.1.2.3 Hydrogen

Despite being the most common element in the whole universe, hydrogen cannot be found on earth in its pure form. In order to obtain pure hydrogen, it must be either electrolyzed from water or stripped out from natural gas. Both these processes are greenhouse gas emitters (Kalogirou, 2009).

Therefore, the only possible manner whereby hydrogen can be considered a renewable energy source is producing it electrolytically from wind or direct energy power sources. It must be noted that hydrogen is not a fuel but an energy carrier, as it is commonly defined the other way round (Kalogirou, 2009).

1.1.2.4 Biomass

Biomass is biological material derived from either a living or recently living organism. There can be found several technological options to convert biomass in a renewable energy source. These technologies can generate energy directly, as electricity or heat, as well as convert biomass to biofuel or combustible biogas (BEC, 2011). Biomass can be broken down in two categories (Kalogirou, 2009):

- **Woody biomass.**
- **Non-woody biomass.**

1.1.2.5 Hydropower

The energy derived from the force or energy of falling is called hydropower. Although it has been used for many different purposes since ancient times, the most interesting application is hydro-electric power, i.e. to generate electricity from hydropower. This application allows consuming the energy from the water long distances away from where it is generated.

1.1.2.6 Wind energy

Wind energy can be transformed into a useful form of energy by different methods such as the use of wind turbines to make electricity, wind pumps to propel ships or windmills to generate mechanical power (which can be converted into electricity).

UK is one of the biggest wind energy generating countries and it is ranked eighth worldwide in wind energy installed with 5,204 MW by the end of 2010 (GWEC, 2011).

1.1.3 Solar energy

The energy coming directly from the sun can be harnessed by several different methods. These methods can be broken down into two main categories: heat generating systems and electricity generating systems. The last category, also called sun power, is divided into two other categories: photovoltaics and concentrated solar power.

In concentrated solar power the sunlight is concentrated into a small beam by the use of mirrors and tracking system generating a heat point. This heat serves a conventional power plant as its heat source.

On the other hand, in photovoltaics systems, the sunlight received by the collectors is directly transformed into electricity by the photovoltaic effect, which will be explained in the following subsection.

1.1.3.1 Operation of a PV cell

The main component of a PV system is the solar module. This is the element which produces electrical energy from the sun light. Solar modules are composed by a number of solar cells, which are made from appropriate lighting absorbing material. Solar cells consist of a junction of a p-type and an n-type semiconductor (p-n junction). Electrons and holes around the boundary of the junction set up an electric field across it. When photons of sunlight strike the surface of the cell, they generate free electrons in the n layer and some of them create pairs of electrons and holes. These pairs can create a current flow if near enough to the p-n junction; the electric field makes the charges separate, therefore, if the solar cell is connected to a load, there will be a current flow through it (Kalogirou, 2009).

1.1.3.2 Overview of a general PV system

The two main elements within a PV system are the modules and the inverter. The modules generate electrical energy directly from the sunlight by the photovoltaic effect. The electricity generated by the modules is DC current, which normally needs to be converter to AC in order to, either be consumed in situ or be fed into the grid. The device in charge of this task would be the PV inverter, which is a DC/AC converter which adapts the energy generated by the modules to AC current ready to use. Figure 1.1 shows a simple sketch presenting the operation of a usual PV system.

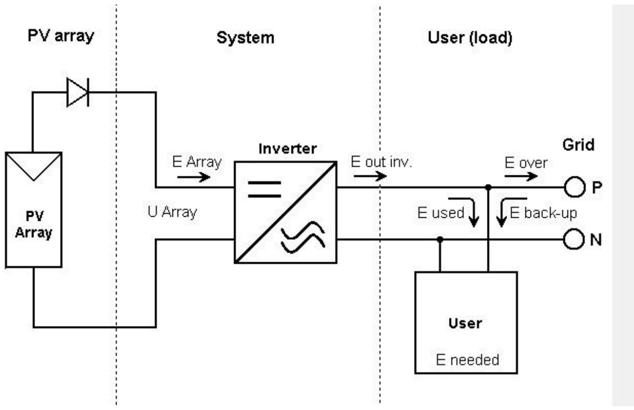

Figure 1.1. Simplified sketch of a PV system.

1.2 Project aims

As the main aim of this paper is to evaluate the feasibility of a grid-connected PV system in a private property, the main targets are the ones leading to this man aim.

Firstly, to know the state of art of PV technology, including system topologies, different components and manufacturers, and economic support schemes.

In addition to that, on important target is to create a computerized model of the system in order to assess the performance of the system under different conditions. This model will allow try different system configuration in order to choose the more feasible.

Another deliverable is to assess the economic viability of the system via a payback study under the current support scheme.

Finally, the last target once proved the feasibility of the system would be to introduce the design of the electrical installation required to interconnect the system with the property and the grid, as well as to indicate the path to follow in order to ensure the structural safety of the installation.

2. Literature Review

The scope of this section is to review the state of art and technique for PV technology. This section will examine the different technologies available for the components forming the PV systems as well as it will review different PV system topologies and configurations. Finally, it will expose an overview of the economic scenario.

2.1 Light absorbing materials for PV modules

In order to absorb photons and generate free electrons (photovoltaic effect), every solar cell needs to be made from a light absorbing material. There are several light absorbing materials available for solar cells and the most important ones will be reviewed within this section.

2.1.1 Silicon

The most dominant light absorbing material since the creation of PV cells has been silicon (Goetzberger & Hebling, 2000; van der Zwaan & Rabl, 2003; Bruton, 2002), nevertheless new materials such as cadmium telluride (CdTe), cadmium sulphide (CdS) and gallium arsenide (GaAs) have gained increasing importance throughout the past decade (Parida, et al., 2011; Birkmire & McCandless, 2010). Silicon cells can be broken down in two main categories, crystalline silicon and amorphous silicon. These two categories are discussed below.

2.1.1.1 Crystalline silicon cells

Crystalline silicon PV modules give the highest efficiency within the complete span of light absorbing materials (Parida, et al., 2011). Today, this efficiency has overpassed 20% (SunPower, 2011). The two main categories within crystalline silicon cells are monocrystalline and multicrystalline cells.

2.1.1.1.1 Monocrystalline silicon cells

These are the most efficient cells available, however, due to their complicate manufacture process, their price use to be the highest (Kalogirou, 2009).

2.1.1.1.2 Multicrystalline silicon cells

These cells are cheaper to manufacture than monocrystalline cells because of the simplicity of their manufacture process, however, their efficiency is rated below monocrystalline cells (Kalogirou, 2009).

2.1.1.2 Amorphous silicon cells

This technology has become the most popular among thin film technologies, even though the maximum efficiency achieved (with triple-junction designs) is around 10% (Parida, et al., 2011). The main difference between these cells and crystalline cells is that these cells consist of silicon atoms in a thin homogeneous layer, instead of having a crystalline structure, as crystalline cells (Kalogirou, 2009). The main advantage attributed to these cells is the fact that they absorb solar radiation better than crystalline cells (Parida, et al., 2011) and, because of this, they perform higher under non-direct radiation. Furthermore, their performance is less affected by high temperatures than the performance of crystalline silicon cells (Kenny, et al., 2003).

2.1.2 Thin film technology

In contrast to silicon wafers, these cells are essentially thin layers of semiconductor materials. These materials have to be applied to a solid material which acts as a backing. The main advantage in these cells is that, since the amount of material required for each cell is lower, the price of production decreases and, therefore, these cells are cheaper than silicon wafers. In contrast, these cells tend to give a significantly lower efficiency with respect to silicon cells (Candelise, et al., 2011; Zweibel, 2000). Typical materials for this technology are gallium arsenide (GaAs) and cadmium telluride (CdTe), among others (Parida, et al., 2011).

2.2 PV system configuration

In terms of the PV system configuration, i.e. the manner of connecting the PV modules to the inverter or inverters, there are three main arrangements available: central inverter, string inverter and module integrated inverter. The three of them have been widely discussed, for instance, Rohouma et al. (2007) conducted a mathematical study in terms of reliability of these configurations. This study resulted extremely favourable for the module integrated inverter configuration with regard to its higher redundancy, longer useful life of the inverter and smaller cable losses from module to inverter. Furthermore, this configuration happens to be the one which performs better against shadows owing to its modularity. Nevertheless, this study only regards reliability, which is one of the most important factors to consider but not the only one; extremely determinant factors such as the overall cost as a result of each type of configuration must be also examined when determining the most suitable configuration for a particular PV system.

2.3 Grid-connected PV inverters topologies

Regarding the selection of the appropriate inverter for a grid-connected PV system, several options can be found in the current market. One of the main differences would be whether they include a transformer or not. Therefore, three types of inverters can be stated regarding this aspect: those including either low-frequency transformers or high-frequency transformers and those which do not include any transformer, i.e. transformerless.

The transformerless topology is the newest of the three technologies, having advantages such as higher efficiency, lower cost, weight, embodied energy and smaller size when compared to the other two technologies (Calais, et al., 2001). Some research has been conducted in this issue; e.g. Salas & Olias (2009), concluded that, apart from the obvious advantages (smaller size, lower cost and weight), transformerless inverters perform at higher efficiencies than inverters including transformers.

However, in spite of its proved advantages, the use of transformerless inverters presents some problems, especially related to the galvanic connection between the grid and the PV system, such as the possible safety problems derived from this fact (Patrao, et al., 2011). These problems are well known and every system including this type of inverter has to be especially designed with regard to electrical safety, especially earthing (DTI, 2006).

Another interesting feature available for grid-connected inverters is the Maximum Power Point Tracking feature. This consists of an electronic system which maximizes the output of the PV modules by varying their electrical operating point to allow them to produce as much energy as possible for a particular amount of solar irradiation (Cullen, 2000).

Much has been researched related to Maximum Power Point Tracking (MPPT), for instance Ahmed & Miyatake (2008) presented an alternative strategy for MPPT based on Fibonnacci search algorithm and they proved experimentally and by simulation this method to be more efficient than other traditional methods based on module characteristics and insolation data. In contrast, the method proposed by these authors bases its operation in a constant mathematic Fibonacci exploration to select the most optimum operating power point.

Other MPPT methods have been designed and presented as the one exposed by Algazar, et al. (2012), consisting of a fuzzy logic controller which is applied to a DC-DC converter device to control the MPPT of a stand-alone PV water pumping system, or the direct method to calculate the MPP using hardware based on a DC-DC converter presented by Zhaoa, et al. (2011) for grid-connected systems. This last method used recursive calculation to regulate the pulse width modulation duty cycle of the hardware system and, therefore, obtain optimum voltages and current for every combination of insolation and temperature.

2.3.1 Inverter sizing

Once selected the inverter topology for a particular PV system, the inverter has to be sized with respect to the PV module field. The sizing of a grid-connected PV system consists of establishing the ratio between the nominal PV capacity and rated inverter capacity. This ratio depends on a considerable number of factors such as module orientation, inverter characteristics, economic cost, location and, evidently, PV output power.

This issue has been deeply researched, including studies of many types, such as numerical simulation (Peippo & Lund, 1994), energy approach (Notton, et al., 2010) and computer simulation by TRNSYS (Deb Mondol, et al., 2006). All these studies agree that the ratio between the PV output power and the inverter rated power must be between 1 and 2. They also agree that the more efficient the inverter is, the lower the ratio should be.

On the other hand, the Department of Trade and Industry of the UK (2006) recommends ratio values between 1 and 1.25 for installations within the UK. Nevertheless, they also recommend to be informed by the manufacturer of the modules and to simulate the system with specialized software.

2.4 Economics of PV systems

The final cost of a grid-connected PV system is quite difficult an issue to predict. It would depend on very variable aspects such as installer and designer costs, logistic costs, duration of the installation, etc. In this section the current cost of the two main devices into a PV system will be reviewed: modules and inverters. Besides, economics aspects regarding the payment of the produced energy will be reviewed, focusing in the situation within the UK.

2.4.1 PV modules and PV inverters cost.

The data exposed in this section was obtained from the German publication Photon International Magazine (2011) and, therefore, this data have been extracted from the German market, which was accepted as representative since Germany is the European country with more photovoltaic energy installed, with more than 17 GW installed by the end of 2010 (EurObserv'ER, 2011).

Regarding module prices, every technology experimented a slight fall in the German spot market throughout the second half of 2011, being the amorphous silicon modules the most stable: from 0.96€/W in May, it slightly fluctuated to reach 0.89€/W in November. On the other hand, crystalline and CdTe modules experimented more pronounced declinations: monocrystalline modules experimented a decrease of 17%, from 1.24€/W in May to 1.03€/W in November, whereas multicrystalline modules decreased even more, from 1.27€/W to 0.98€/W, i.e. a 23% fall. With regard to CdTe modules the decrease was similar than with crystalline modules, descending from 1.04€/W in May to 0.81€/W in November. Figure 2.1 shows a combined plot of the module prices variation within this period.

In contrast, inverter prices on the German market remained practically constant along the second semester of the past year, except for a very slight decrease between 5 kW and 10 kW, where the price at the end of the November was 0.18€/W, a little lower than the price in May, 0.23€/W. The ranges under 5 kW and over 10 kW rested approximately steady on 0.30 €/W and 0.20€/W respectively.

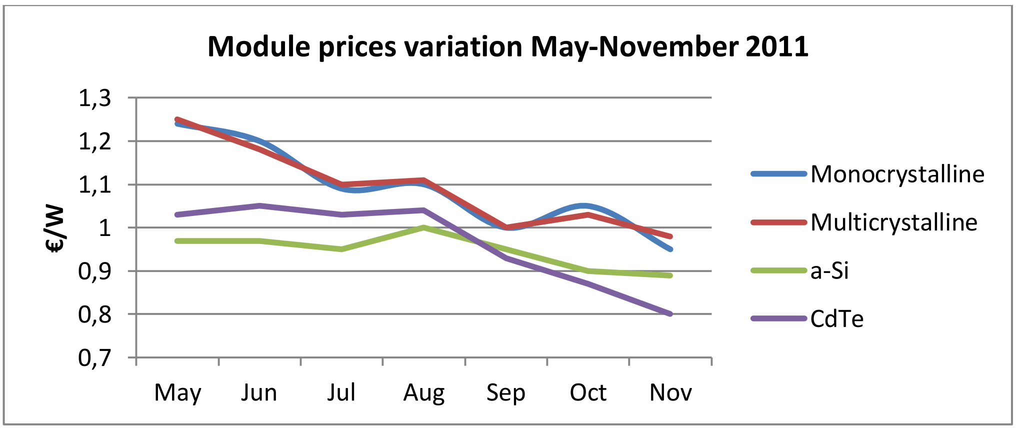

Figure 2.1. Module prices variation throughout the 2011 second semester (Siemer, 2011).

2.4.2 Feed-In Tariffs

In order to support the deployment of renewable energy technologies, many different economic support schemes have been developed worldwide, such as feed-in models, quota models, tendering systems and net metering. According to Mendoça (2007), the feed-in model has proved to cause the most rapid and lowest-cost spread of renewable energy in the countries where it has been correctly implemented. In this section, the situation of the feed-in model in the UK will be reviewed. Besides, a brief review of the state of investigation into feed-in models will be exposed.

2.4.2.1 Feed-in Tariffs in the UK

Feed-in tariffs (FiT) were first announced in the UK in October 2008 by the Secretary of State for Energy and Climate Change (DECC, 2012) and finally implemented in April 2010. These tariffs apply to small-scale power generation. These generators receive a fixed income, depending on the type of eligible technology, for every unit of electrical energy generated. In the case of PV systems, the specific condition is that the systems maximum output power must be 5 MW or below. The income will be guaranteed for 25 years for these systems, and it would be indexed to the Retail Price Index (Energy Saving Trust, 2012).

When a renewable grid-connected electricity generation system in the UK is under the prescriptions of the Feed-in Tariff scheme, it receives a fixed sum for every kWh generated. If the energy generated is not able to be consumed in situ, it would be exported to the grid and the system would receive and extra export fee (Energy Saving Trust, 2012). Therefore, this system allows the owner of the system saving through three ways:

- Every kWh generated is paid at a rated fee, whether it is consumed in situ or exported to the grid.
- If the energy is consumed in situ, the owner is not buying it for an electricity supplier and, therefore, is saving.
- If the energy cannot be consumed in situ, it is exported and the owner would receive a fixed export rate.

The export tariff was established at 3 p/kWh for all technologies eligible when the FiT scheme was first launched in 2010 and it has remained unchanged but increasing with RIT, the current value would be 3.2 p/kWh. However, the actual FiT depends on the technology and the installed power and it has been revised two times during 2011 because of the Comprehensive Review launched by the government. Also a new phase of this review was launched to consultation on 9th February 2012. The arguments made by the government to support these reviews were that the complete costs of a PV system have been decreased up to 50% (DECC, 2012). The evolution of FiTs for PV technology is summarized in Table 2.1, depending on the eligibility date of the installation (ICAX, 2012).

*This tariff would affect if the eligibility date of the system is on or after 3rd March 2012.

2.4.2.2 Feed-in Tariff schemes research

FiT schemes have been a much researched issue along with the development of renewable energies. The effectiveness of the existing systems worldwide was assessed, as well as alternative schemes were proposed.

Mendoça (2007) reviewed the start of art of feed-in schemes throughout the world, with special focus in Germany and Spain. This author also proposed some recommendations for the future as the design of stepped tariff for each technology. Other authors assessed the effectiveness of these schemes in different countries, as Zahedi (2010) examined the FiT scheme in Australia and proposed some improvements, Huang & Wu assessed the effectiveness of the Taiwan scheme (2011) or Schallenberg-Rodriguez & Hass (2012) reviewed the Spanish system.

On the other hand, many authors, e.g. Lesser & Xuejuan and Del Rio (2008; 2012), studied the determining variables into the design of an effective FiT scheme and proposed some alternative designs to the current schemes.

Scale	FiT before 1st August 2011 (p/kWh)	FiT from 1st August 2011 (p/kWh)	FiT from 1st April 2012*(p/kWh)	Lifetime
<4kW (retrofit)	37.8	43.3	21	25 years
<4kW (new building)	37.8	37.8	21	25 years
4kW - 10kW	37.8	37.8	16.8	25 years
10kW - 50kW	31.9	32.9	15.2	25 years
50kW - 100kW	31.9	19	12.9	25 years
100kW - 150kW	29.3	19	12.9	25 years
150kW - 250kW	29.3	15	12.9	25 years
250kW - 5000kW	29.3	8.5	8.5	25 years

Table 2.1. Evolution of FiTs in the UK.

3. Feasibility study

Within this chapter, the feasibility of the PV system will be examined. Firstly, the necessary data for the study such as property characteristics and electricity consumption and solar irradiation and temperature data were obtained. Afterwards, the optimum locations for solar PV panels were discussed, as well as the main components of the system were selected. Once essentially designed the system, the performance of the system was simulated using PVSyst and an economic study was carried out. Also, a brief environmental study was conducted and, finally, the basics of the electrical installation required were established, as well as some structural calculation was performed.

3.1 Property characteristics and electricity consumption

The feasibility study object of this paper is based on a private property in the City of Edinburgh (United Kingdom). The property is located within the postcode EH8 7JZ. The front facade of the property can be seen in Figure 3.1.

The property is situated in a residential area on the Edinburgh periphery. The street running in front of the front facade has a slight slope, nevertheless, the property is built on flat ground. It must be noted the absence of external elements which could generate shadows over the property and, therefore, lower the performance of a solar system.

The property consists of a main building with an attached garage, in addition to both front and rear yards. The main building has a pitched roof with each side inclined 43°, whereas the attached garage has a flat roof. The front facade is facing South-West, concretely at an angle of 70° towards West from South, as it can be observed in the satellite picture shown in Figure 3.2. The relevant approximate exterior dimensions of the property can be seen in Figure 3.3, which offers both annotated front and a side view of the property.

Figure 3.1. Front facade of the property.

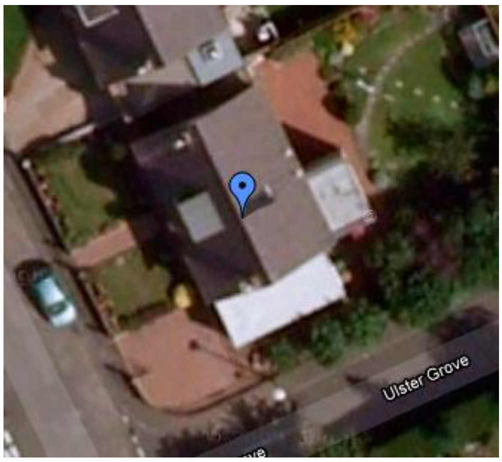

Figure 3.2. Satellite view of the property (Google Earth).

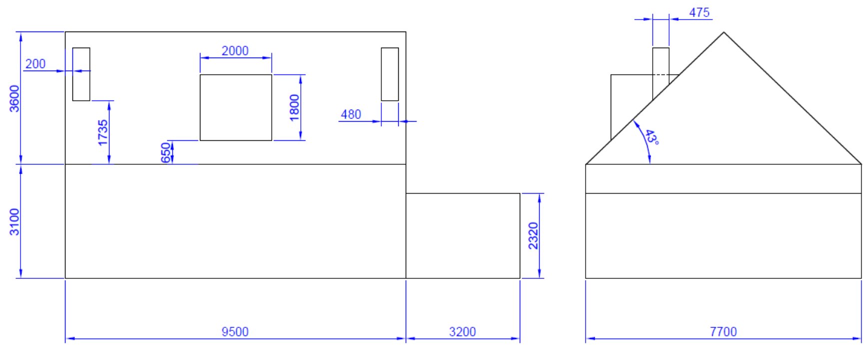

Figure 3.3. Annotated front and side view of the property (all measures expressed in mm).

3.1.1 Electrical energy consumption

The electrical energy demanded by the property is an important factor in order to determine the size of the PV system as the system will be intended to produce at least as much energy as the property consumes. This data has been acquired from electricity bills from July 2010 to June 2011. The data shows that the property had a **5220 kWh** demand during the period studied, distributed bimonthly as shown by Figure 3.4.

3.2 Radiation data and temperature

In order to estimate the energy production of the PV system and, therefore, its feasibility, the first step would be to determine the amount of energy available, i.e. the solar radiation on the property. In addition to this, it is also a crucial factor to assess the ambient temperature in the area where the system will be located as it affects seriously the performance of the PV system, especially the PV modules.

The simulation software PVSyst includes data for both solar radiation and average temperatures for the City of Edinburgh. Nevertheless, this data comes from 1997 NASA Database and it is not adjusted for a specific postcode but general for the City of Edinburgh. To adjust the data to the current global climate situation and to the specific postcode where the PV system will be located, alternative more up to date data sources will be used.

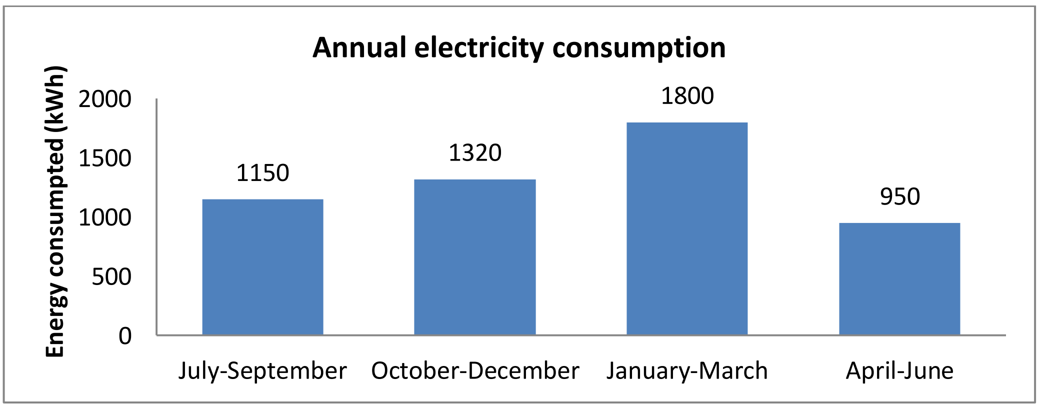

Figure 3.4. Annual electricity consumption in the property.

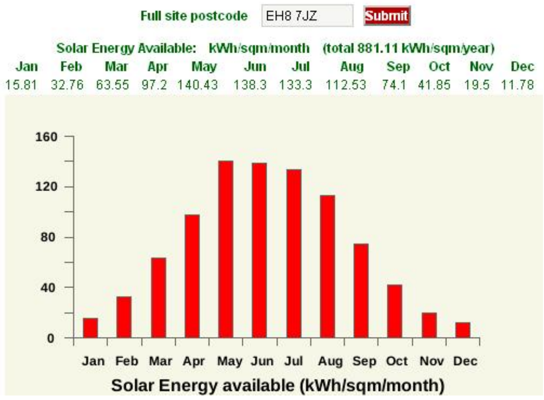

Figure 3.5. Solar energy available over EH8 7JZ (Encraft, 2011).

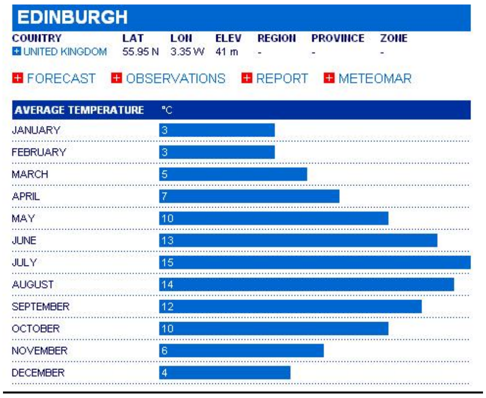

Figure 3.6. Monthly average ambient temperatures in Edinburgh (Euro Weather, 2011)

3.2.1 Annual solar radiation over the property

The database employed to determine the annual insolation over the property was NASA Database V3, accessed through Encraft website (2011). This application allows obtaining the annual horizontal solar radiation over a selected postcode, based on previous years' data records. Figure 3.5 shows the data corresponding to the location of the property studied, showing the solar radiation in kWh per square metre on the horizontal plane. The data corresponds to a complete year and is broken down into months.

It can be observed that more than 47% of the annual radiation is concentred throughout May, Jun and July, whereas the addition of January, February, November and December altogether only represents 9% of the annual total. This is due to the fact that Edinburgh is situated at a relatively elevated latitude (around 56°) and, therefore the daily sunlight hours suffer dramatic changes from summer to winter; an average day of June could have about 17 hours of sunlight, in December the average would be around 7 hours (Time and Date, 2012).

3.2.2 Ambient temperature

This data was obtained from the website Euro Weather (2011), which develops its data from Meteosat satellite measurements. The monthly average temperatures for the City of Edinburgh are shown in Figure 3.6.

Figure 3.6 shows that the average monthly temperature evolves from a minimum of 3°C registered in both January and February to a maximum of 15°C, registered in July, being the annual average temperature 8.5°C. This data contrasts slightly with the solar radiation: in spite of being the month with more solar radiation, May registers an average temperature of 10°C, considerably under June, July and August, even September. It has the same average temperature than October, whereas the solar radiation is 235% superior in May.

3.2 PV module technology selection

The purpose of this section is to establish the PV module technology which will be used in the PV system. The target is to generate as much energy as possible in order to satisfy the energy requirements of the property. To accomplish this target, space constraints and the final feasibility of the project must be regarded cautiously. The technologies to consider will be the main technologies commercially available, i.e. crystalline cells (monocrystalline and multicrystalline) and thin film cells.

As it has been exposed before, monocrystalline cells have the highest efficiency on the market. Nevertheless, this technology is the most expensive one and thin films cells absorb better the sunlight, besides being lighter because of the less semiconductor material needed. In this section, mainly energy performance assessment will be conducted, leaving the economic feasibility to the posterior economic study.

In order to evaluate the different technologies, several simulations were carried out with PVSyst, simulating the performance of the different technologies under the same circumstances. The different scenarios for the simulation corresponded to the different suitable areas to install PV modules on the property. These would be the surfaces shown by Table 3.1. The simulation of a PV system based on each one of the three technologies considered was conducted in each scenario. The results of the simulation are shown in Figure 3.7.

Area	Azimuth angle (measured from North)	Tilt Angle	Available area (approx.)
Western roof	250°	43°	43 m^2
Eastern roof	70°	43°	50 m^2
Garage roof	160°	0°	24 m^2

Table 3.1. Available areas for the installation of PV modules.

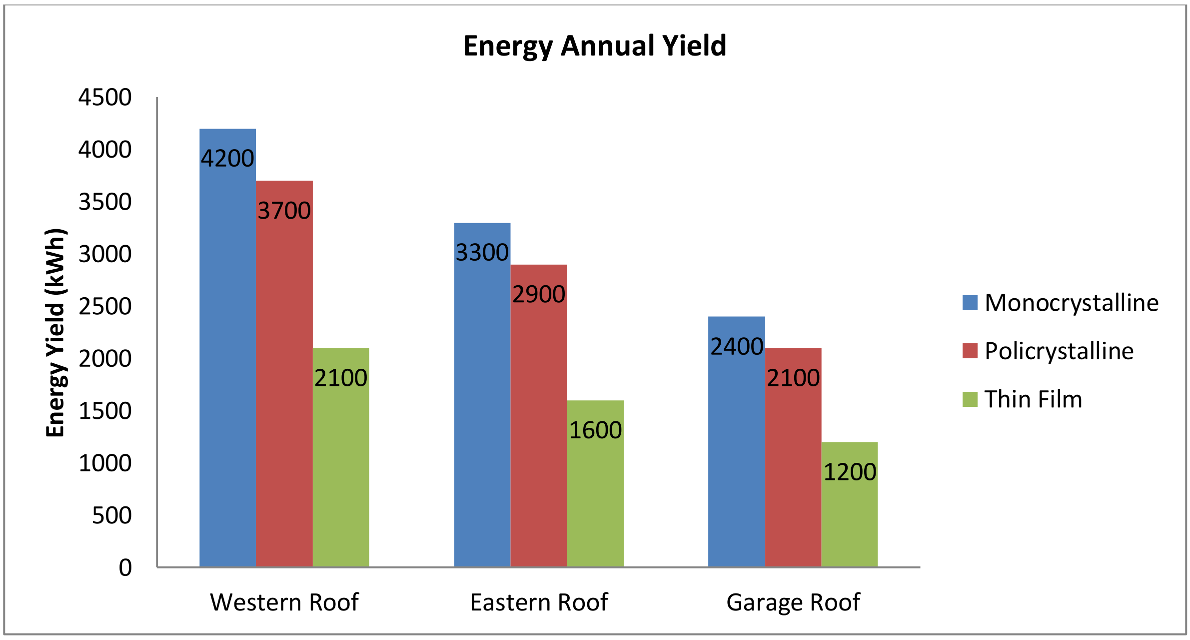

Figure 3.7. Energy generated by the PV system in the different scenarios.

From the results obtained, it can be seen that in either scenario crystalline modules produced considerably more energy than thin film modules, in the case of monocrystalline modules the ratio was at least 2:1 in each case. In addition to this, according to this simulation, the energy requirements of the property would not be met with thin film technology even installing modules in the three areas available. According to this brief study, thin film technology should be discarded for this particular case.

This study also shows that in each scenario monocrystalline modules obtain a higher annual energy yield than multicrystalline, nevertheless, the difference appreciated is not too significant: monocrystalline technology produces an average of 14% more energy than multicrystalline technology in the three scenarios considered. However, as it was reviewed previously, during the last year the prices of both monocrystalline and polycrystalline technology were similar, with slight fluctuations.

In conclusion, after this overview, thin film technology is discarded due to its poor energy performance. On the other hand, regarding crystalline technologies, monocrystalline showed a slightly higher energy yield. This, in addition to the similarity with regard to the both technologies prices, leaded to the election of monocrystalline technology as the technology that will be employed from now on within this study.

3.3 Module model selection

Once selected the module technology to be employed, it is necessary to choose a particular module model in order to perform the corresponding simulations and, therefore, to determine the ultimate feasibility of the PV system. To achieve this, a technical study was conducted to select the most appropriate model, within the ones available on the market, for this particular requirement.

Manufacturer	Model	Pmax (W)	Efficiency (%)	Weight (kg)	Dimensions (mm)	Area (m^2)	W/ m^2	(kg/ m^2)
Aleo Solar	S79 245	245	14.9	21.0	1660x990	1.6	149.4	12.8
BP Solar	BP Q 235	235	14.1	19.0	1667x1000	1.7	140.7	11.4
Eging	EGM190	190	14.9	15.5	1580x808	1.3	146.2	11.9
Helios	9T6 420	420	-	31.5	1976x1310	2.6	162.2	12.2
JINKO	JKM200	200	15.7	14.5	1580x808	1.3	153.8	11.2
Samsung	LPC250S	250	15.6	18.6	1630x982	1.6	156.3	11.6
Sharp	Q235F4	235	14.4	19.0	1640x994	1.6	144.2	11.7
Siliken	SLK72M6	300	15.5	23.0	1960x490	1.9	154.6	11.9
Sun Earth	TDB 190	190	14.9	16	1580x808	1.3	148.4	12.5
Sunmodule	SW 255	255	15.2	21.2	1675x1001	1.7	151.8	12.6
SunPower	E19/245	245	19.7	15.0	1559x79	1.2	197.6	12.1
Sunrise	180D-48	180	13.8	15.6	1316x992	1.3	138.5	12.0
Suntech	STP250S	250	15.2	19.8	1665x991	1.7	151.5	12.0
Trina Solar	195DC01	195	15.2	15.6	1581x809	1.3	152.3	12.2
ZNShine	ZX90MS	190	14.9	17	1580x808	1.3	146.2	13.1

Table 3.2. Module comparison.

Due to space constraints, one of the most important features of the desired module will be the ability to produce as much energy as possible using as little space as possible, i.e. the most desired quality for the ideal module will be its efficiency. Based on this, the technical study mainly regarded to the efficiency of the modules. This was measured via two parameters: the efficiency given by the manufacturer and the ratio between the nominal power of the module and its area. These two coefficients, despite giving practically the same information are usually different between them in each manufacturer. Both efficiency and nominal power are given by the manufacturer under Standard Test Conditions (STC), which means module temperature at 25°C, a solar spectrum of AM 1.5 and solar irradiance of 1,000 W/m².

The modules included in this study were selected from the most important manufacturers available on the market. This selection was based in the reviews and test presented by the publication Photon International throughout the year 2011. The sample chosen consisted of 15 modules by 15 of the foremost PV modules manufacturers, as it can be seen in Table 3.2.

The results of the study showed that all modules have efficiencies between 14% and 16% except for the SunPower model, which has an outstanding efficiency of 19.7%, being four points above the second most efficient, JINKO JKM200 module. This outstanding performance is accompanied, obviously, by the equivalent nominal power - area ratio.

Given the results of this study, and its outstanding efficiency rating, SunPower E19/245 was the module chosen for the development of the PV system studied. The characteristics of this module can be seen in its datasheet available in SunPower website.

3.4 Modules location selection

After selecting the particular PV module for the system, it is time to start designing and developing the actual PV system. The first step was to assess which areas were suitable for the installation of the modules in order to achieve the best performance and, ultimately, the feasibility of the system.

According to the Department of Trade and Industry of the UK (2006), to achieve the highest output from PV modules within the UK, they should be facing south and the tilt angle should be between 30° and 40°. An estimation of the yearly output of a PV system with respect to the maximum output depending on the orientation of the modules is shown in Figure 3.8.

		Orientation - Compass bearing (°) measured from North												
		West 270°	255°	240°	SW 225°	210°	195°	South 180°	165°	150°	SE 135°	120°	105°	EAST 90°
Tilt (°) from Horiz.	Horiz. 0°	90	90	90	90	90	90	90	90	90	90	90	90	90
	10°	89	91	92	94	95	95	96	95	95	94	93	91	90
	20°	87	90	93	96	97	98	98	98	97	96	94	91	88
	30°	86	89	93	96	98	99	100	100	98	96	94	90	86
	40°	82	86	90	95	97	99	100	99	98	96	92	88	84
	50°	78	84	88	92	95	96	97	97	96	93	89	85	80
	60°	74	79	84	87	90	91	93	93	92	89	86	81	76
	70°	69	74	78	82	85	86	87	87	86	84	80	76	70
	80°	63	68	72	75	77	79	80	80	79	77	74	69	65
	Vert. 90°	56	60	64	67	69	71	71	71	71	69	65	62	58

Figure 3.8. Relative output for different orientations of PV modules in the UK (DTI, 2006).

At this point, one of the three surfaces available at the property could be discarded according to DTI (2006): the western roof faces 70 from North and this orientation is not even contemplated by Figure 3.8 due to the extremely poor performance ratio that it would offer.

With regard to Figure 3.8, the other two available surfaces would give performance ratios of between 89% and 93% (western roof) and between 98% and 100% (garage roof) respectively. In the garage roof case, modules can be orientated freely to achieve the output desired only taking into account space constraints and mutual shadows effect (this aspect will be discussed further later).

3.4.1 Google Sketch Up simulation

A 3D model of the property using Google SketchUp software was built to evaluate the most suitable locations of the panels. This software also has an interesting tool which allows the user to simulate shadows over the built model. The resultant model is shown by Figure 3.9. It was built exactly over the coordinates of the actual property, synchronizing with Google Maps.

Since the two remaining surfaces available for the installation of PV modules were the western roof and the garage roof, the quantity of PV modules and, therefore, the hypothetic installed power at each location were evaluated. The target was to place as many modules as possible to achieve the maximum possible installed power.

Regarding the western roof, there options span for the location of modules was considerably reduced as the modules will be superposed to the roof for aesthetic and safety reasons. The optimum spaced layout for the western roof would consist of 25 modules, which would correspond to an output power of 6125 W. The mentioned layout is showed by Figure 3.10.

On the other hand, with regard to the garage roof, there are plenty of options available as the modules would be standing free over this roof. The tilt angle for these modules would be undoubtedly 30° as this would be the most optimum tilt angle, according to Figure 3.8. In terms of the azimuth angle, Figure 3.8 exposes that, despite the optimum orientation would be modules facing South, a deviation of 15° towards East, as long as the modules have a tilt angle of 30°, would not affect the performance of the modules, which would remain at its optimum. Since the garage roof is deviated 20° from South towards East, a 99% performance ratio could be expected from modules orientated along with this direction in accordance with Figure 3.8. For this roof, two different layouts were proposed, as showed by Figures 11 and 12.

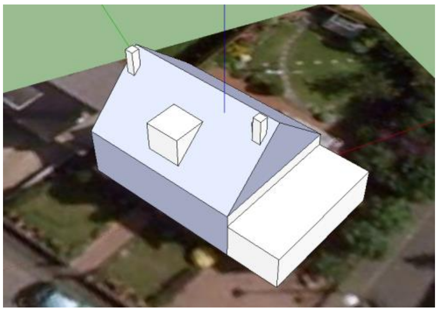

Figure 3.9. Property 3D model in Google SketchUp.

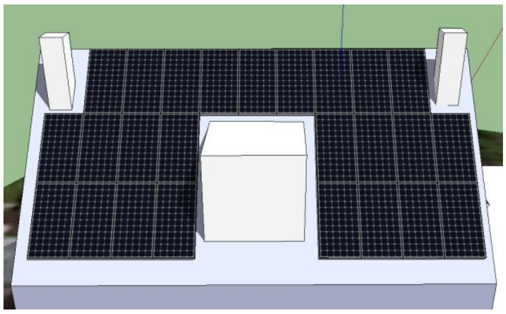

Figure 3.10. Modules located on the western roof.

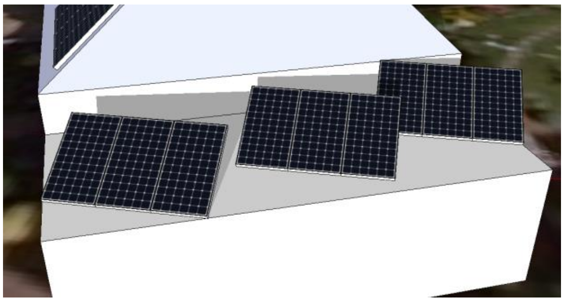

Figure 3.11. Layout A for the garage roof.

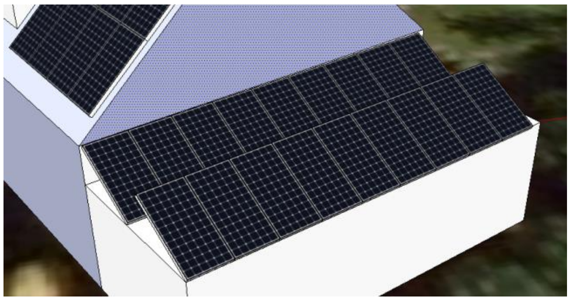

Figure 3.12. Layout B for the garage roof.

Layout A would consist of three rows of three modules each, with a nominal output power of 2205W (9 modules). All modules were facing south and they were displayed in order to minimise the mutual shade effect. On the other hand, Layout B was composed by two rows of nine modules each, which added an output power of 4410 W (18 modules). The modules in this display were orientated, as the garage roof is, 20° deviated from South to East. The two layouts had in common the fact that the tilt angle of every module is 30° to maximise the output power.

In order to decide which one of the two proposed layouts would be more feasible, the two of them were simulated as independent systems using PVSyst. The two main features to consider within this simulation were the shade effect and the output yield achieved.

3.4.2 Simulation results

The results from the simulation of Layout A showed an annual output energy yield of 1533 kWh, whereas the overall shading losses were estimated about 11.3%. Detailed shading factors can be observed in Figure 3.13 for every sun position from sunrise to sunset. It can be seen how, due to the proposed disposition of the modules, they practically avoided the shade effect for low sun heights and for negative azimuth angles, nevertheless this layout caused a noticeable shadow effect for higher sun heights and it is especially appreciable for positive azimuth angles.

Regarding the results obtained from the simulation of Layout B, the annual yield obtained was 2854 kWh, while the shading losses were calculated around 14%. From the shading factor table shown in Figure 3.14, it can be appreciated how this disposition performed at its best for high sun heights and negative azimuth angles, whereas, because of the rows layout, it suffered intensely from shading effect at very low sun heights, besides the performance of this disposition was also lowered by shading effects at positive azimuth angles.

Shading factor table (linear), for the beam component

Azimuth / Height	-180°	-160°	-140°	-120°	-100°	-80°	-60°	-40°	-20°	0°	20°	40°	60°	80°	100°	120°	140°	160°	180°
90°	0.989	0.989	0.989	0.989	0.989	0.989	0.989	0.989	0.989	0.989	0.989	0.989	0.989	0.989	0.989	0.989	0.989	0.989	0.989
80°	0.981	0.988	0.992	0.995	0.994	0.993	0.991	0.988	0.985	0.982	0.980	0.980	0.980	0.981	0.979	0.976	0.975	0.976	0.981
70°	0.874	0.937	0.985	0.998	0.998	0.996	0.994	0.989	0.983	0.977	0.972	0.969	0.970	0.969	0.947	0.907	0.850	0.836	0.874
60°	0.644	0.810	0.959	0.997	1.000	0.999	0.996	0.991	0.983	0.972	0.963	0.957	0.957	0.947	0.864	0.703	0.555	0.569	0.644
50°	0.351	0.451	0.863	0.996	1.000	1.000	1.000	0.993	0.983	0.967	0.952	0.942	0.941	0.917	0.706	0.496	0.423	0.394	0.351
40°	0.151	0.278	0.692	0.994	1.000	1.000	1.000	0.997	0.985	0.961	0.939	0.923	0.918	0.880	0.567	0.341	0.309	0.194	0.151
30°	Behind	0.188	0.548	0.991	1.000	1.000	1.000	1.000	0.985	0.955	0.923	0.897	0.884	0.825	0.508	0.329	0.172	0.061	Behind
20°	Behind	0.099	0.403	0.985	1.000	1.000	1.000	1.000	0.987	0.947	0.901	0.859	0.827	0.731	0.431	0.286	0.034	Behind	Behind
10°	Behind	Behind	Behind	0.978	1.000	1.000	1.000	1.000	0.992	0.937	0.866	0.791	0.708	0.587	0.341	0.243	Behind	Behind	Behind
2°	Behind	Behind	Behind	Behind	1.000	1.000	1.000	1.000	1.000	0.925	0.819	0.687	0.468	0.826	0.252	Behind	Behind	Behind	Behind

Figure 3.13. Shading factor table for Layout A.

Shading factor table (linear), for the beam component

Azimuth / Height	-180°	-160°	-140°	-120°	-100°	-80°	-60°	-40°	-20°	0°	20°	40°	60°	80°	100°	120°	140°	160°	180°
90°	0.980	0.980	0.980	0.990	0.990	0.980	0.980	0.980	0.980	0.980	0.980	0.980	0.990	0.990	0.980	0.980	0.980	0.980	0.980
80°	0.850	0.876	0.914	0.958	0.998	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.997	0.958	0.914	0.876	0.850	0.841	0.850
70°	0.683	0.743	0.836	0.934	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.934	0.836	0.745	0.685	0.668	0.683
60°	0.571	0.623	0.726	0.905	1.000	1.000	1.000	0.981	0.973	0.981	1.000	1.000	1.000	0.905	0.736	0.625	0.571	0.544	0.571
50°	0.361	0.480	0.639	0.868	1.000	1.000	0.962	0.935	0.925	0.936	0.962	1.000	1.000	0.869	0.646	0.505	0.382	0.349	0.361
40°	0.235	0.324	0.583	0.839	1.000	0.973	0.919	0.887	0.874	0.887	0.919	0.973	1.000	0.843	0.591	0.340	0.240	0.205	0.235
30°	0.129	0.245	0.511	0.812	1.000	0.932	0.870	0.832	0.816	0.833	0.870	0.932	1.000	0.817	0.522	0.257	0.135	0.062	0.129
20°	0.023	0.167	0.421	0.782	0.996	0.879	0.808	0.766	0.744	0.766	0.809	0.879	0.996	0.787	0.434	0.175	0.030	Behind	0.023
10°	Behind	Behind	0.332	0.745	0.950	0.805	0.725	0.677	0.648	0.678	0.726	0.806	0.950	0.751	0.346	Behind	Behind	Behind	Behind
2°	Behind	Behind	Behind	0.707	0.998	0.726	0.629	0.575	0.536	0.576	0.630	0.727	0.999	0.715	Behind	Behind	Behind	Behind	Behind

Figure 3.14. Shading factor table for Layout B.

Comparing the two dispositions, it can be seen that, whilst it is undoubtedly true that Layout A used the solar irradiation more efficiently, the losses due to shading effect in Layout B were less than 3% above the losses in Layout A, besides, this disposition was capable to generate nearly double energy than the other one. With regard to the energy produced per installed power, whereas Layout A produced 695 kWh/kW/year, Layout B can produce 647 kWh/kW/year, which is only 7% below Layout A figure.

In conclusion, by choosing Layout B, the annual energy yield would be nearly duplicated with efficiency estimated between 6% and 7% below Layout A and, even though the installation of nine extra modules would suppose an extra economic cost for the project, it seems reasonable that this increase could lower the general cost of the installation per installed power (£/W). Given these conclusions, the disposition chosen for the modules on the garage roof was Layout B.

Once settled the choice of Layout B, a slight variant of this disposition was simulated in order to try to reduce the shading losses effect. This consisted on varying the tilt angle of the front module row from the initial 30° to 25°. This reduced the shadowing losses caused by the front row over the rear row, however, the simulation showed that the action proposed was not globally beneficial for the system in terms of energy yield.

After simulating this last variant, it can be seen how this new disposition for the front row improves the performance of the modules at low sun heights, nevertheless, the effect was not very significant. On the other hand, the annual output yield obtained from this simulation was 2845 kWh. This value was within 0.4% below the previous one, which could be neglected, however, it showed how the efficiency gained by reducing shading losses was lost by varying the tilt angle. Summarizing this, the result obtained by taking this action would be, though very slightly, negative, and therefore this action was not implemented.

Therefore, to this point the PV system was defined as two separate sub-fields of PV modules, one located on the western roof consisting of 25 modules (6.125 kW), and the other one situated over the garage roof, composed by 18 PV modules (4.41 kW). The features of each sub-field are summarized in Table 3.3.

Sub-field	Azimuth angle	Tilt Angle	Number of modules	Installed power
Western roof	250° from North	43°	25	6.125 kW

Garage roof	160° from North	30°	18	4.41 kW
TOTAL			**43**	**10.535 kW**

Table 3.3. Summarize of sub-fields features.

3.5 PV System configuration design

After establishing the PV modules layout on the property, it is time to study the system configuration. The modules will be arranged in strings, which are series adding of modules in order to obtain the desired DC output voltage, whereas these strings will be arranged in arrays, which are parallel adding of strings to achieve the desired DC output current.

With regard to PV system configuration, there are three main options available: central inverter, string inverter and module integrated inverter (Rohouma, et al., 2007). Even though module integrated inverter configuration is undoubtedly the most reliable of the three of them, this configuration was discarded because of both its evidently higher cost and the relative difficulty to find competitive commercial solutions. This decision narrowed down the possibilities to central inverter and string inverter. As Rohouma, et al. (2007) concluded, the modularity offered by the string inverter configuration helps palliating the shading effect, besides it has an evidently higher reliability than the central inverter configuration. It is well known the fact that with only on row fully shaded, a PV module is likely to reduce its production to zero (Envirohasrvest, 2011), besides, when a module situated within a particular string is not producing due to shadows, the whole string is likely to decrease its performance to levels surrounding zero. Figure 3.15 shows indicative examples of PV modules with reduced performances due to shading effect.

Another well-known fact to be taken into account is that when several strings connected in parallel to create an array are connected to an inverter, if the two strings are performing differently (due to shadows, different angles, etc.), the output from the best performing string would be lowered by the performance of the other string, in terms of output power (SMA, 2011). In conclusion, it can be stated that it is strongly recommended to connect to a common array strings which would receive approximately the same solar irradiation, whereas it would be also a good practice to select for the same string modules equally irradiated.

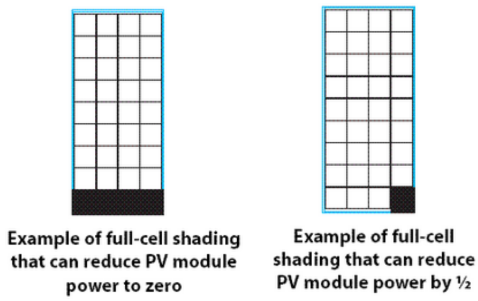

Figure 3.15. Shadows effect over solar PV modules (Envirohasrvest, 2011).

3.5.1 System distribution into arrays and strings

This specific PV system consists of two differentiated sub-fields, each one of them with different orientation, tilt angle a shadows distribution, therefore, it seems clear that these two subfields would make two different arrays into the PV system.

Regarding the array resultant on the garage roof, it is formed by two parallel rows of 9 modules each and, it can be perceived how shadows distribution would be completely different for the two rows, whereas within each row, it would be similar for each module, especially regarding the front row. Therefore, this array will consist of two strings: one corresponding to the front row and the other one corresponding to the rear row. The distribution of the strings can be observed in Figure 3.17.

On the other hand, in terms of the array situated on the western roof, it is composed by a homogeneous distribution of modules, to a total of 25, as showed by Figure 3.10. As all modules are superposed to the roof, they are all situated within the same plane and, therefore, they do not produce shadows to other modules. In this case, the decision was made based on the shadows produced by both of the side chimneys and the central window, as well as regarding complexity and length of the array wiring. The resulting 3-string distribution is showed by Figure 3.16. String #3 would have a considerably high annual yield with respect to the possible maximum as it has no shadows at irradiation peak hours, it is mainly affected by shadows produced for the right-sided chimney early in the morning, especially in summer, nevertheless at this moment, the solar irradiation is not truly significant. On the other hand, both strings #1 and #2 would be more affected by shadows and that is the reason for grouping those modules together: String #1 is normally affected by shadows from the right-sided chimney from sunrise until past noon, while it starts being affected by shadows generated by the left-sided chimney at this point. Finally, String #2 is apparently more heavily affected by shadows that strings #1 and #3, this is because of the size of the central window and its location; it blocks considerably sunlight during, normally, the first half of the sunlight time, especially on the bottom row of this string. To support these assumptions, a simulation of every string as an individual system was conducted using PVSyst.

The results obtained from the simulations carried out for Array A showed that, whilst the string selection seems appropriate regarding the performance of the system, the most efficient string within this system wold be String #1, in contrast with the prediction above about String #3 having the best performance ratio. This is due to the negative effect of the shadows caused by the central window over String #3 during the last hours of sunlight before sunset, as it can be observed in Figure 3.18, where the performance decays considerably for positive azimuth angles. Whilst the effect is not too serious, it lowers the performance ratio of this string below String #1. The summarised results of these simulations are shown in Table 3.4.

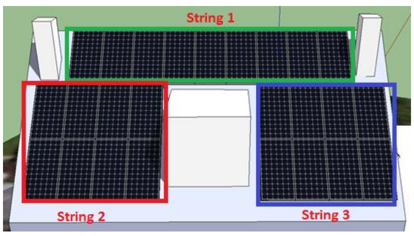

Figure 3.16. String layout for Array A.

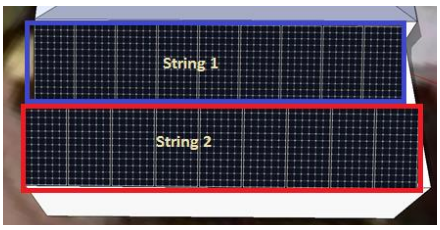

Figure 3.17. String Layout for Array B.

String	Shading Losses
Array A - #1	5%
Array A - #2	8%
Array A - #3	6%

Table 3.4. Simulated string shading losses for Array A.

Shading factor table (linear), for the beam component

Azimuth / Height	-180°	-160°	-140°	-120°	-100°	-80°	-60°	-40°	-20°	0°	20°	40°	60°	80°	100°	120°	140°	160°	180°
90°	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
80°	1.000	1.000	0.998	0.995	0.994	0.997	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
70°	0.977	0.984	0.986	0.971	0.961	0.967	0.983	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.999	0.992	0.984	0.977
60°	0.924	0.947	0.971	0.938	0.891	0.902	0.942	0.988	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.989	0.968	0.946	0.924
50°	0.856	0.894	0.941	0.927	0.824	0.772	0.848	0.960	1.000	1.000	1.000	1.000	1.000	1.000	0.998	0.973	0.937	0.893	0.856
40°	0.761	0.817	0.895	0.916	0.756	0.763	0.714	0.891	1.000	1.000	1.000	1.000	1.000	1.000	0.992	0.954	0.899	0.820	0.761
30°	0.612	0.741	0.848	Behind	Behind	0.755	0.581	0.847	1.000	1.000	1.000	1.000	1.000	1.000	0.984	0.931	0.850	0.704	0.612
20°	0.412	Behind	Behind	Behind	Behind	Behind	Behind	0.847	1.000	1.000	1.000	1.000	1.000	1.000	0.973	0.902	0.781	0.526	0.412
10°	0.212	Behind	Behind	Behind	Behind	Behind	Behind	0.847	1.000	1.000	1.000	1.000	1.000	1.000	0.959	0.863	0.669	0.358	0.212
2°	Behind	Behind	Behind	Behind	Behind	Behind	Behind	Behind	1.000	1.000	1.000	1.000	1.000	1.000	0.943	0.816	0.537	0.232	Behind

Figure 3.18. Shading factor table for String #3 (Array A).

3.6 PV Inverter selection

Once distributed the PV modules into arrays and strings, the last step throughout the main design of the system would be to select the inverters which will transform the DC current generate by the modules into AC current. These were selected in order to maximize the efficiency of the system and, therefore, obtain the highest output yield.

As it was discussed above, the system configuration for this system would be string inverter configuration. Along with the idea of achieve the maximum possible efficiency, both one inverter for each string and multiple MPPT inverters for two or more strings were considerate.

The manufacturer selected for the inverters was SMA for several reasons as having a vast catalogue of inverters for a considerably large span of applications such as grid-connected and stand-alone PV systems, or wind energy systems. Within PV inverters, regarding those for grid-connected applications, SMA covers every parcel, from the Sunny Boy variety for small powers and one-phase systems, to Sunny Central for three-phase systems with output powers of several hundreds of kilowatts. Equally, SMA is an up to date firm and between its products inverter including high frequency galvanic isolation transformers can be found, as well as transformerless ones. Besides, a considerable range of its products features various MPPT systems, which is a very interesting characteristic with regard to the system treated in this study due to the fact that it would have many different operation points.

Not only all this but the fact that 8 out of the 50 top inverters of 2010 by Photon International were manufactured by SMA recommended earnestly the choice of this builder.

To develop the selection of the suitable inverters the electrical characteristics of the strings were studied. Table 3.5 summarizes these characteristics. All the characteristics studied are referred to Standard Test Conditions.

String	Number of modules	Output power (W)	Vmpp (V)	Impp(A)	Voc (V)	Isc (A)
Array A - #1	9	2205	364.5	6.05	439.2	6.43
Array A - #2	8	1960	324	6.05	390.4	6.43
Array A - #3	8	1960	324	6.05	390.4	6.43
Array B - #1	9	2205	364.5	6.05	439.2	6.43
Array B - #1	9	2205	364.5	6.05	439.2	6.43

Table 3.5. Electrical characteristics for the different arrays in the system.

According to these characteristics, the range was narrowed down to SMA Sunny Boy variety. In addition to this, it was decided to choose transformerless inverters due to their higher efficiency and lower costs, dimensions and weight, between other interesting features, as it was discussed before. In order to cover the hypothetical safety problems derived by the use of these inverters, the PV system earthing would be connected to the property earthing system (DTI, 2006).

The appropriate inverters were selected in order to obtain different MPP trackers for different performing strings, in addition to this, the recommendation about sizing PV inverters by the Department of Trade and Industry was followed (2006). It was also regarded, obviously, that the inverters are suitable for the string characteristics in Table 3.5.

3.6.1 String adaptation

The first issue to consider when adapting the arrays output to the inverters where the fact that is highly recommended that every string is composed by the same number of modules (SMA, 2011). Whilst the originally defined Array B complies with this characteristic, that does not happen with Array A; it consists of three strings, two of them composed by 8 modules and the other one composed by 9.

Therefore, to match the module number in every string, the solution adopted was to remove one module in order to obtain three 8-module strings.

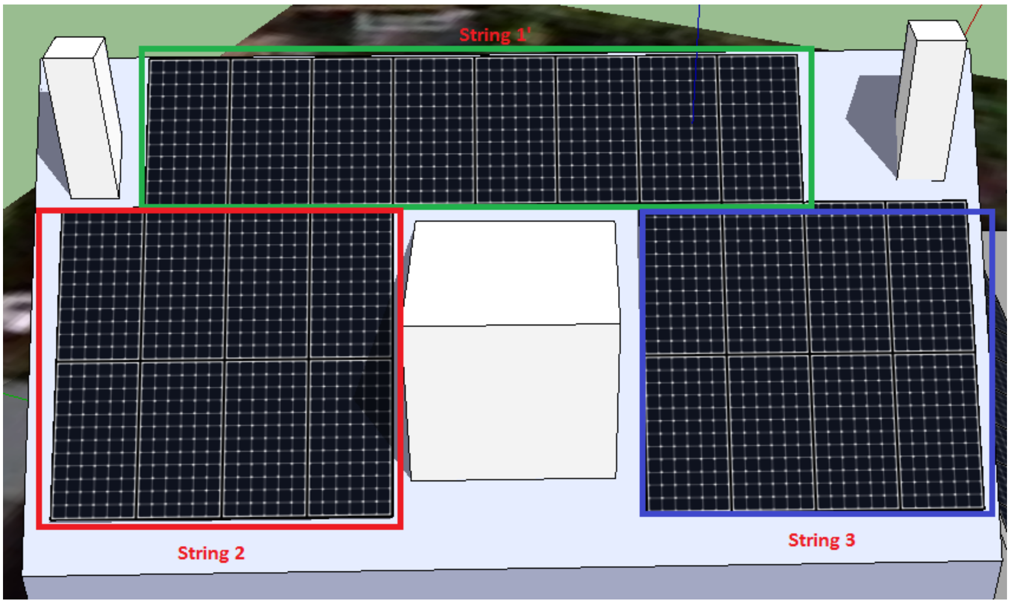

Figure 3.19. New string distribution in Array A.

String	Number of modules	Output power (W)	Vmpp (V)	Impp(A)	Voc (V)	Isc (A)
Array A - #1'	8	1960	324	6.05	390.4	6.43
Array A - #2	8	1960	324	6.05	390.4	6.43
Array A - #3	8	1960	324	6.05	390.4	6.43
Array B - #1	9	2205	364.5	6.05	439.2	6.43
Array B - #1	9	2205	364.5	6.05	439.2	6.43

Table 3.6. New electrical characteristics for the different arrays in the system.

To choose which module was to be removed, a shadows simulation was conducted using Google SketchUp. This showed that the module situated at the right end of String #1 was the one which was covered by shadows longer, furthermore, it was shadowed during the peaks of solar irradiation (around noon and especially during the summer). Therefore, this module was removed with the consequent match of the number of modules in each string. The new distribution of modules on the western roof (Array A) is shown by Figure 3.19 and the new electrical characteristics of the strings can be observed in Table 3.6.

3.6.2 Final system layout

The final layout is shown in a simplified manner by Figures 3.20 and 3.21. One inverter was selected for each array; SMA 5000TL was selected for Array A, whereas for Array B the one chosen was SMA 4000 TL. The datasheet for these components can be found in SMA Webpage.

On the one hand, taking advantage of the two separate MPP inputs of SMA 5000TL, String #2 (as it is has the best performance) would have a different MPP tracker and, therefore, its yield will not be affected by the inferior performances by Strings #1' and #3. As each MPP input allows to connect two strings, both String #1' and #3 will be connected together. In addition to this, this inverter meets the characteristics of this array, being its maximum DC voltage 550 V and allowing 15 A of DC current per string. Ultimately, the sizing ratio would be 1.28, as a result of divide 5880W from the array by 4600W, which is the rating of the inverter. This value does not remains within the recommendations of the Department of Trade and Industry (2006), nevertheless, the sizing is justified by the fact that String #2 will never produce as rated as there times when it is not affected by any shadows coincide with moments of scarce solar radiation. Furthermore, this design has two extra advantages; first, it would be a safer system, according to DTI and secondly, it will allow the system to remain under 10kW of rated power and, therefore, receive a greater economic feed-in tariff (this would be discussed in the economic section later on).

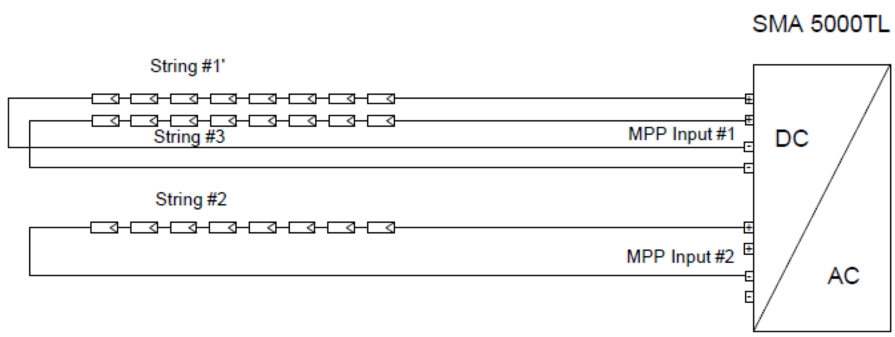

Figure 3.20. String distribution towards the inverter for Array A.

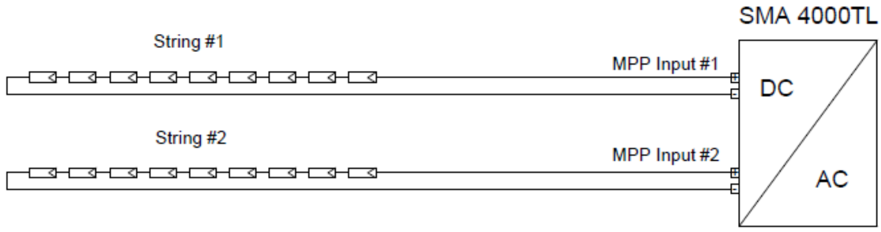

Figure 3.21. String distribution towards the inverter for Array B.

On the other hand, Array B also takes advantage of the Multi MPPT technology in SMA 4000TL; in this case, each string is connected to a different MPP input, in order to avoid that the inferior yield by String #1 could affect the higher performance of String #2. This inverter also can stand a DC voltage of 550 V, as well as a 15 A DC current per string. Because of this, the inverter suits the electrical requirements for this array. For this array, the inverter sizing ratio would be of 1.10, which, in spite of being closer to unity, rests within the recommendations.

It can be observed that, in both arrays, the nominal DC power of the PV modules exceeds the maximum DC input power of the inverters, nevertheless, this is justified by the fact that either array is not capable to produce as much power as it is rated due to their orientation and the shading effect, therefore, the system will remain safe and reliable.

3.7 PVSyst system simulation.

Once finished the design of the system, a complete simulation of the system was conducted using PVSyst. This simulation included the solar radiation and temperature data discussed before, as well as a 3D model of the building and the system in order to simulate shading effect. This 3D model is showed by Figure 3.22. In addition to this, the both manufacturer data for modules and inverter were included in order to make the simulation as accurate as possible.

Array A and array B were simulated separatedly, as the software does not allow modules with different orientation and tilt angles within the same system. The main results of the simulation are tabulated in Table 3.7. Fuerthermore, Appendix A includes a complete inform generated by PVSyst for each of the arrays simulated.

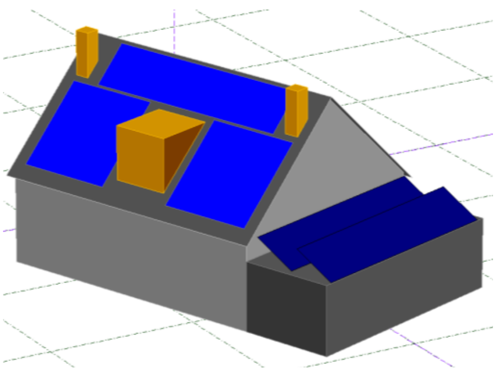

Figure 3.22. 3D model of the system in PVSyst.

System	Number of modules	DC Power	AC Power	Tilt Angle	Azimuth Angle	Shading Losses	Specific Production per year	Energy produced per year
Array A	24	4.4 kW	4.0 kW	43°	250°	3%	636 kWh/kWp	**3739 kWh**
Array B	18	5.9 kW	4.6 kW	30°	160°	14.5%	657 kWh/kWp	**2896 kWh**

Table 3.7. Simulation results.

According to the simulation results, Array A produces 3739 kWh/year, which added to the 2896 kWh/year produced by Array B, make a total of **6635 kWh** of electric power generated annually by the designed system. This means more than 120% of the property needs for the first year.

The results show that Array B is greatly more affected by shadows than Array A; whilst Array A only presents 3% shading losses, Array B has a considerably higher number: 14.5%. The main reason for this difference is, as it was exposed before, the effect of the shadows generated by the front row on the back row. Nevertheless, it can be observed how Array B, despite the shading losses, is capable of generating more energy per installed power than Array B, even though the difference is only around 3%. This would be due to the better orientation and tilt angles in Array B.

3.8 Economic study

Once determined the technical feasibility of the project, the last step was to determine the ultimate economic feasibility. In order to achieve this, a payback study was conducted to determine the investment amortization and the return period. Before performing the study, the following suppositions were made:

- The system will be situated under the current Feed-In Tariff Scheme, under the *Solar photovoltaic (other than stand-alone) with total installed capacity greater than 4kW but not exceeding 10kW* (DECC, 2012). Therefore, the Feed-in Tariff applied will be 16.8 p/kWh.
- The export rate will not be negotiated with any supplier. The system will be exporting energy at the established rate of 3.2 p/kWh.
- The current electrical energy buying tariff in the property would be supposed as 14.4 p/kWh, according to the UK home average tariff in 2011 (Energy Saving Trust, 2012).
- Electrical home tariffs will rise at a rate of 5% per year.
- The RPI will have a constant annual value of 3.345. This value was obtained from the average value of the ten last annual RPIs (Office of National Statistics, 2011).
- The price estimated for the system comes from the quote of Energy Saving Trust (2012) for a 4kW system, £13,000. Extrapolating this quote, the cost of this installation was estimate, conservatively, in £35,000. This value did not consider economies of scale.
- 25% of the energy produced by the system will be consumed at the property (Energy Saving Trust, 2012).
- The output of the system will decrease 1% each year with respect to the previous one, with the result of a relative performance of 78% in Year 25 with respect to Year 1. The manufacturer guarantees 80% after 25 years, therefore this assumption is conservative.

- The annual energy yield throughout Year 1 will be the result of the previous simulation: 6635 kWh.
- As the two tariffs mentioned above are guaranteed by the government for 25 years, the economic study will have this length.
- The installation will be paid without bank loan, therefore, interests were not considered.
- Taxes of any kind were not considered.
- The property has an Energy Performance Certificate (EPC) of at least D, as it is required after the settling of the 1st Phase of the Government Comprehensive Review of Feed-in Tariffs (DECC, 2012).

3.8.1 Economic study results

After carrying out the economic study along with the considerations above, results showed that the payback time for this project within the scenario proposed would be **19 years**, while the total profit over 25 years would be **£15,982**.

Apart from this scenario, two alternative ones were studied:

- <u>Scenario B</u>: it would correspond to an installation with eligibility date for Feed-In Tariff before the 3rd of March 2012. The FiT would be 39.6 p/kWh in this case. Every other assumption was maintained.
- <u>Scenario C</u>: corresponding with the most unfavourable future possible for FiTs between the proposed by the Government in the Comprehensive Review Phase 2 (DECC, 2012). The FiT would be 9 p/kWh in this case. Every other assumption was maintained.

Table 3.8 shows results obtained from the three different scenarios. It can be seen that, whilst with the current scenario the project is economically feasible, with the previous one the payback time would be nearly halved, whereas the total profit would be nearly multiplied by four. On the other hand, it can be seen how in the worst of the scenarios proposed in the Comprehensive Review Phase 2, this project would not be even economically feasible.

Detailed data from the study of these three scenarios can be seen in Appendix B.

3.9 Environmental study

Solar photovoltaic energy is a clean, non-polluting energy, therefore, while producing energy by this technology, there is an amount of polluting emissions which is being avoided, as it the same energy were to be produced by traditional technologies using fossil fuels, e.g. gasoil, natural gas or coal (JSolar, 2008).

Scenario	Payback Time	Total Profit
FiT 16.8 p/kWh	19 y	£15,398
FiT 39.6 p/kWh	11 y	£59,607
FiT 9 p/kWh	28 y	-

Table 3.8. Economic results for the different scenarios.

In order to quantify the polluting emissions avoided, the tonne of oil equivalent unit can be used. This unit corresponds to the amount of energy released by burning a tonne of crude oil. This unit is quantified to be 11630 kWh.

Based on the tonne of oil equivalent (toe), the CO_2 emissions by the burning of some fossil fuels have been quantified as (JSolar, 2008):

- 1 Natural Gas toe = 2.1 tonnes of CO_2.
- 1 Coal toe = 3.8 tonnes of CO_2.
- 1 Gasoil toe = 2.9 tonnes of CO_2.

As the designed PV system would generate around 6635 kWh/year, this would be equivalent to 0.57 toe. Throughout 25 years of operation, the system would generate about 147415 kWh (assuming a 1% decrease in the production every year); this quantity would be equivalent to 12.68 toe. Therefore, the CO_2 emissions avoided during the expected lifetime of the system would be:

- 26.2 tonnes of CO_2, if the same energy were to be produced by Natural Gas.
- 48.2 tonnes of CO_2, if the same energy were to be produced by Coal.
- 36.8 tonnes of CO_2, if the same energy were to be produced by Gasoil.

3.10 Summary of Results

This section will summarize all the results achieved during the feasibility study, from the radiation study to the environmental calculations, including every other result reached such as simulation results and system component selections.

3.10.1 Property consumption

The features of the property were presented, as well as the annual electrical energy consumption based on a series of electrical bills from July 2010 to June 2011. The electrical energy consumption throughout that period was 5220 kWh.

3.10.2 Annual solar irradiation

Solar irradiation data over the postcode the property is situated in where obtained from NASA, with a result of an annual available energy from sunlight of 881.1 kWh per square metre. Also, the average monthly temperature data was obtained, as it affects the system performance.

3.10.3 PV module technology selection

As it is the main component of a PV system, module technology was selected based on research and simulations. Finally, monocrystalline technology was selected for this study.

3.10.4 PV Module selection

After selecting monocrystalline technology for PV modules, a comparative market study was conducted to determine which model was the most suitable for this study. The module selected was SunPower E19/245.

3.10.5 PV Modules location selection

Within the locations available in the property for the installation of solar modules, after a study considering orientation and tilt angles of the surfaces, as well as the negative effect of shadows, the locations selected for the installation of the modules were the western roof and the garage roof.

3.10.6 PV Modules distribution

A performance simulation study (including shading effect) was conducted in order to determinate the distribution of the modules in the locations selected previously. The results of this examination dictated to place 18 modules over the garage roof, distributed into two consecutive rows of 9 modules each, orientated 70° from North and inclined 30°. With regard to the western roof, the result was to locate 24 modules superposed to the roof distributed over the available surface; therefore, these modules would have an orientation angle of 250° from North and a tilt angle of 43°, same as the roof.

3.10.7 PV Array and string distribution

To achieve the best possible performance and palliate as much as possible shading effect, the system was distributed into two arrays: Array A (western roof field), consisting of three strings of 8 modules each, and Array B (garage roof field), consisting in two strings of 9 modules.

3.10.8 PV Solar inverter selection

Solar inverters were investigated in order to find the most suitable ones for the characteristics of the PV module field. The final decision was to select SMA 5000TL for Array A, and SMA 4000TL for Array B.

3.10.9 Global system characteristics

The resulting system has an output is composed by 42 PV modules and has a 10.3 kW DC power generation capacity, whereas the output AC nominal power is 8.6 kW.

3.10.10 System simulation results

The complete system was simulated in PVSYST and the results estimate an annual electrical energy production of 6335 kWh/year, which is over 120% of the property electricity consumption.

3.10.11 Economic study results

Finally, an economic study was conducted in order to determine the payback period of the system and the total benefit after its lifetime. These figures resulted a payback time of 19 years and an overall profit of £15,398 with the current economic scenario.

3.10.12 Environmental calculation results

Some environmental calculations were carried out in order to known the emissions of CO_2 which would be avoided because of this system energy generation. The calculations showed that the energy generated throughout the expected lifetime of this system (25years) would be equivalent to 12.68 tonnes of oil equivalent. This means that at least 26.2 tonnes of CO_2 emissions would be avoided, if the same energy were to be generated using Natural Gas. Nevertheless, if the energy were to be extracted from Coal, the emissions avoided would be 48.2, whereas they would be 36.8 in the case of Gasoil.

3.11 Preliminary design of the electrical installation

The aim of this section is to establish the basic parameters in which the final design of the electrical installation for the PV system designed should be based. All the calculations conducted within this section are based on recommendations by the DTI in the *Guide to the installation of PV systems in buildings* (2006).

3.11.1 DC system

3.11.1.1 Minimum voltage and current ratings

Every DC component within the PV system (cables, connectors, switches, isolators, etc.) must be rated over the maximum voltage and current of the PV array. In the case of crystalline silicone modules, all DC components must have a minimum rate of:

- Voltage: $V_{oc(STC)} \cdot 1.15$
- Current: $I_{sc(STC)} \cdot 1.25$

This would mean that, the DC ratings for the components in Array A and Array B in this system must be rated, at least, as showed by Table 3.9.

3.11.1.2 DC cables

3.11.1.2.1 DC cables – general

All DC cables must be rated to the values in Table 3.9, as a minimum. For the design of the cables, de-rating factor included in BS 7671 (2008) must be also applied.

Also, it is a good practice to design the cables that the voltage drop between modules and inverter is less than 3%.

$V_{oc(STC)}$ (V)	$I_{sc(STC)}$ (A)	Minimum DC Voltage rating (V)	Minimum DC Current rating (A)
48.8	6.43	56.1	8.1

Table 3.9. Minimum DC ratings.

Every DC cable routed behind a PV array must have a temperature rating of, at least, 80°C. In addition to this, cables must be selected in order to lower the risk of short-circuits and earth faults to a minimum.

3.11.1.2.2 String cables

String cables in arrays with no string fuses must be rated, as a minimum to:

- Voltage: $V_{oc(STC)} \cdot M \cdot 1.15$
- Current: $I_{sc(STC)} \cdot (N-1) \cdot 1.25$

Where N represents the number of strings and M represents the number of modules per string.

On the other hand, in arrays with string fuses, the rating must be, as a minimum:

- Voltage: $V_{oc(STC)} \cdot M \cdot 1.15$
- Current: $I_{sc(STC)}) \cdot 1.25$

The resultant ratings for string cables are showed in Table 3.10.

3.11.1.2.3 Main DC cable

Main DC cables must be rated, as a minimum to:

- Voltage: $V_{oc(STC)} \cdot M \cdot 1.15$
- Current: $I_{sc(STC)} \cdot N \cdot 1.25$

Results are shown in Table 3.11.

Array	Number of strings (N)	Modules per string (M)	$V_{oc(STC)}$ (V)	$I_{sc(STC)}$ (A)	Voltage rating with no string fuses(V)	Current rating with no string fuses (A)	Voltage rating with string fuses(V)	Current rating with string fuses (A)
A	3	8	48.8	6.43	449	16.1	449	8
B	2	9	48.8	6.43	506	8.1	506	8.1

Table 3.10. DC Voltage and current ratings for string cables.

Array	Number of strings (N)	Modules per string (M)	$V_{oc(STC)}$ (V)	$I_{sc(STC)}$ (A)	Voltage rating of main DC cable (V)	Current rating with no string fuses (A)
A	3	8	48.8	6.43	449	24.1

B	2	9	48.8	6.43	506	16.1

Table 3.11. Voltage and current minimum rating for main DC cables.

3.11.1.3 Plug and socket connectors

These must be DC rated and they must have at least the same voltage and current ratings as the cable they are fitted to.

Also, if the connectors are accessible to people other than trained personal in the course of PV maintenance, a sign 'Do not disconnect DC plugs and sockets under load – turn off AC supply first' must be visible close to the connectors.

3.11.1.4 Junction boxes

Junction boxes, if any, must be labelled as 'PV array DC junction box' and they must also show a label with 'Danger contains live parts during daylight'. Labels must be easily visible, durables and clearly legible.

3.11.1.5 String fuses

Every array composed by four or more strings must include string fuses. Since the arrays in this system are formed of three and two strings respectively, string fuses are not compulsory, nevertheless, there is an extra requirement for omitting string fuses when arrays have three or less strings: PV modules must be able to withstand a reverse current of 2 x 1.15 x I_{sc} and the current rating of the string cables should be as stated before

SunPower E19/245 PV modules are capable of withstanding a reverse current of 16.1 A, according to the manufacturer. This current is clearly above the 14.8 A resultant of applying the equation above. However, the figures are quite close and the installation of string fuses should be studied.

If string fuses were to be installed, they must be fitted in positive and negative cables for every string.

3.11.1.6 Blocking diodes

Blocking diodes are not a common feature of PV grid-connected systems, as their function is perfectly covered by string fuses. Nevertheless, if blocking diodes were installed, they must have a minimum reverse voltage of 2 x V_{oc} x number of modules per string, i.e. blocking diodes for Array A must have a reverse voltage of 781 V, at least, whereas the reverse voltage of the diodes for Array B must be 878 V as a minimum.

3.11.1.7 DC switch

In order to isolate PV positive array and PV negative array, DC switch must be double pole. Also, it must be rated for DC operation as above.

In addition to this, DC switches must be labelled with 'PV array DC isolator' and both ON ad OFF positions must be neatly marked.

3.11.2 Earthing and lightning protection

Even though this part is recommended to be consulted with specialists, since the inverter topology is transformerless, the array frame should be earthed directly to the property earthing.

3.11.3 AC system

3.11.3.1 AC cabling

The PV inverter must be installed in a circuit in which no current-consuming equipment is connected, also socket-outlets are not permitted in that circuit. Besides, there must be no provision for the connection of the mentioned current-consuming equipment.

In addition to that, all AC cables must be designed, specified and installed following BS 7671.

3.11.3.2 AC switch-disconnector

A manual AC switch-disconnector must be installed in an accessible position throughout the Customer installation in accordance with G83/1 or G59/2, whichever applies.

This switch must be clearly labelled as 'PV main ac isolator'.

3.11.3.3 Fault Current protection

The electrical protection must be designed, specified and installed according to BS 7671 and protection against short-circuit must be provided at the consumer unit for the output cable from the inverter(s).

3.11.3.4 Metering

A metering device should be installed in order to show and store the energy generated by the PV system. A kWh meter approved by OFGEM is highly recommended in order to facilitate the fees payment.

3.12 Preliminary structural study

The aim of this section is to set the path to a further structural study which should be carried out prior the installation of the PV system in order to ensure the structural safety in the building. All the calculations and equations throughout this section are extracted from the document *Digest 489: Wind loads on roof-based photovoltaic systems* (Blackmore, 2004).

In order to perform the structural calculations, the following considerations have been made:

- The PV array on the western roof would be hypothetically mounted 150 mm above the roof surface, as recommended in Digest 489 (Blackmore, 2004).
- The site is Edinburgh (Zone III).
- The building ridge edge is 6.7 metres.
- The site is on ground level.

- The site is around 40 above sea level.

3.12.1 Wind force on modules in Array A

The wind force acting on the modules situated on the western roof, both upwards and downwards was calculated as follow.

The equation used for wind force, extracted by Digest 489, was:

$$F = q_s \cdot C_{p,\ net} \cdot C_a \cdot A_{ref}$$

Where q_s would be the dynamic wind pressure, $C_{p,\ net}$ would be a pressure coefficient which depends on the system, C_a would be the size effect factor taken by Digest 489 from BS6399-2 and A_{ref} would be the loaded area, i.e. the module area.

3.12.1.1 <u>Wind force on modules situated in the centre of the roof</u>

Selecting the correct values from the tables in Digest 489, the wind force applied on the modules situated in the centre of the western roof would be:

$$F = 1469 \cdot 1.0 \cdot 1.0 \cdot 1.2 = 1763\ N \text{ (downwards acting)}$$
$$F = 1469 \cdot (-1.3) \cdot 1.0 \cdot 1.2 = -2291\ N \text{ (upwards acting)}$$

Therefore, both PV modules and their fixings must be designed in order to withstand these forces.

3.12.1.2 <u>Wind force on modules situated near the edge of the roof</u>

Selecting the correct values from the tables in Digest 489, the wind force applied on the modules situated in the centre of the western roof would be:

$$F = 1469 \cdot 1.8 \cdot 1.0 \cdot 1.2 = 3173\ N \text{ (downwards acting)}$$

$$F = 1469 \cdot (-1.3) \cdot 1.0 \cdot 1.2 = -2291\ N \text{ (upwards acting)}$$

Therefore, both PV modules and their fixings must be designed in order to withstand these forces.

3.12.2 Wind force on modules in Array B

As the modules on the garage roof would be free-standing modules over a flat roof with no parapet, they must be calculated against sliding and overturned as specified in Digest 489. The addition of ballasts should be considered in order to raise safety.

4. <u>Discussion</u>

This chapter will discuss the results obtained previously, regarding the main strengths and weaknesses of the study. Also, some recommendations will be made in order to lead possible future work.

After finishing the feasibility study, the main outcome was that the project is in fact feasible, in both technical and economic ways. Implementing the PV system designed, the property would be able to generate annually more than consume, since the annual generation for the first year was estimated about 120% of the estimated electricity consumption in the property.

Nevertheless, the work in this field is unfinished and some actions would be needed in order to finally install the system in the property. The next section will examine the strong and weak points of the progress done so far.

4.1. Strengths and weaknesses

If one of the strengths of this study were to be highlighted over the others, it would be the environmental-friendly character of this project. As it has been commented above, with this system the property would be able to generate the energy required, and the polluting emissions to the atmosphere avoided were estimated at a minimum of 12 tonnes of CO_2.

Another strong point would be the facts that, in spite of renewable energies have a relatively short history, solar energy and most concretely PV is a field which has been much researched and, therefore, a reliable technology. Furthermore, the PV market is getting more competitive every day and this boosts manufacturers to develop prime quality devices in order to situate themselves in a priority spot.

The last strength to be mentioned would be the economic feasibility of the project, even though the payback time has been calculated as 19 years, the final profit over 25 years was estimated in over £15,000. Nevertheless, this is a discouraging figure if compared to the nearly £60,000 of lifetime benefit and the 11 years of payback time obtained in the economic simulation with the previous FiT scheme. This is a clear indicative that, despite the prices of PV system have obviously decreased, they have not decreased as the same rate than the fees and, therefore, these results in nearly double payback periods and benefits quartered.

On the other hand, the work done has its obvious weaknesses. Again, if one of them were to be highlighted over all of them, that might be the inaccuracy caused by the weather data employed; whilst the fact that weather is, essentially, unpredictable both at short and long term, it can be denied how more reliable results were obtained if the data were actually measured on the property studied during a sample year.

Furthermore, it must be noted that simulation software, despite being a very useful tool, has its limitations and the predictions must not be trusted a hundred per cent.

Finally, one more weakness would be the fact that the complete system cost was estimated by extrapolating an average of quotes data and it was not obtained directly from either the manufacturers of the component separately or from an authorised PV installer.

4.2. Conclusion

In conclusion, it can be said that the result of this study was a feasible grid-connected PV system that, even though might not be totally interesting to implement with regard to economic aspects, would be a renewable, non-polluting, clean manner of generating more than the electrical energy demanded by the property.

Only the fact that the total of the energy would not be generated and demanded by the property at the same time forbids saying that, if implementing the system studied in this paper, the property would be energy self-sufficient.

4.3. Future work

If further work were to be conducted within this study, it should first lead to palliate the weaknesses discussed above: the most desired deliverable would be to obtain actual insolation data from the property, if possible, exactly over the considered areas throughout this study.

A handier target would be to acquire a concise economic budget for the installation, either from a PV installer or calculating by adding the different component prices and estimating design and installation costs.

If these targets were completed and the ultimate feasibility of the system were reaffirmed, the last piece of work would be to accomplish the complete electrical design, under the premises established in this paper, as well as to perform the convenient structural study with the guidance given previously in this project.

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Appendix A: PVSyst Simulation Results

UNIVERSITÉ DE GENÈVE PVSYST	PVSYST V5.11	Alfonso Diaz Munoz	Page 1/2

Grid-Connected System: Main results

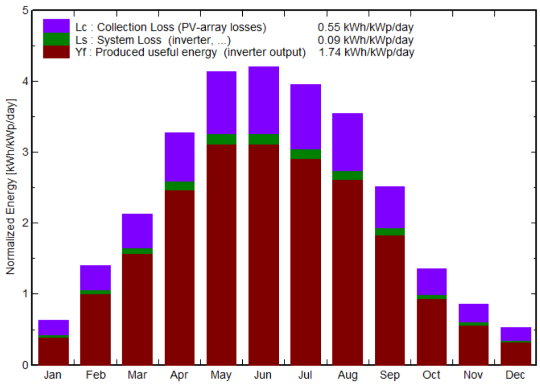
Project : **Honours Project**

Simulation variant : **Array A (Western roof)**

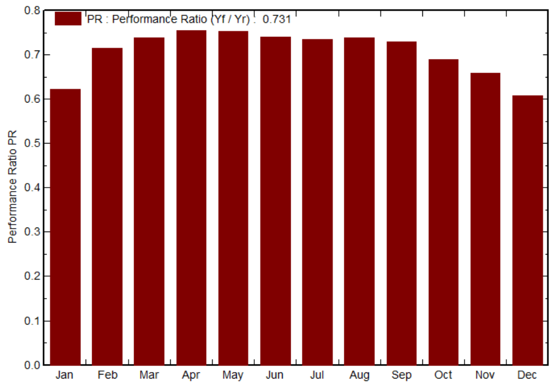
Main system parameters	System type	**Grid-Connected**		
Near Shadings	Linear shadings			
PV Field Orientation	tilt	43°	azimuth	70°
PV modules	Model	E19 / 245	Pnom	245 Wp
PV Array	Nb. of modules	24	Pnom total	**5.9 kWp**
Inverter	Model	Sunny Boy SB 5000 TL	Pnom	4.6 kW ac
User's needs	Unlimited load (grid)			

Main simulation results				
System Production	**Produced Energy**	**3739 kWh/year**	Specific prod.	636 kWh/kWp/year
	Performance Ratio PR	73.1 %		

Normalized productions (per installed kWp): Nominal power 5.9 kWp



Performance Ratio PR



Array A (Western roof)

Balances and main results

	GlobHor	T Amb	GlobInc	GlobEff	EArray	E_Grid	EffArrR	EffSysR
	kWh/m²	°C	kWh/m²	kWh/m²	kWh	kWh	%	%
January	15.8	3.00	19.5	17.6	77.4	71.5	13.26	12.25
February	32.8	3.00	39.4	36.4	175.1	165.6	14.90	14.09
March	63.6	5.00	66.0	61.8	302.1	286.8	15.33	14.56
April	97.2	7.00	98.2	92.7	457.9	436.3	15.61	14.87
May	140.4	10.00	128.4	121.2	595.6	568.3	15.53	14.82
June	138.3	13.00	126.1	119.1	576.5	549.6	15.31	14.60
July	133.3	15.00	122.8	116.0	556.5	530.3	15.18	14.46
August	112.5	14.00	109.9	103.8	500.8	477.3	15.26	14.55
September	74.1	12.00	75.5	70.7	340.8	324.0	15.11	14.37
October	41.8	10.00	42.2	39.1	181.8	171.3	14.42	13.59
November	19.5	6.00	25.7	23.4	106.5	99.4	13.87	12.95
December	11.8	4.00	16.3	14.4	63.1	58.2	12.97	11.97
Year	881.1	8.53	870.1	816.1	3934.0	3738.6	15.14	14.39

Legends:				
	GlobHor	Horizontal global irradiation	EArray	Effective energy at the output of the array
	T Amb	Ambient Temperature	E_Grid	Energy injected into grid
	GlobInc	Global incident in coll. plane	EffArrR	Effic. Eout array / rough area
	GlobEff	Effective Global, corr. for IAM and shadings	EffSysR	Effic. Eout system / rough area

Figure A 1. PVSyst simulation results for Array A (part 1).

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Grid-Connected System: Loss diagram

Project : **Honours Project**

Simulation variant : **Array A (Western roof)**

Main system parameters	System type	**Grid-Connected**		
Near Shadings	Linear shadings			
PV Field Orientation	tilt	43°	azimuth	70°
PV modules	Model	E19 / 245	Pnom	245 Wp
PV Array	Nb. of modules	24	Pnom total	**5.9 kWp**
Inverter	Model	Sunny Boy SB 5000 TL	Pnom	4.6 kW ac
User's needs	Unlimited load (grid)			

Loss diagram over the whole year

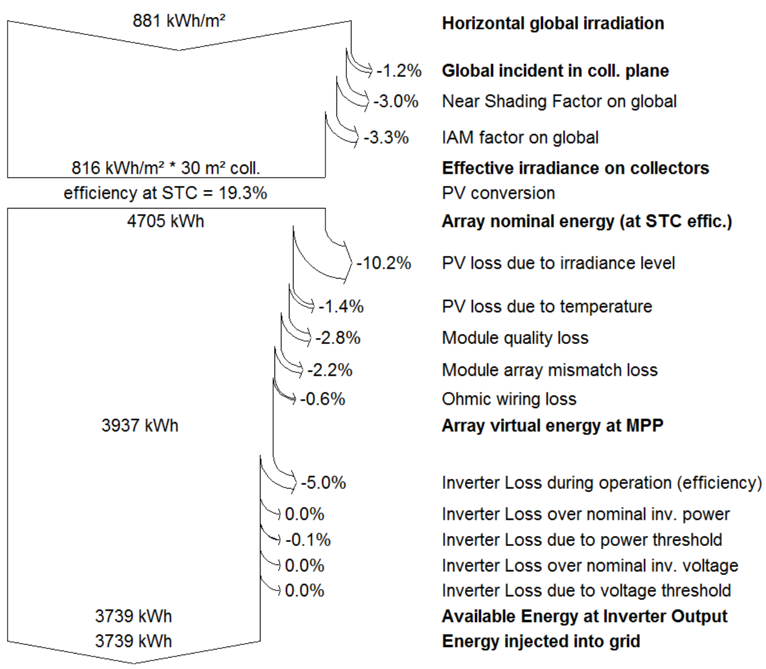

Figure A 2. PVSyst simulation results for Array A (part 2).

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Grid-Connected System: Main results

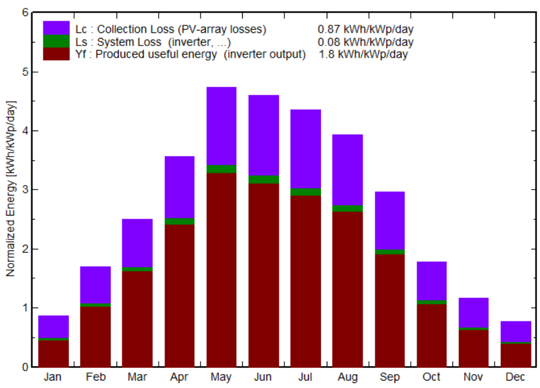
Project : **Honours Project**

Simulation variant : **Array B (Garage roof)**

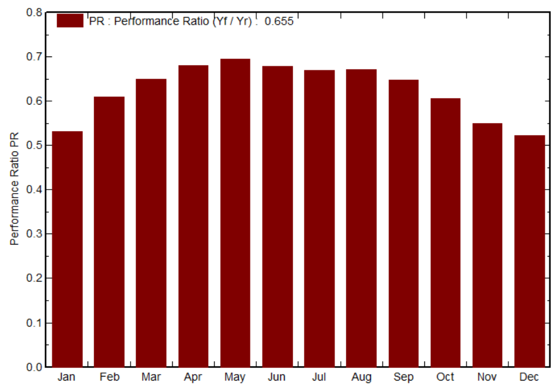
Main system parameters	System type	**Grid-Connected**		
Near Shadings	Linear shadings			
PV Field Orientation	tilt	30°	azimuth	-20°
PV modules	Model	E19 / 245	Pnom	245 Wp
PV Array	Nb. of modules	18	Pnom total	**4.4 kWp**
Inverter	Model	Sunny Boy SB 4000 TL	Pnom	4.0 kW ac
User's needs	Unlimited load (grid)			

Main simulation results				
System Production	**Produced Energy**	**2896 kWh/year**	Specific prod.	657 kWh/kWp/year
	Performance Ratio PR	65.5 %		

Normalized productions (per installed kWp): Nominal power 4.4 kWp



Performance Ratio PR



Array B (Garage roof)
Balances and main results

	GlobHor	T Amb	GlobInc	GlobEff	EArray	E_Grid	EffArrR	EffSysR
	kWh/m²	°C	kWh/m²	kWh/m²	kWh	kWh	%	%
January	15.8	3.00	26.9	19.9	67.6	62.9	11.24	10.46
February	32.8	3.00	47.4	37.0	134.0	127.5	12.62	12.01
March	63.6	5.00	77.7	63.1	232.9	222.6	13.39	12.80
April	97.2	7.00	106.9	89.9	334.1	320.4	13.96	13.38
May	140.4	10.00	146.8	126.2	468.2	450.1	14.24	13.69
June	138.3	13.00	137.9	118.0	430.5	412.9	13.94	13.37
July	133.3	15.00	134.8	115.1	415.3	398.3	13.76	13.19
August	112.5	14.00	121.8	103.4	376.2	361.0	13.79	13.23
September	74.1	12.00	88.9	72.8	264.9	253.8	13.31	12.75
October	41.8	10.00	55.1	43.6	154.9	147.1	12.55	11.92
November	19.5	6.00	34.9	25.8	89.6	84.5	11.47	10.81
December	11.8	4.00	23.7	17.1	58.1	54.5	10.94	10.27
Year	881.1	8.53	1002.8	832.0	3026.3	2895.6	13.48	12.89

Legends:				
	GlobHor	Horizontal global irradiation	EArray	Effective energy at the output of the array
	T Amb	Ambient Temperature	E_Grid	Energy injected into grid
	GlobInc	Global incident in coll. plane	EffArrR	Effic. Eout array / rough area
	GlobEff	Effective Global, corr. for IAM and shadings	EffSysR	Effic. Eout system / rough area

Figure A 3. PVSyst simulation results for Array B (part 1).

PVSYST V5.11	Alfonso Diaz Munoz	Page 2/2

Grid-Connected System: Loss diagram

Project : **Honours Project**

Simulation variant : **Array B (Garage roof)**

Main system parameters	System type	**Grid-Connected**		
Near Shadings	Linear shadings			
PV Field Orientation	tilt	30°	azimuth	-20°
PV modules	Model	E19 / 245	Pnom	245 Wp
PV Array	Nb. of modules	18	Pnom total	**4.4 kWp**
Inverter	Model	Sunny Boy SB 4000 TL	Pnom	4.0 kW ac
User's needs	Unlimited load (grid)			

Loss diagram over the whole year

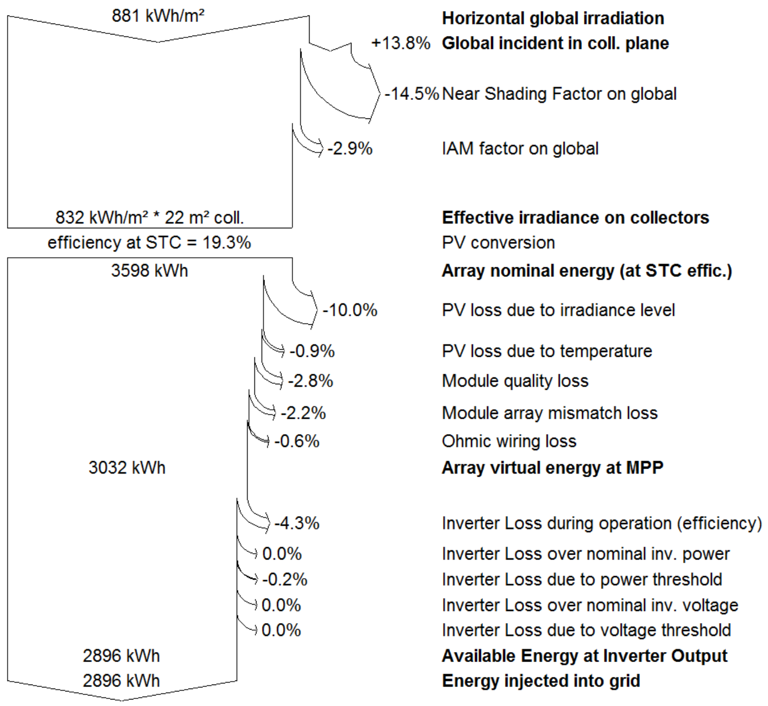


Figure A 4. PVSyst simulation results for Array B (part 2).

Appendix B: Economic Study Tables

SCENARIO A	Energy Generated (kWh)	FiT Tariff (p/kWh)	Export rate (p/kWh)	Home electric tariff (p/kWh)	Energy Exported (kWh)	Energy Consumed (kWh)	FiT Income (£)	Export Income (£)	Bill Savings (£)	Annual Income (£)	Accumulate Income (£)	Payback (£)
Year 1	6635.00	16.80	3.20	14.40	4976.25	1658.75	1114.68	159.24	238.86	1512.78	1512.78	-33487.22
Year 2	6568.65	17.36	3.31	14.88	4926.49	1642.16	1140.39	162.91	244.37	1547.67	3060.45	-31939.55
Year 3	6502.96	17.94	3.42	15.38	4877.22	1625.74	1166.70	166.67	250.01	1583.37	4643.83	-30356.17
Year 4	6437.93	18.54	3.53	15.89	4828.45	1609.48	1193.61	170.52	255.77	1619.89	6263.72	-28736.28
Year 5	6373.55	19.16	3.65	16.42	4780.17	1593.39	1221.14	174.45	261.67	1657.26	7920.98	-27079.02
Year 6	6309.82	19.80	3.77	16.97	4732.36	1577.45	1249.30	178.47	267.71	1695.49	9616.47	-25383.53
Year 7	6246.72	20.46	3.90	17.54	4685.04	1561.68	1278.12	182.59	273.88	1734.59	11351.06	-23648.94
Year 8	6184.25	21.14	4.03	18.12	4638.19	1546.06	1307.60	186.80	280.20	1774.60	13125.66	-21874.34
Year 9	6122.41	21.85	4.16	18.73	4591.81	1530.60	1337.76	191.11	286.66	1815.54	14941.20	-20058.80
Year 10	6061.19	22.58	4.30	19.35	4545.89	1515.30	1368.62	195.52	293.28	1857.41	16798.61	-18201.39
Year 11	6000.58	23.33	4.44	20.00	4500.43	1500.14	1400.19	200.03	300.04	1900.26	18698.87	-16301.13
Year 12	5940.57	24.11	4.59	20.67	4455.43	1485.14	1432.49	204.64	306.96	1944.09	20642.96	-14357.04
Year 13	5881.16	24.92	4.75	21.36	4410.87	1470.29	1465.53	209.36	314.04	1988.93	22631.89	-12368.11
Year 14	5822.35	25.75	4.91	22.07	4366.76	1455.59	1499.33	214.19	321.29	2034.81	24666.69	-10333.31
Year 15	5764.13	26.61	5.07	22.81	4323.10	1441.03	1533.92	219.13	328.70	2081.74	26748.44	-8251.56
Year 16	5706.49	27.50	5.24	23.57	4279.87	1426.62	1569.30	224.19	336.28	2129.76	28878.20	-6121.80
Year 17	5649.42	28.42	5.41	24.36	4237.07	1412.36	1605.49	229.36	344.03	2178.88	31057.08	-3942.92
Year 18	5592.93	29.37	5.59	25.17	4194.70	1398.23	1642.53	234.65	351.97	2229.14	33286.22	-1713.78
Year 19	5537.00	30.35	5.78	26.01	4152.75	1384.25	1680.41	240.06	360.09	2280.56	35566.78	566.78
Year 20	5481.63	31.36	5.97	26.88	4111.22	1370.41	1719.17	245.60	368.39	2333.16	37899.95	2899.95
Year 21	5426.81	32.41	6.17	27.78	4070.11	1356.70	1758.83	251.26	376.89	2386.98	40286.93	5286.93
Year 22	5372.54	33.49	6.38	28.71	4029.41	1343.14	1799.40	257.06	385.58	2442.04	42728.96	7728.96
Year 23	5318.82	34.61	6.59	29.67	3989.11	1329.70	1840.90	262.99	394.48	2498.37	45227.33	10227.33
Year 24	5265.63	35.77	6.81	30.66	3949.22	1316.41	1883.36	269.05	403.58	2555.99	47783.32	12783.32
Year 25	5212.97	36.96	7.04	31.68	3909.73	1303.24	1926.81	275.26	412.89	2614.95	50398.28	15398.28

Table B 1. Economic study table for Scenario A.

SCENARIO B	Energy Generated (kWh)	FiT Tariff (p/kWh)	Export rate (p/kWh)	Home electric tariff (p/kWh)	Energy Exported (kWh)	Energy Consumed (kWh)	FiT Income (£)	Export Income (£)	Bill Savings (£)	Annual Income (£)	Accumulate Income (£)	Payback (£)
Year 1	6635.00	36.80	3.20	14.40	4976.25	1658.75	2441.68	159.24	238.86	2839.78	2839.78	-32160.22
Year 2	6568.65	38.03	3.31	14.88	4926.49	1642.16	2498.00	162.91	244.37	2905.28	5745.06	-29254.94
Year 3	6502.96	39.30	3.42	15.38	4877.22	1625.74	2555.62	166.67	250.01	2972.30	8717.36	-26282.64
Year 4	6437.93	40.61	3.53	15.89	4828.45	1609.48	2614.57	170.52	255.77	3040.85	11758.21	-23241.79
Year 5	6373.55	41.97	3.65	16.42	4780.17	1593.39	2674.87	174.45	261.67	3110.99	14869.21	-20130.79
Year 6	6309.82	43.37	3.77	16.97	4732.36	1577.45	2736.57	178.47	267.71	3182.75	18051.96	-16948.04
Year 7	6246.72	44.82	3.90	17.54	4685.04	1561.68	2799.69	182.59	273.88	3256.17	21308.13	-13691.87
Year 8	6184.25	46.32	4.03	18.12	4638.19	1546.06	2864.27	186.80	280.20	3331.27	24639.40	-10360.60
Year 9	6122.41	47.86	4.16	18.73	4591.81	1530.60	2930.34	191.11	286.66	3408.11	28047.51	-6952.49
Year 10	6061.19	49.46	4.30	19.35	4545.89	1515.30	2997.93	195.52	293.28	3486.72	31534.24	-3465.76
Year 11	6000.58	51.11	4.44	20.00	4500.43	1500.14	3067.08	200.03	300.04	3567.15	35101.39	101.39
Year 12	5940.57	52.82	4.59	20.67	4455.43	1485.14	3137.83	204.64	306.96	3649.43	38750.81	3750.81
Year 13	5881.16	54.58	4.75	21.36	4410.87	1470.29	3210.20	209.36	314.04	3733.61	42484.42	7484.42
Year 14	5822.35	56.41	4.91	22.07	4366.76	1455.59	3284.25	214.19	321.29	3819.73	46304.15	11304.15
Year 15	5764.13	58.29	5.07	22.81	4323.10	1441.03	3360.00	219.13	328.70	3907.83	50211.98	15211.98
Year 16	5706.49	60.24	5.24	23.57	4279.87	1426.62	3437.51	224.19	336.28	3997.97	54209.95	19209.95
Year 17	5649.42	62.25	5.41	24.36	4237.07	1412.36	3516.80	229.36	344.03	4090.19	58300.13	23300.13
Year 18	5592.93	64.33	5.59	25.17	4194.70	1398.23	3597.91	234.65	351.97	4184.53	62484.66	27484.66
Year 19	5537.00	66.48	5.78	26.01	4152.75	1384.25	3680.90	240.06	360.09	4281.05	66765.72	31765.72
Year 20	5481.63	68.70	5.97	26.88	4111.22	1370.41	3765.81	245.60	368.39	4379.80	71145.51	36145.51
Year 21	5426.81	70.99	6.17	27.78	4070.11	1356.70	3852.67	251.26	376.89	4480.82	75626.34	40626.34
Year 22	5372.54	73.36	6.38	28.71	4029.41	1343.14	3941.54	257.06	385.58	4584.18	80210.51	45210.51
Year 23	5318.82	75.81	6.59	29.67	3989.11	1329.70	4032.45	262.99	394.48	4689.92	84900.43	49900.43
Year 24	5265.63	78.35	6.81	30.66	3949.22	1316.41	4125.46	269.05	403.58	4798.09	89698.52	54698.52
Year 25	5212.97	80.96	7.04	31.68	3909.73	1303.24	4220.62	275.26	412.89	4908.77	94607.29	59607.29

Table B 2. Economic study table for Scenario B.

SCENARIO C	Energy Generated (kWh)	FiT Tariff (p/kWh)	Export rate (p/kWh)	Home electric tariff (p/kWh)	Energy Exported (kWh)	Energy Consumed (kWh)	FiT Income (£)	Export Income (£)	Bill Savings (£)	Annual Income (£)	Accumulate Income (£)	Payback (£)
Year 1	6635.00	9.00	3.20	14.40	4976.25	1658.75	597.15	159.24	238.86	995.25	995.25	-34004.75
Year 2	6568.65	9.30	3.31	14.88	4926.49	1642.16	610.92	162.91	244.37	1018.21	2013.46	-32986.54
Year 3	6502.96	9.61	3.42	15.38	4877.22	1625.74	625.02	166.67	250.01	1041.69	3055.15	-31944.85
Year 4	6437.93	9.93	3.53	15.89	4828.45	1609.48	639.43	170.52	255.77	1065.72	4120.87	-30879.13
Year 5	6373.55	10.26	3.65	16.42	4780.17	1593.39	654.18	174.45	261.67	1090.30	5211.17	-29788.83
Year 6	6309.82	10.61	3.77	16.97	4732.36	1577.45	669.27	178.47	267.71	1115.45	6326.62	-28673.38
Year 7	6246.72	10.96	3.90	17.54	4685.04	1561.68	684.71	182.59	273.88	1141.18	7467.80	-27532.20
Year 8	6184.25	11.33	4.03	18.12	4638.19	1546.06	700.50	186.80	280.20	1167.50	8635.30	-26364.70
Year 9	6122.41	11.71	4.16	18.73	4591.81	1530.60	716.66	191.11	286.66	1194.43	9829.74	-25170.26
Year 10	6061.19	12.10	4.30	19.35	4545.89	1515.30	733.19	195.52	293.28	1221.98	11051.72	-23948.28
Year 11	6000.58	12.50	4.44	20.00	4500.43	1500.14	750.10	200.03	300.04	1250.17	12301.89	-22698.11
Year 12	5940.57	12.92	4.59	20.67	4455.43	1485.14	767.40	204.64	306.96	1279.01	13580.89	-21419.11
Year 13	5881.16	13.35	4.75	21.36	4410.87	1470.29	785.10	209.36	314.04	1308.51	14889.40	-20110.60
Year 14	5822.35	13.80	4.91	22.07	4366.76	1455.59	803.21	214.19	321.29	1338.69	16228.09	-18771.91
Year 15	5764.13	14.26	5.07	22.81	4323.10	1441.03	821.74	219.13	328.70	1369.57	17597.66	-17402.34
Year 16	5706.49	14.73	5.24	23.57	4279.87	1426.62	840.69	224.19	336.28	1401.16	18998.81	-16001.19
Year 17	5649.42	15.22	5.41	24.36	4237.07	1412.36	860.09	229.36	344.03	1433.48	20432.29	-14567.71
Year 18	5592.93	15.73	5.59	25.17	4194.70	1398.23	879.92	234.65	351.97	1466.54	21898.83	-13101.17
Year 19	5537.00	16.26	5.78	26.01	4152.75	1384.25	900.22	240.06	360.09	1500.37	23399.20	-11600.80
Year 20	5481.63	16.80	5.97	26.88	4111.22	1370.41	920.99	245.60	368.39	1534.98	24934.18	-10065.82
Year 21	5426.81	17.36	6.17	27.78	4070.11	1356.70	942.23	251.26	376.89	1570.38	26504.56	-8495.44
Year 22	5372.54	17.94	6.38	28.71	4029.41	1343.14	963.96	257.06	385.58	1606.60	28111.16	-6888.84
Year 23	5318.82	18.54	6.59	29.67	3989.11	1329.70	986.20	262.99	394.48	1643.66	29754.82	-5245.18
Year 24	5265.63	19.16	6.81	30.66	3949.22	1316.41	1008.94	269.05	403.58	1681.57	31436.40	-3563.60
Year 25	5212.97	19.80	7.04	31.68	3909.73	1303.24	1032.22	275.26	412.89	1720.36	33156.76	-1843.24

Table B 3. Economic study table for Scenario A